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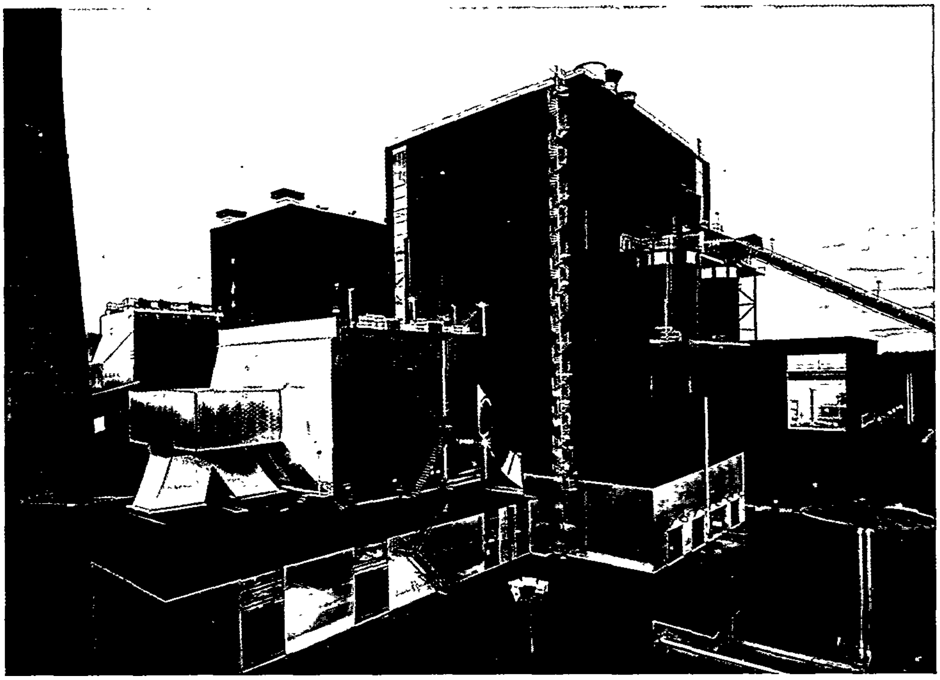
BALTICA IV

Plant Maintenance for Managing Life & Performance

Vol. 2



Helsinki Energy

IVO GROUP

PVO GROUP

VTT TECHNICAL RESEARCH CENTRE OF FINLAND ESPOO 1998

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Oy EDITA Ab, Espoo 1998

Preface

A competitive plant must perform in a changing economical environment without compromising on safe service. This creates an optimisation task in which solutions are shaped by increasingly free market forces both in Europe and elsewhere, future costs of available fuels, the regulatory environment of the plant, and new or emerging technology that could set new standards for the industry.

All this affects not only new but also existing plants – and for both, these turbulent times offer plenty of opportunity to explore the technological basis for new solutions. The BALTICA IV Conference aims to provide state-of-the-art professional experience on current issues in plant maintenance for managing the life and performance of critically important systems and components.

Compared with earlier BALTICA Conferences the volume of combined presentations has again increased, hopefully reflecting the response by the BALTICA conference series to the needs of companies and professional personnel in this field. The first part of the programme and the publication are structured around major processes and subsystems in the plant, and the second part around technological viewpoints for tackling major issues or new trends.

The editors wish to express their sincere gratitude to the authors, referees, organisers and the Board of the Conference for their invaluable contribution in preparing the BALTICA IV Conference. Financial support by the CEC and other sponsoring organisations is also gratefully acknowledged.

Espoo, September 1998

Seija Hietanen　　　　Pertti Auerkari

BALTICA IV Editors

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Opening address

Dear Colleagues,

On behalf of VTT Manufacturing Technology I have the pleasure of welcoming you to the BALTICA IV Conference on Plant Maintenance for Managing Life & Performance. The Conference, this being already the fourth in the series, has become an important meeting for reviewing the evolving technology.

Management of the life and performance of power plants is of considerable economic, environmental and community value. A reliable, environmentally sustainable and competitive production of energy is one of the cornerstones of modern society. However, attaining good plant performance requires a vast range of knowledge and technologies. This is clearly reflected in the programme of this conference. In addition to the use of materials and inspection technologies for evaluating and maintaining the reliability and safety of power plants, ever stronger emphasis is being placed on maintenance management and the application of information technology in predicting the behaviour of plants and their components. One essential feature of this conference is that the greater part of the work presented is application oriented. We therefore look forward to an interesting exchange of views between researchers and those involved in practical plant maintenance.

The presentations of the BALTICA IV Conference reflect a great variety of topics covering the whole range referred to above. Together with the contributions of the participants, an interesting and fruitful meeting is anticipated. Organising part of the conference on board a cruise ship will provide an easy forum for discussions and getting acquainted with other participants.

I would like to acknowledge the contribution of the International Board of the Conference and the Executive Committee in organising the Conference. It is also my pleasure to thank the authors for their presentations, the session chairmen, and all the participants for their contributions which will make this conference.

Prof. Heikki Kleemola
Research Director

VTT Manufacturing Technology

Power Plant Asset Market Evaluations: Forecasting the Costs of Power Production

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Abstract

This paper discusses the process of evaluating and valuing power plants for sale. It describes a method to forecast the future costs at a power plant using a portion of the past fixed costs, variable energy costs, and most importantly the variable cycling-related wear-and-tear costs. The paper then discusses how to best determine market share, expected revenues, and then to forecast plant future costs based on future expected unit cycling operations. The paper concludes with a section on recommendations to power plant buyers or sellers on how to manage the power plant asset and how to increase its market value.

1 Introduction

Many people in the electric utility industry are shaking their heads in wonder at the huge premiums winning bidders are paying for generation assets that have been sold in auction to date. We have been surprised by this trend as well. However, as APTECH has become more involved in assisting bidders in the due diligence process (incidentally, most of the clients we have assisted have been the successful bidders, "winning" 35 of 42 plant bids), we have a better understanding of why these premiums may be justified.

This presentation summarizes our experience and views of how the bid preparation process typically proceeds, and how it should proceed. Since APTECH's primary focus as consultants to bidders has been on engineering due diligence (i.e., estimating future costs), and to a lesser extent, estimating future revenues, we will mostly discuss these areas.

2 Estimating Future Cost Requirements

Tight time frames, and limited access to plant personnel and the "data rooms," make accurate cost forecasting a major challenge. Our clients typically arrive at the conclusion that they and their financial institutions need good technical help but still wait until about three weeks prior to the final round bid date to procure our services. This is about the time they are informed that they have been found to be an acceptable bidder and passed the first round of bidding.

We generally go through a process like a "Level 1 or 2 Condition Assessment" for each unit under consideration. This consists of reading plant descriptions, failure reports, condition assessment reports, engineering analysis, heat rate studies, fuel switching studies, environmental reports, accident/spill reports, maintenance schedules, overhaul plans, and every other sort of study or analysis of the power plant. APTECH uses this data and its probabilistic models of key power plant components to estimate remaining life. These models rely on component design data, materials, environment, water chemistry, and failure rates (e.g., unit outages, and boiler tube failures). However, unlike doing this for utilities for their own units, where they have an incentive to cooperate and provide as much assistance as possible in data gathering, we must contend with the asset sales agents of the utility, data rooms that allow only one bidder at a time, and direct interfaces with plant personnel and plant walkdowns that are strictly regulated by the sales agent. Due to time limitations, a great amount of expert judgment and insight based on industry experiences with similar types of power generation equipment are needed to help "fill in the gaps" and ensure reasonable estimates of component remaining useful life, component replacements, expected/needed maintenance, and future costs are derived.

The primary elements of future costs are:

1. Fixed costs related to the capital purchase (e.g., interest, depreciation, taxes, insurance, etc.)

2. Fixed costs related to operation and maintenance (mostly based in-house and contract personnel needed no matter whether unit is operating)

3. Fuel costs

4. Non-fuel capital, operating, and maintenance costs directly related to the amount of energy generated

5. Capital, operating, and maintenance costs related to the amount of on-off and load following cycling

The items we that we focus on are items two, four, and five; the various components of capital, maintenance, and operation costs. We believe these costs should be expressed in the form:

$$\text{Total COM} = \text{Fixed COM} + A^* (E) + B^* (EHSs) \quad (1)$$

where,

COM = Annual recurring Capital, Operation and Maintenance costs
A = A coefficient with units $/MWH
E = Energy produced in MWH per year
EHSs = Equivalent Hot Starts per year—an indicator of the total amount of cycling (i.e., cold, warm, and hot starts and load follow cycles)
B = Cost per EHS

Many people in the industry have totally ignored the last term in this equation, or have arbitrarily forced their historical costs to fit an equation without this cycling-related term. We guarantee that this will be disastrous if the operation of the unit changes in the future, particularly if due to market forces it must cycle more while generating less MWHs. In a recent evaluation of a plant with two large super-critical units in California that were frequently load cycled to minimum loads, we estimated that this cycling component was approximately $8 million per year out of a total non-fuel COM budget of about $22 million. For this plant, the cycling component of COM costs far exceeded the energy-related component. This had a big impact on how the client viewed how he should price various energy services such as load following, ramp rates for load control, on-off cycles, and Automatic Generation Control (AGC).

Using the above equation, looking at old fixed costs and estimating what fraction of these fixed costs need to remain in the equation for future cost projection is then a much easier task. One can examine fixed plant staffing and maintenance and evaluate these in light of a meaner, leaner plant staff and contracted maintenance.

How do we accurately estimate the cycling components of costs? We have written a number of technical papers (1, 2, 3, 4) that have outlined our methods for deriving the cycling-related costs. These papers discuss the many types of generation unit damage that is caused (or accelerated) by cycling, and present our methods for estimating the cost impacts of cycling in more detail.

In essence, APTECH relies on both "bottom-up" and "top-down" methods of cost estimation as defined below.

Bottom-up methods refer to detailed engineering assessment and accounting methods looking at individual historical events that are related to cycling, and adding up their costs by year as well as estimating such major cost items in future years based on remaining useful life analyses. A detailed analysis of past maintenance and cost records must be performed. Through APTECH's many years of studying power plant component failures and their underlying causes, we are able to recognize which failures and their corresponding replacement costs are due to cycling, or at least can be partially attributed to cycling.

Top down methods refer to the use of advanced statistical and engineering damage models to relate historical and future COM costs to the effects of cycling, age, and the operation characteristics of a generation unit. We call this "top-down" because we start with accounting data that are aggregated for the entire unit—not trying to identify and relate various costs to specific causes such as the extensive cycling shown in Figure 1. Rather, we use statistical methods on cost and operations data over a long period of time (more than ten years is desired) to develop relationships between costs and the amount of cycling. See Figure 2 for a projection of a heavily cycled power plants' capital and maintenance costs to the year 2000. It is noteworthy that while these future costs were projected by our cost of cycling methodology, they were independently determined using conventional remnant life techniques by a leading authority in remaining life analysis. It is important to realize that if this unit had been baseloaded, we would have seen that 55% of these costs in early years could be attributed to cycling beyond pure baseloaded operation. Later, as creep and fatigue interaction and damage accelerate, this portion is forecast to increase substantially to nearly 75% from two-shifting and load following.

We stress the point of needing good cycling cost information because, as the market changes in the future, there will likely be a need for many older fossil-steam units to cycle more—and this can add millions of dollars per year in what we call cycling wear-and-tear costs.

Another interesting aspect of estimating future costs is to recognize that there is a significant amount of uncertainty in terms of when major capital replacements have to be made and how much they will actually cost. One might consider the cost profile for each future year to be a probability distribution, and it is up to the client (buyer) to determine how aggressive (erring on the low cost side) or conservative (erring on the high cost side) he wants to be. Most of the clients we have worked with that have been the successful bidders have been very aggressive—trying to find ways to make cost projections for plant, equipment, and fuel go as low as possible.

3 Determining Market Share and Expected Revenues

One of the most critical and uncertain aspects of determining the value of a generation asset is forecasting total revenues. That is because the nature of markets is changing rapidly, and the old rules of how generation units are dispatched under a utility controlled cost minimization objective function no longer holds true. This is largely because in an open market system, resources and loads can be pooled from a much larger area, with electrical and fuel transmission constraints being the primary inhibitors of a completely open market.

APTECH has mostly worked with clients who have their own (or another vendor's) generation and transmission simulation or transaction models, and they typically do the bulk of this work themselves. Where we get involved is the iterative process of using initial market model results to determine the capacity factors and the amount of cycling likely to be needed by the market (as shown in Figure 3). One thing is clear to us in viewing these market modeling attempts: The models and how the plants are used are probably not representative of what is going to happen. For example, none of the models we have seen used in this process has explicitly taken into account equipment wear-and tear costs (i.e., increased capital, maintenance, and operating costs) due to cycling, operating for extended periods at minimum loads, or at levels higher than rated capacity. Recent spot prices of electricity of $5,000 to $10,000 per megawatt hour will ensure a significant amount of peaking and cycling.

APTECH has developed a short-term unit commitment model called CYCLING ADVISOR™ that includes a rigorous treatment of wear-and-tear costs in that determination of optimal dispatch. A CYCLING ADVISOR dispatch of a 4,000 MWe utility is shown in Figure 4. We have found in various system studies that when equipment wear-and-tear costs are properly included in the optimization, the dispatch changes significantly from what people normally do. In Figure 5, the optimal dispatch has been compared to a code developed by EPRI called "Dynamics" and it avoids some $600,000 of costs in the heavily-cycled months of April through May in the 4,000 MWe utility system. Note in Figure 5 that the optimization of the unit dispatch leads to lower total costs that are less than the base case. For example, in a system of about 4,000 MW total installed capacity, we estimated the "overall" cost savings (note: by overall we refer to fuel costs and wear-and-tear costs) of properly accounting for wear-and-tear costs in system dispatch to be $15 million to $25 million per year.

Lack of cycling cost consideration is only one area where the models used are deficient. The way that the market will treat ancillary services is so uncertain at this time, one is forced to use a combination of best judgment and pre-established long-term agreements for ancillary services to estimate what the revenues will be in this area. Calculating the additional cycles and load following required for minute-by-minute AGC is a relatively straightforward process with our cost of cycling methodology. However, forecasting when and how much new competitive generation and transmission to the market areas of interest is also very tenuous at this time, since much of this will be highly dependent on the evolving regulatory environments of each state.

4 Adding Value to Assets

One thing that tends to reduce the uncertainty of forecasting costs and revenues is that most of our clients have a shorter time frame—10 to 15 years—for fully utilizing and depreciating their generating assets than what was commonly done by utilities in the past—25 to 35 years. This puts a lot of pressure on making the assets effective in the marketplace in the near term. APTECH has worked with clients to find a number of ways to add value to the asset, both by increasing unit efficiencies through heat rate improvement projects, and by decreasing costs through component failure mitigation measures. For example, we can often find ways to improve heat rates by 1% to 2% through various measures that are not very costly (i.e., less than one million dollars for a large fossil steam unit). More aggressive capital improvements, such as turbine redesigns, can improve heat rates by more than 5%, but they are also costly.

We can help reduce future COM costs by identifying specific temperature and pressure transients in various boiler and turbine components that need to be better controlled during cycling operation. We have studied the real-time monitoring data of more than 100 plants, and have found that in many of them temperatures of selected tubes in waterwalls, superheaters, and reheaters are not well controlled during cycling operations—even during the relatively small load changes from AGC. We have also been working with plant control system vendors to develop a software product called COSTCOM™ that allows plants operators to visualize how current and planned unit operation is effecting the unit in terms of wear-and-tear costs. This program is based on real-time monitoring data of temperatures and pressures at selected monitoring points. Using a combination of fuel cost and COSTCOM, a plant can obtain a real-time profit and loss, as well as input several "what if" scenarios to determine if today's or tomorrow's generation cycle is profitable, given the current bid price.

Plant personnel and executives should realize that proper condition assessment, planning, and maintenance does pay off for operating plants and plants for sale. We have observed higher prices paid when unit condition is well documented and future costs are minimized by proactive maintenance. In order to reduce plant costs, APTECH has developed and applied another technology, called TubeMod®, that can extend the life of reheaters and superheaters by 10 to 15 years at a cost of less than 10% of a replacement. Another technology, Roll Bowl Cop™ can be used to minimize vibration, maintenance cost, and failures of coal mills at coal plants. These are just a few examples of damage mitigation technologies that should be considered in order to reduce cost forecasts and add value to units in a competitive bid.

The successful clients we have been associated with have also found ways to add value to particular units in the following ways:

- Developing alliances with a fuel supplier, or having a separate division of the company that is a fuel supplier, that can provide leverage in providing low cost fuel

- Developing alliances with a marketer that can be effective in increasing revenues and supplying cheap controlled power, thus minimizing excessive plant cycling and its costs

- Optimizing the use of the assets (e.g., using existing highly efficient base loaded units to pump hydro at night; the hydro is used to shave expensive spot peaks in the day time).

- Having management skills that motivate employees to perform better at lower cost

- Developing strong relationships and a good reputation in the financial community that leads to a lower "cost of money"

- Taking a reasonable reduction in the old fixed COM costs by reducing personnel and management inefficiency

- Contracting out maintenance

- Maintain the condition of power plants for sale and document the remaining life of key components

- Understanding the value of operating (hour-to-hour) and planning (year-to-year) flexibility and being able to take advantage of them

On this last point, we see that there can be a tremendous value in a unit being able to serve a number of operating requirements (e.g., baseload energy, load following, AGC, VAR control, spinning reserve) with high reliability. Since the market is changing rapidly, the way a plant can maximize its revenues will likely change from year to year—maybe even from week to week. The ability of a plant to be flexible in meeting multiple market needs could turn out to be very valuable.

Another comment we would like to make on this last point is that the site where the plant sits may have space, incoming fuel lines, a historical use permit for a power plant, environmental, and outgoing transmission lines that will allow for future capacity expansion or repowering after a certain period. This type of planning flexibility could add significantly to the value of the asset being considered.

By looking into the ways clients can add value to an asset, it becomes clearer to us why most of the bids have far exceeded the book values of the plants auctioned. Assessing the track records of the corporate clients we have helped in winning bids, they are probably going to do very well with their investments.

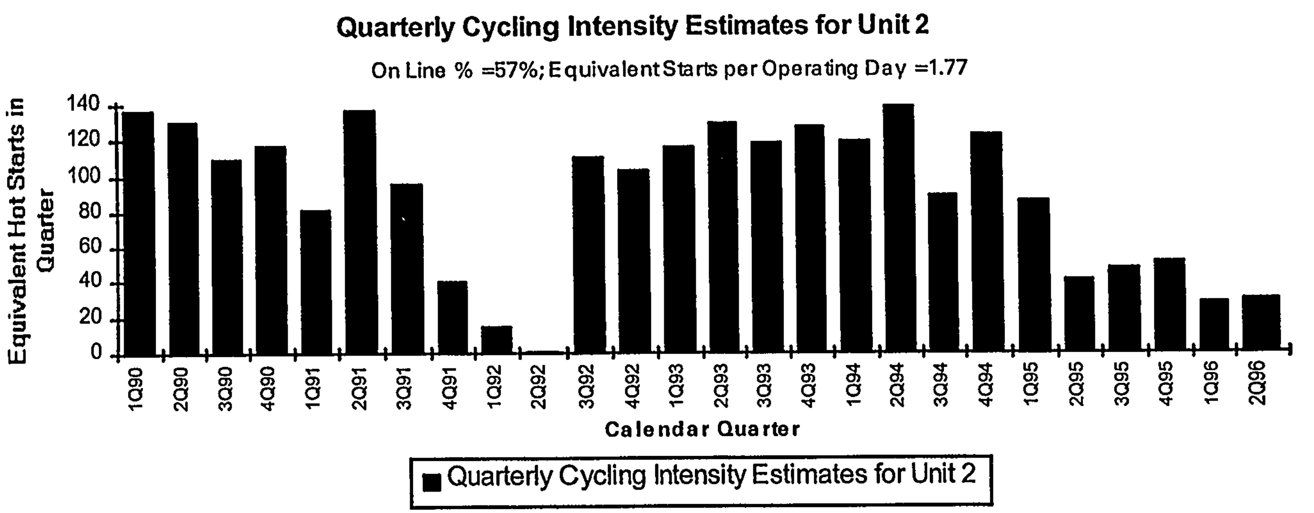

Fig. 1. Quarterly cycling intensity estimates for oil-fired power plant Unit 2.

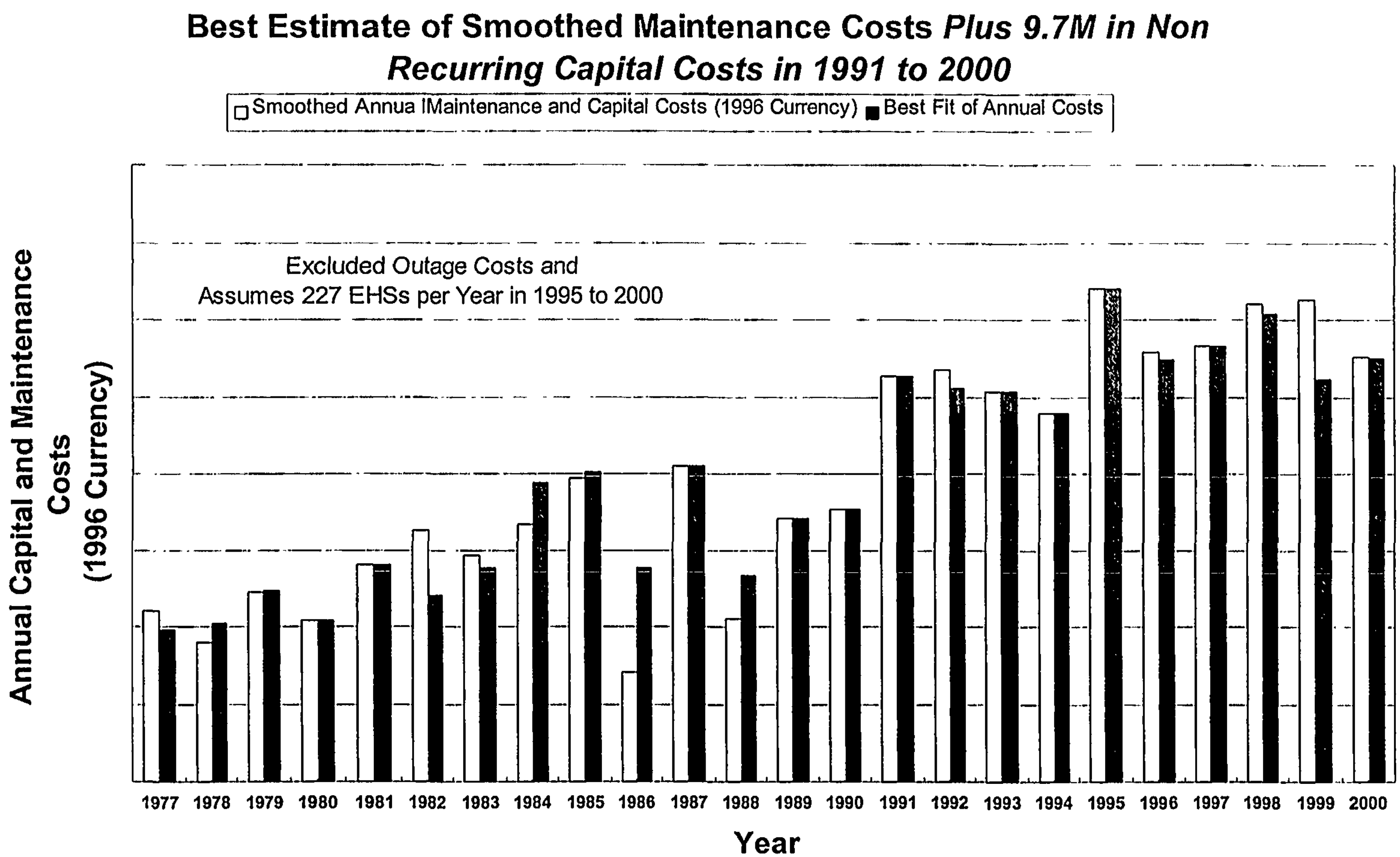

Fig. 2. Best estimate of smoothed oil-fired power plant Unit 2 maintenance costs plus 9.7 million in nonrecurring capital costs in 1991 to 2000.

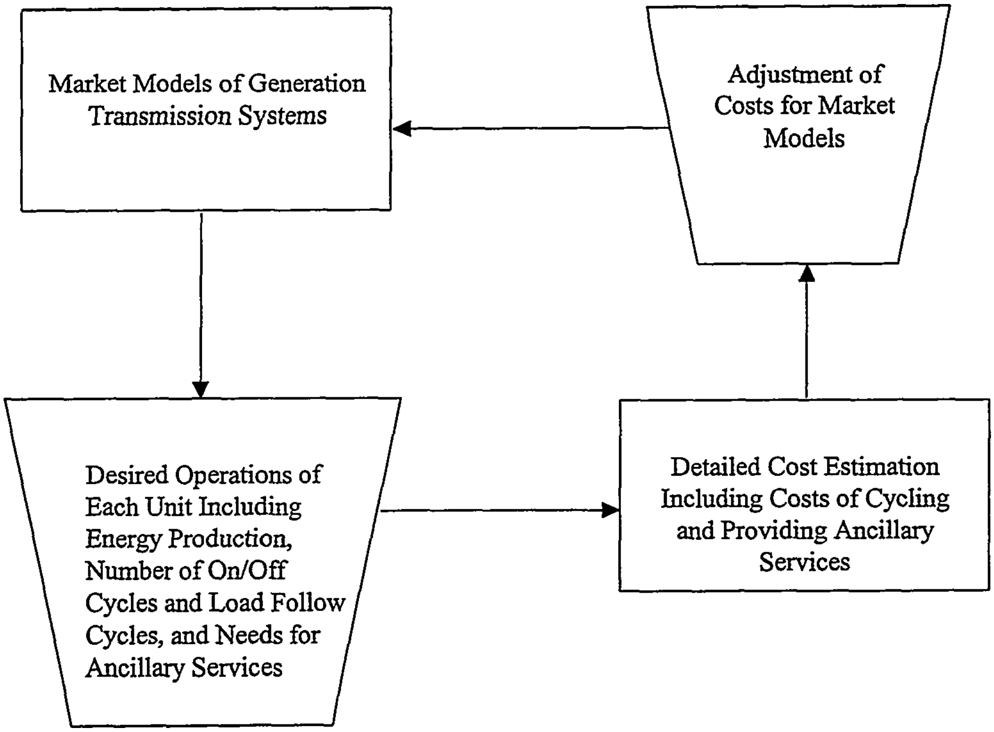

Fig. 3. Logic flow of market and cost models to determine most favorable operation of units.

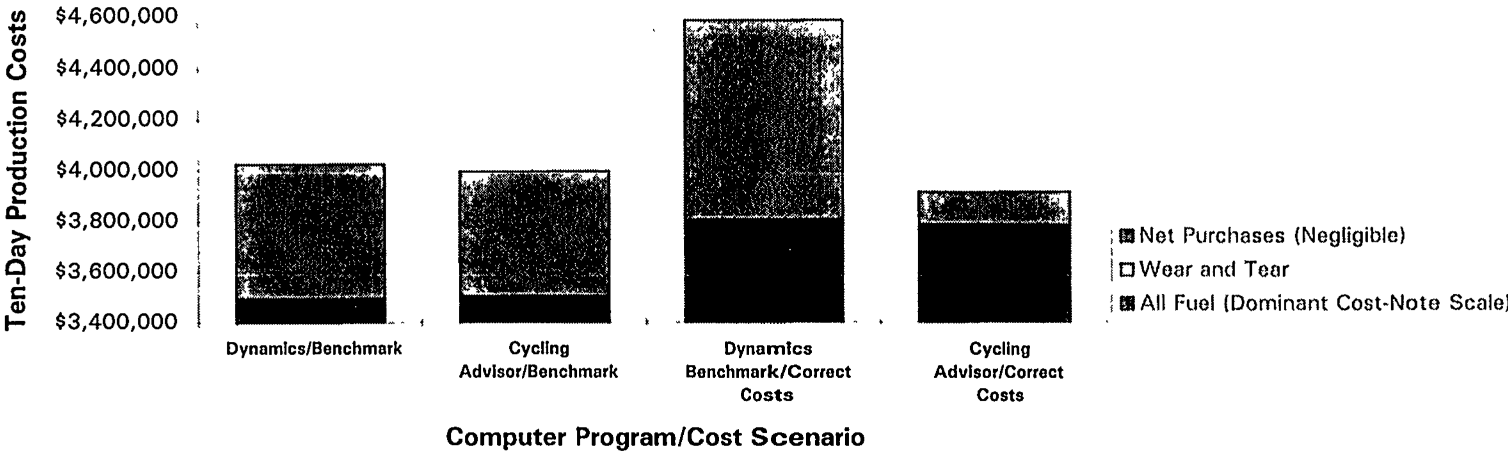

Fig. 4. Breakdown of four ten-day cycling cost scenarios for HAL April-May load demand.

Best Cycling Strategy to Cope With Most Challenging Ten-Day System Loads

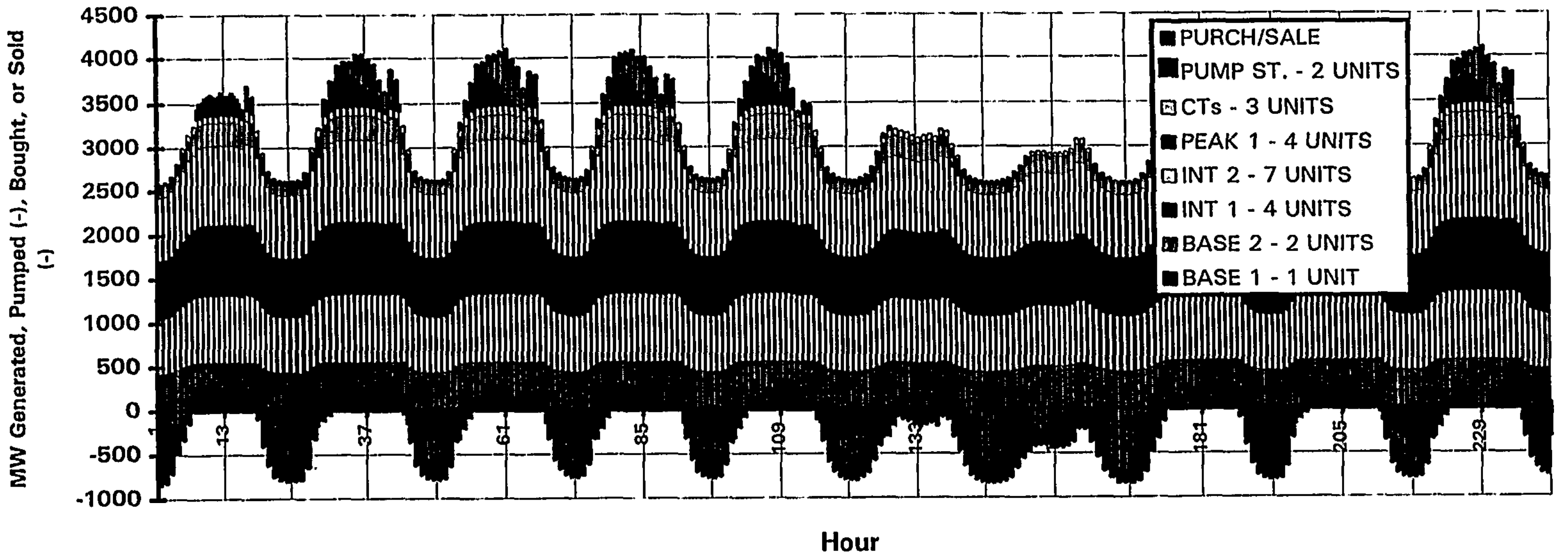

Fig. 5. Optimize hourly dispatch for high load period using CYCLING ADVISOR and APTECH-derived total cycling costs.

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The Role of Enterprise Asset Management System in the PVO Group's Business

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Abstract

This paper describes the role of the Enterprise Asset Management (EAM) and Enterprise Document Management (EDM) in the PVO Group's business. The use of the functionality of the EAM (Immpower) and EDM (Documentum) is not limited only to the plant maintenance. All power plants and some other business functions and units will use the system in the future for financial management, activity based costing, purchasing, of materials, office supplies and fuel, invoice matching, project budgeting and costing, real estate management etc. The technical service concept of IT solution is also described in this paper.

The Information Management Strategy development as background to the project is also outlined together with the company information. The benefits of the common EAM system and related business process needs are also described.

1 Introduction

Information systems are essential to the power production and electricity distribution. The role of the information systems to manage the business functions are growing. The reason for this is mainly the straightening concurrence and demand for cost reductions.

The role of the Information Management Strategy of the PVO Group gives the guidelines to the development of applications for the business. Special emphasis in this paper will be given to the role of the PVO Group's common Enterprise Asset Management (EAM) and Enterprise Document Management system (Documentum).

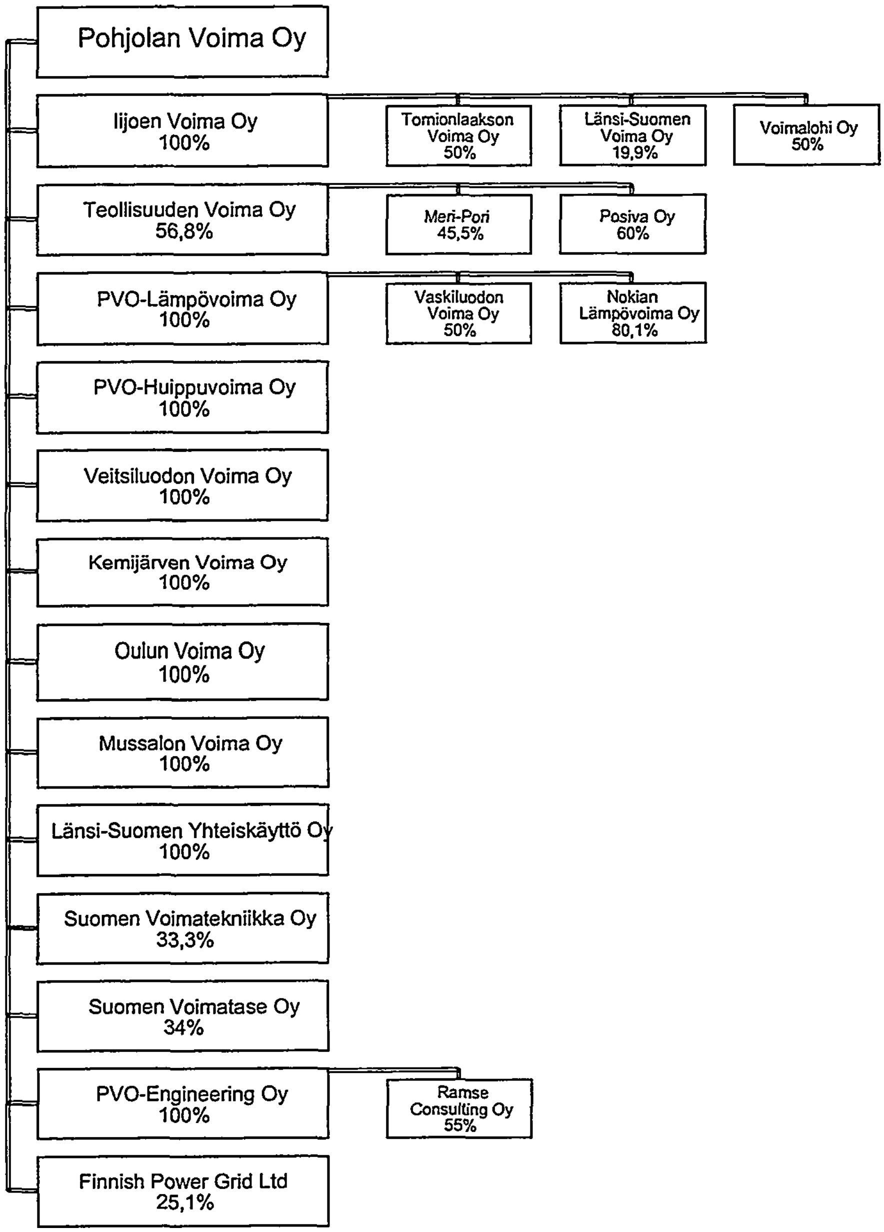
2 PVO Group and RAMSE Consulting Oy

The PVO Group is an energy firm owned by the Finnish export industry and its domestic, local-level co-operation partners.

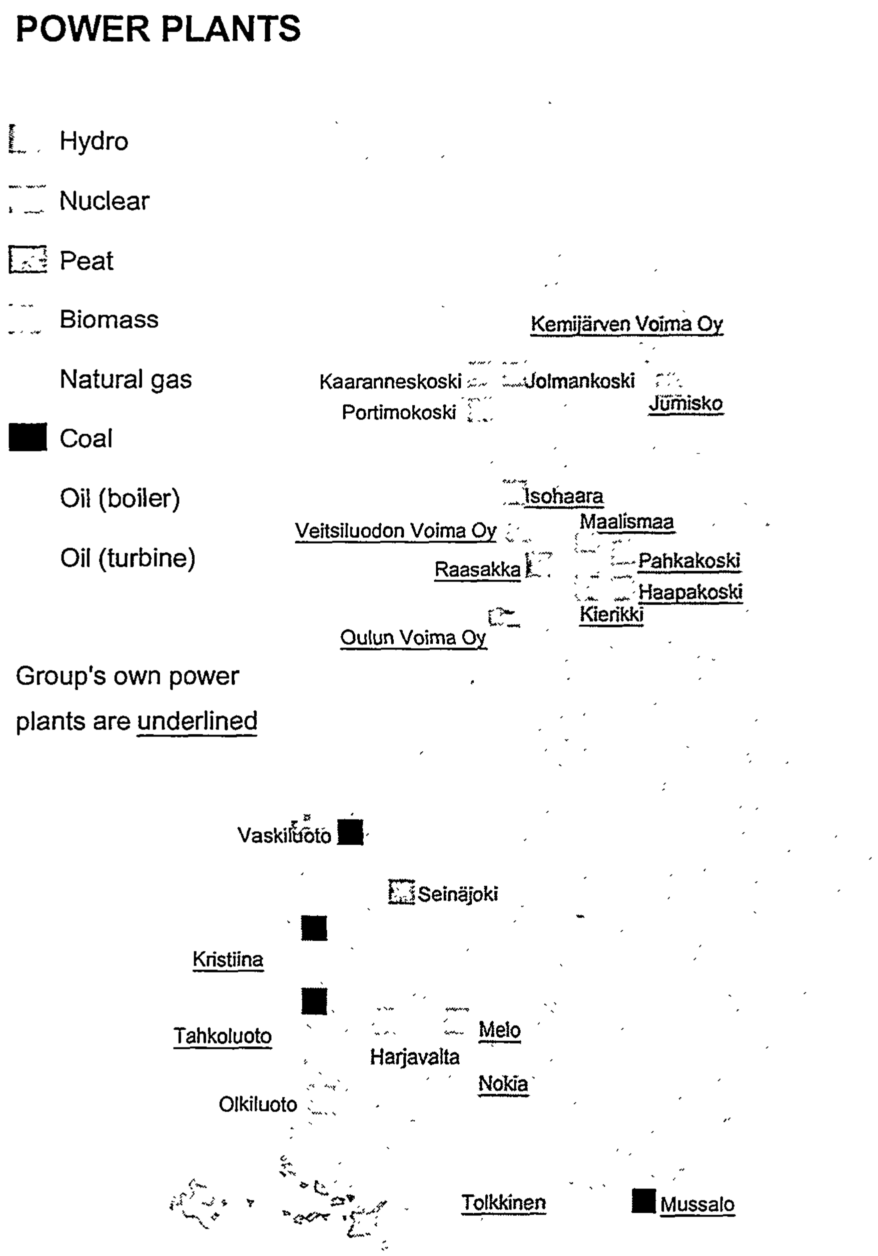
PVO produces electrical power in its hydro, nuclear, coal, gas turbine, peat and industrial cogeneration plants. PVO Group structure is presented in picture 1. Power plants are presented in Picture 2. Capacity is presented in Picture 3.

PVO provides its owners and other clients a wide range of services: power line design, production machinery and network control as well as operating centre services within the energy sector.

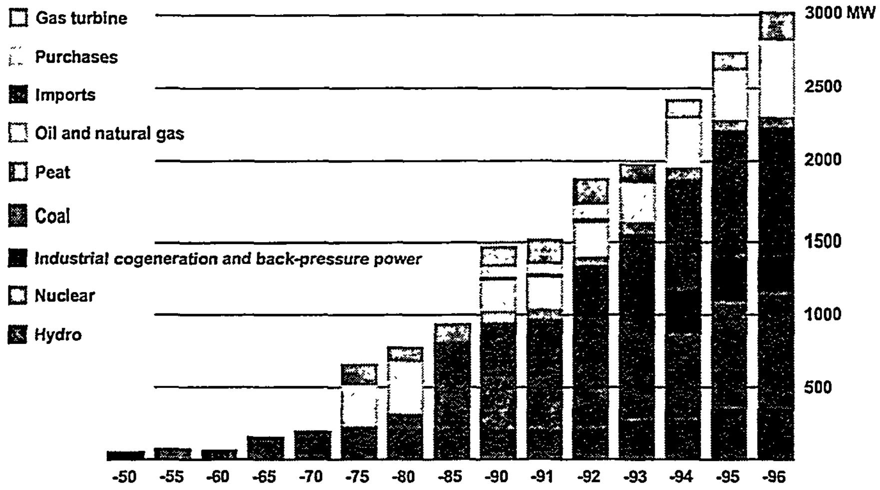
RAMSE Consulting is a business management consultant company whose mission is to improve its clients' productivity and efficiency by developing the clients' EDP systems and renewing their functional processes. As developer of operational and maintenance functions, reliability, safety, and information management, we are one of the leading consultant companies in The Nordic Countries. Currently RAMSE employs more than 30 internationally experienced consultants who also have good knowledge of Finnish industry.



Picture 1. PVO Group Structure December 31st 1997.



Picture 2. PVO Group power plants.



Picture 3. PVO Group Capacity (MW).

3 Information Management Strategy

Information Management Strategy (IMS) in the PVO Group is a development plant of applications, technical systems and related services. It is a frame to the schedule of renewing and updating applications, IT-network and hardware. It also includes a description of organisation of Information Technology (IT) and Information Management (IM). The job descriptions of organisations together with procedures are attached.

Some of the main components of Information Management Strategy are:

- Information architecture
- Application architecture
- Technical architecture
- IT and IM organisation
  - System services
  - Development projects and procedures
- Order and schedule of development projects

These components are constantly updated along with the development of applications and information tehnology. The strategy is confidential and therefore only limited parts are publicly available.

Information architecture descriptions of the business functions and data needs associated to the functions

Technical architecture defines the network, hardware, database, operation system, vendor criteria among others.

Application architecture can be divided to platform type of solutions which are office automation system, e-mail and document management, and to business applications like financial system and maintenance management.

System services are provided by PVO Engineering Oy through the PVO data network.

Development projects are owned by the business units and function responsible. Development projects are supported by RAMSE Consulting Oy providing project management and development resources.

3.1 Strategy Development

In December 1995 The PVO Group decided to start development of Information Management Strategy. RAMSE Consulting Oy was chosen to be the consultant to manage the strategy process by utilising the Information Engineering (IE) method developed by James Martin & co Ltd. First phase was finished in May 1996 and the second, extended phase in August 1997.

Project team consisted of Information Technology and Information management expertise. The work was controlled by the Board Executive Officers. The representative persons of business functions were chosen to work together with business process analysis workgroups.

Workgroups were divided to cover the following business functions

- financial functions
- production planning and management
- personnel management
- maintenance
  - work management
  - inventory
  - item management
  - purchasing
- project management
- real estate management
- *document management*
- environmental management
- laboratory management

Main phases when analysing the business processes in the workgroups were:

- Analyse the current business process
- Define the business objectives and new functionality required
- Analyse the data needs to perform the business process

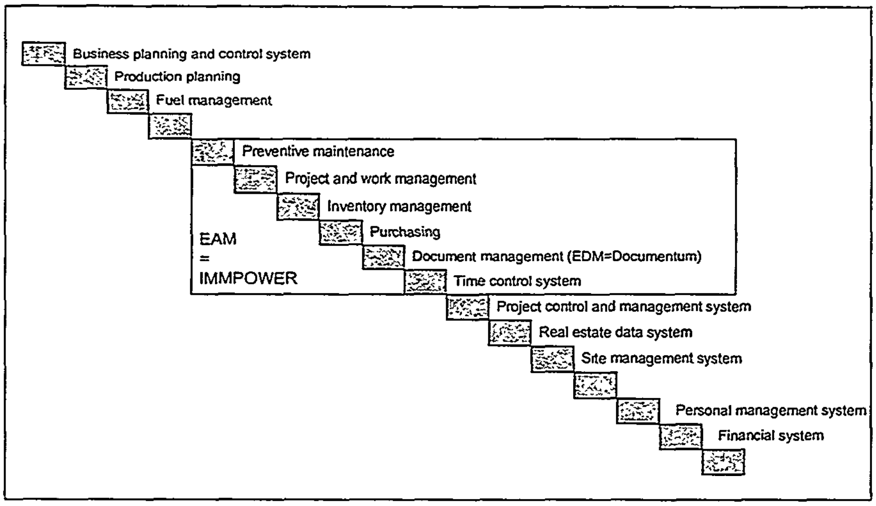
The results of this phase i.e. functional hierarchy of business processes and entity-relationship models, were fed into the CASE tool (Computer Aided Software Engineering). With the help of the tool the application architecture was developed.

Results of the study gave also the order and schedule of the development projects. One of the first projects was to choose and implement a new system to serve the maintenance functions in all the PVO maintained power plants.

3.2 Application architecture

Application architecture shows the business applications. Immpower system in PVO will cover several applications.

Illustrative picture of the Application architecture and EAM coverage is shown in picture 4.



Picture 4. PVO Application architechture: Modified example - not comprehensive picture of PVO applications.

3.3 Business processes that will be managed with Immpower and Documentum

Based on the Information architecture the PVO Group will manage the following business functions with Immpower and Documentum.

Power Plant Management

- work management
- resource management
- shutdown planning
- preventive maintenance
- time sheet reporting
- inventory
- item management
- purchasing
- expediting
- invoice matching

- project management
- plant configuration management
- real estate maintenance
- activity based costing
- safety management
- document management (Documentum)

Engineering

- work management
- resource management
- document management (Documentum)
- time sheet reporting

Financial and bookkeeping

- invoice matching
- activity based costing
- general ledger access

Purchasing

- fuel
- materials
- expediting

Payroll

- time sheet reporting
- Interface to the payroll system

Capital investment projects

- work management
- resource management
- preventive maintenance planning
- time sheet reporting
- inventory
- item management
- plant configuration management
- purchasing
- project management
- invoice matching
- expediting
- document management (Documentum)

IT systems maintenance

- work management
- resource management
- preventive maintenance
- time sheet reporting
- project management
- system configuration management
- purchasing
- invoice matching

Enterprise Document Management (Documentum) functionality in general

- version maintenance
- document distribution
- document publishing
- workflow management
- integration to Immpower
- security and backup routines
- virtual/ compound documents
- www publishing

3.4 System service concept

System services are provided by PVO Engineering Oy through the PVO data network. System maintenance agreement has been created between the power plant and the PVO Engineering IT department. PVO Engineering provides the following services according to the agreement.

- Hardware platform installation and maintenance
- System platform and maintenance
- Information network services
- Development and maintenance of interfaces
- Conversions
- System maintenance and development
- System control and monitoring
- Help Desk services

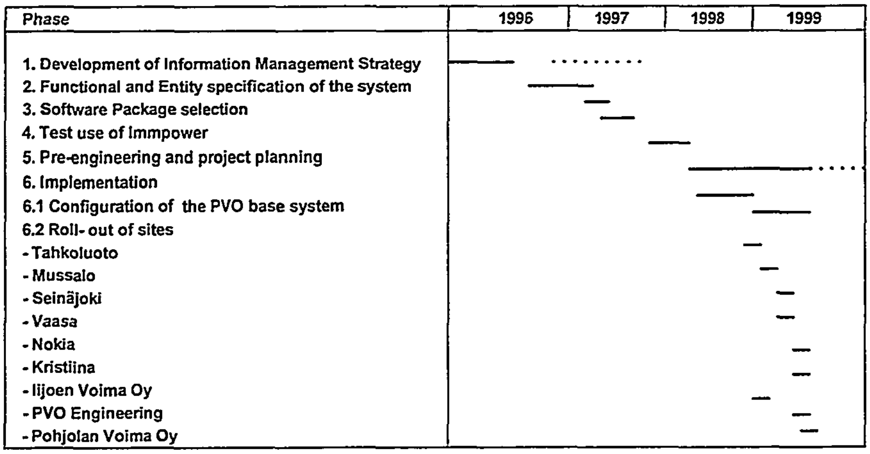
Established service concept is unique serving multiple users according to the same principles. The business benefit is based on the improved service level of the end-user. Service concept allows also radical cost saving in system maintenance.

4 Immpower implementation project

4.1 Project phases

Immpower implementation project is demanding task for the PVO Group. This is one of the first projects in Finland where a company-wide solution has been made in the are a of EAM. The outline of the schedule of the whole activity starting from IMS study to the roll out is presented in picture 5.

Project core-team is responsible for configuring Immpower and Documentum to suite the needs of PVO. Core team members represents all sites.



Picture 5. The outline of the development schedule.

4.2 Business Benefits

PVO has set several objectives to the project. Some of the areas of future improvement have been listed above.

Plant maintenance
- Work planning
- Shut-down planning
- Warehouse and inventory
- Internal cost control and accounting

Co-operation between the plants
- Spare part co-operation

- Purchasing operations
- Project and resource management
- Standardisation of equipment and parts control
- Document exchange
- Standard and model jobs
- Problem solving
- Reporting

Improving the capital investment project management
- Purchasing
- Standardisation of equipment
- Project management
- Developing the database during the project for further use

5 References

More information about the companies, parties, software and methods involved can be found in Internet.

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RAMSE Consulting Oy; http//www.ramse.fi
Walker; http//www.walker.com
James Martin; http://www.jamesmartin.com/
Documentum; http://www.documentum.com
TT-Technology http//www.tt-tech.fi

6 Conclusions

Company-wide solution made by the PVO Group in the area of Enterprise Asset Management and Enterprise Document Management should encourage other companies to take the same step. The expected business benefits have been analysed completely. Benefits of a common solution for every plant is evident both from business development and IT- service concept point of view.

The use of modern packaged software solutions to run the daily business has shown to be the right solution for the PVO Group. PVO is now able to concentrate to the core business and leave the software development to the applicable vendors. The functionality and technology of the products will be developed constantly by the vendors and the results will be in use even earlier than you can expect.

PVO sees that this solution is an investment to the future.

Advanced targeted monitoring of high-temperature components in power plants

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Abstract

The paper presents the idea of targeted monitoring of high-temperature pressurized components in fossil-fueled power plants, implemented within a modular software system and using, in addition to pressure and temperature data, also displacement and strain measurement data. The concept has been implemented as a part of a more complex company-oriented Interne/Intranet system of MPA Stuttgart (ALIAS). ALIAS enables to combine smoothly the monitoring results with those of the off-line analysis, e. g. sensitivity analyses, comparison with preceding experience (case studies), literature search, search in material databases (experimental and standard data), non-linear FE-analysis, etc. The concept and the system have been implemented in real plant conditions several power plants in Germany and Europe: one of these applications and its results are described more in detail in the paper.

1 Introduction

1.1 Increasing importance of monitoring

The importance of monitoring of high-temperature critical components in conventional power plants has been steadily increasing in the recent years due to:

a) the trend of having always less people with less qualification in the operation and maintenance (O&M) of power plants (in an unmanned plant the essential importance of monitoring is obvious: the monitoring system in such a case virtually replaces the operator), and due to

b) the fact that monitoring has become more and more connected to the life assessment and management - only with data from monitoring it is possible to assess the past history of the system/component and provide a more reliable basis for future management of the system/component life.

Monitoring "connected to life assessment", must take into account the processes governing component/system life - the damage accumulation processes at the first place. The processes to be monitored depend on type of components, materials operating conditions. In this paper the monitoring of damage accumulation caused by creep and fatigue is considered.

1.2 Monitoring operation vs. monitoring of damage

"Monitoring connected to life assessment" can be made in two main ways, namely:

a) indirect way: to monitor the operation, i. e. parameters supposed to stay within virtually unchanged ranges during the whole life of the monitored plant or component - e. g. fluid pressures or temperatures ("global monitoring"), and assess the "remaining life" on the basis of these parameters, and

b) direct way: to monitor the damage processes, i.e. parameters the values of which changes with time of operation - i. e. accumulated creep and/or fatigue damage ("local monitoring").

The first case equals to "typical" continuos monitoring, with acquisition of data and their on- or off-line use in life assessment analysis. Most of the technical solutions, available so far, are of this type.

In the second case, except for the corrosion, the available technical solutions are far less numerous, and the more direct damage monitoring (e. g. using capacitative strain gauges or displacement transducers – Figure 1, Figure 12) are usually classified as "advanced".

On the other hand, putting an ordered series of inspection results together can sometimes also be considered as "monitoring".

1.3 Global vs. local monitoring

Most of currently available systems are essentially global monitoring systems (see e. g. Eckel, Ausfelder, Tenner, Sunder 1996) – i. e. they monitor the operating parameters at a relatively large number of locations, generally not those locations where the maximum damage may/will appear. The "exhausted life" and/or "remaining life" are calculated uniformly for all the monitored locations, on the basis of the monitored global values and using relatively simple algorithms. Comparison with the design life (usually 100.000 or 200.000 hours, see TRD) is in this approach the basis for determination of "exhausted life" and/or "remaining life".

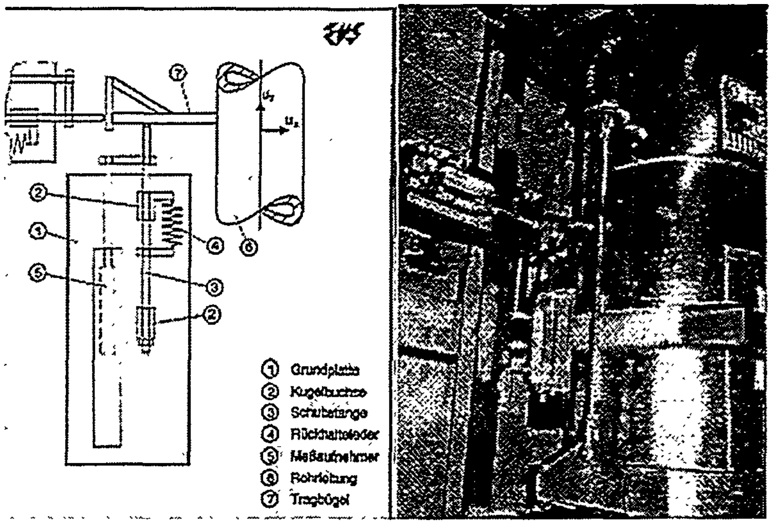

Figure 1: Example of displacement monitoring (Roos, Kessler,Eckel, Ausfelder 1996, see also Kaum and Reiners 1996).

Performing this type of calculation for a large number (say 200+ measurement points), with tight time steps (say 30 sec) over years of plant operation obviously creates a huge amount of data: in itself something that can easily lead to "computerized data cemeteries". Piles of magnetic tapes, printouts, files and similar, in which the important and significant data, if present at all, might easily get lost and/or remain hidden from the user. Furthermore, calculated damage, e. g. creep or fatigue exhaustion in these outputs is often just the repetition of pure inverse design (e. g. TRD), not involving the "real life conditions" like wrong heat treatment, external moments and forces, misalignment, etc. Final result - a huge amount dubious, often useless and/or, in the terms of damage really appearing, "false" results, calculated with "high precision", however, and real damage appearing at locations never spotted as critical by global monitoring.

Understandable is therefore the wish to improve the situation and search for solution by monitoring the location where damage is more likely to appear. Typically, the goal of this type of monitoring is to catch the "peaks of damage" that may arise on some very particular locations and not, like in the case monitoring of operating parameters, to monitor the "average situation". Damage caused by creep and fatigue in high-temperature components is usually limited to particular zones: e. g. header ligaments, pipe elbow intrados/extrados, crotch or saddle points in T-pieces, safe-ends, transition welds and similar. Monitoring exactly <u>these</u> is very desirable, but, unfortunately, often difficult.

Main difficulty is the choice of. The choice is usually a multi-criteria decision problem (Jovanovic, Auerkari, Brear 1996), with many possible outcomes. The rightfulness of the decision can be usually proven only years later. Even if issue of choice is settled, further difficulties arise due to other reasons like:

a) Monitoring instrumentation (transducers) to be used is still labeled as "experimental" or "early commercial version".

b) It is often complicated or even impossible to place the monitoring instrumentation (e. g. temperature or strain) exactly on the most critical/solicited location, even if the locations are known.

c) Even if these locations are instrumented it might be difficult or expensive to calculate stresses and remaining life for them (especially on-line: e. g. in the case of complex geometry a new finite element analysis might be needed for each type of transients, etc.).

d) Even if all the critical locations are known and instrumented, and it is possible to calculate stresses and remaining life on-line, it is often too expensive and time consuming to do it.

1.4 Modular targeted monitoring

Searching the way to connect

a) the technical easiness and applicability of the indirect and global monitoring (as defined above) and

b) meaningfulness of the direct damage monitoring

an approach designated here as "modular targeted monitoring", is proposed here. It essentially means that one should

a) use the indirect monitoring for

- checking overall "health" of the monitored system/component
- (one of the factors!) defining where to go for direct damage monitoring, see Jovanovic, Auerkari, Brear 1996

b) use the direct damage monitoring at the places indicated as "critical" by

- global monitoring
- previous experience
- other factors (e. g. safety, economical risk, etc.)

c) combine the two approaches above smoothly and optimized for each particular situation (type and level of actions being part of monitoring should be optimized).

The approach has been developed at MPA and embedded into the MPA System ALIAS (Jovanovic 1997). The paper presents results from an application of the approach and the system in a German power plant. The emphasis of the paper is on the optimization showing that a lot of knowledge, data, models, software tools and people who can understand are needed for optimized monitoring. Therein, the emphasis is on software tools and practical application of the system in a German power plant

2 Modular targeted monitoring as a part of the MPA system ALIAS

The concept of modular targeted monitoring is built into ALIAS as an essential part of the overall remaining life assessment concept. A more detailed description of ALIAS is given elsewhere (e. g. Jovanovic 1997) but for better understanding of the example described later, main parts of ALIAS will be shortly listed again.

Basic idea of ALIAS is very simple: various elements are needed for successful life assessment/analysis. Single tools usually "cover" usually one of the activities (e.g. material database). There is, however, a strong need for interaction and synchronization and this can be achieved only if the single elements are put together. ALIAS puts them together, make them match and complete each other, adding on the top the necessary supporting elements.

ALIAS is organized as a notebook (or folder) opening way to two databases (network and local one) and containing the following main tabs:

The functionality of ALIAS is illustrated here using as the example the piping system in a German power plant (Figure 2).

1. Title page tab (Figure 3)
2. Summary tab:
   gives information on who, when and why is performing given analysis, all analyses, data and the so-called meta-data (data about data) are stored as an ALIAS- "session"
3. Advisor tab:
   the modules on this tab provide advice which modules of the system to use and/or how to optimize the decision after several steps of the analysis have been made – this tab provides also links to the the risk and reliability assessment modules.
4. Background Information tab:
   provides link to various codes, standards and other documents relevant or the successful remaining life assessment – e. g.:

- material standards like DIN, VGB and other West European data (SP249, ESR-VGB)
- design/analysis standards like DIN, VGB and other West European data (SP249, ESR-VGB)
- RLA standards - Eastern Europe (TINCA)
- SP249 RLA Guidelines
- MPA Project Documentation Base
- MPA Test Report Database
- MPA Library Database
- Case studies/histories (currently 8000+ case studies)

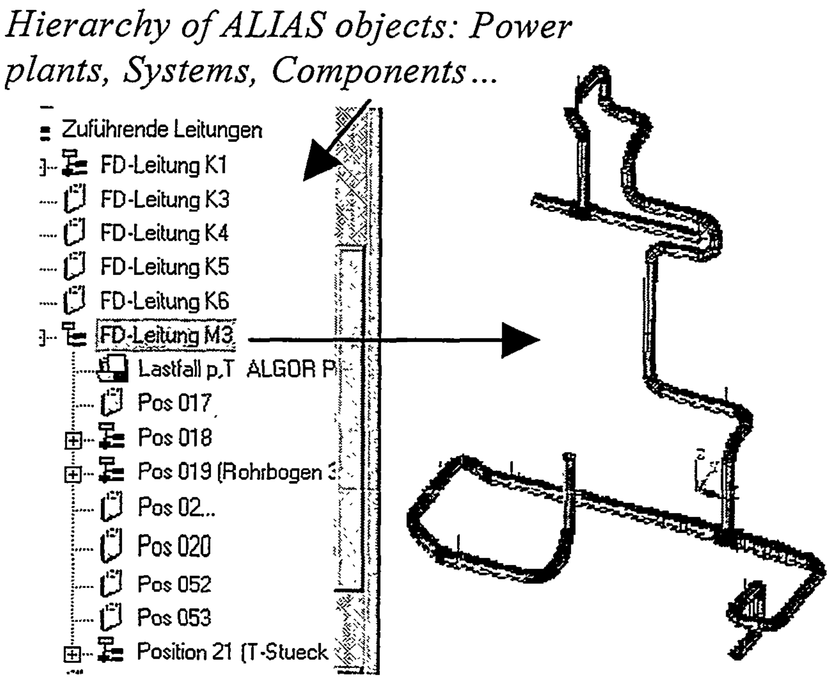

Figure 2: Piping system in a German power plant used as example for targeted monitoring: here as "stored" in ALIAS.

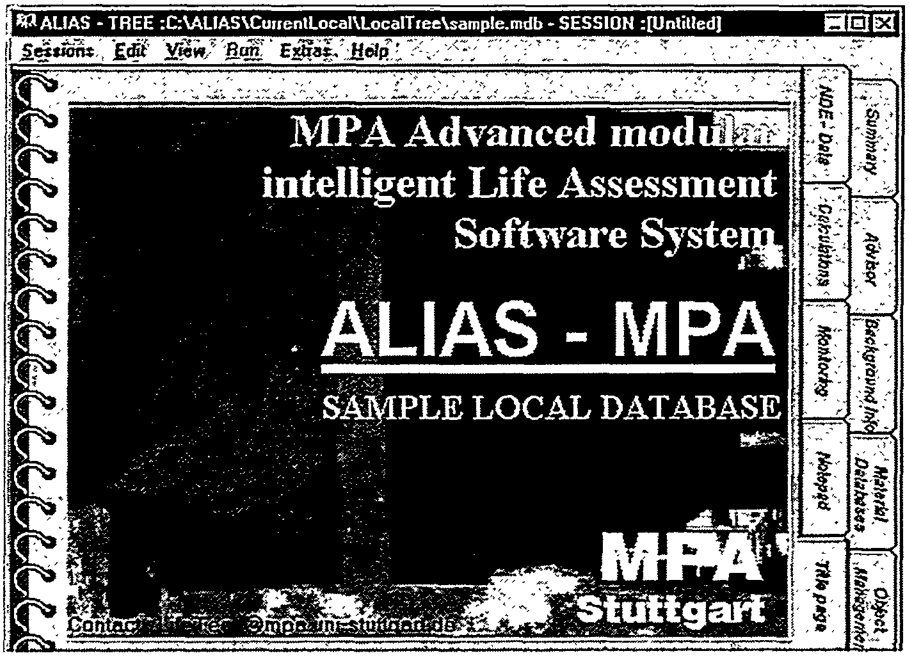

Figure 3: ALIAS "Folder" with single "tabs".

1. Object Management tab (Figure 2)
   containing data about ALIAS-objects – in the form of hierarchical tree data about utility companies, power plants, blocks, systems, components, locations, etc. (up to 20 levels in the hierarchy)

2. Material databases tab
   containing link to ALIAS-Materials database and other material databases

3. Monitoring tab
   is linking ALIAS modules to on-line monitoring system(s)

4. Calculations tab (Figure 4)
   tab activates different types of calculations and analyses available in ALIAS, as for instance for the remaining life assessment

   - Code based:
     TRD-analysis of stresses and remaining life
   - Inspection-based approaches:
     Analysis of remaining life - A-parameter, cavity density, LCF-analysis
   - Interfaces to FE analysis codes for piping analysis

5. Non-destructive testing (NDT) tab
   linking external NDT systems and databases to oter ALIAS

modules and internal ALIAS-NDT data stored under "objects" (Figure 8)

6. Notepad (Session editor) tab
   is the tab with full-featured editor allowing the user to report the results of analyses performed within an ALIAS session.

All the data about applications are dynamically built, based on the data stored in databases. Using the system is intuitiv: starting from one of the tabs, the user can go to the selected module.and obtain the data he wants. The system allows the GroupWare-like work meaning that several experts can work together.

Furthermore, ALIAS allows links and interfaces towards systems managing overall operation of the power plant as a whole (if such systems are availbale in the given plant at all – see Farwick, 1977 and Lefton, Besuner and Grimsrud 1997).

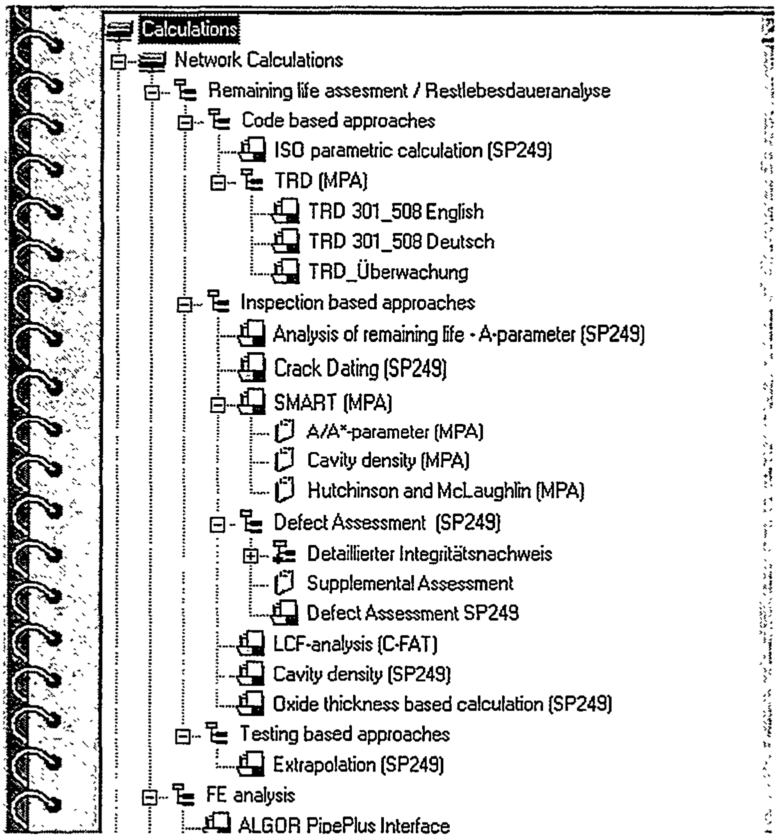

Figure 4: Different calculation modules accessible within ALIAS.

3 Direct application of ALIAS for targeted monitoring in a German power plant

3.1 General

Apart from the data about the objects themselves (Figure 2) – e. g. dimensions, materials used, operating history) the hierarchical model enables linking of analyses performed for these objects (e. g. TRD-analyses) and their results (Figure 5).

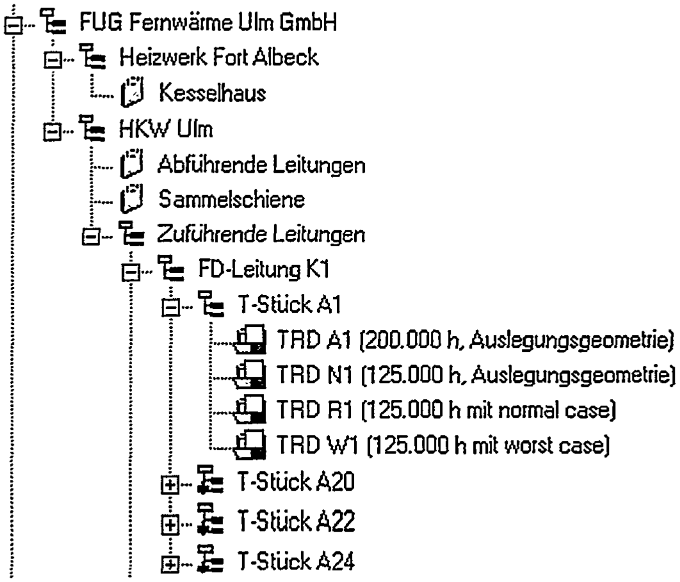

Figure 5: Analyses linked to the objects.

In the same way, taking data directly from the monitoring system (Figure 6) ALIAS user can easily perform the calculations and quickly produce chart for the selected cases (Figure 7). The TRD calculations in ALIAS can, furthermore, be connected to the other available analyses/calculations (cf. Figure 4) and data from non-destructive testing (NDT – Figure 8), called from the corresponding NDT tab of ALIAS – see Figure 3).

3.2 Summary of actions

Action 1:Data about the power plant collected and structured

All available data (approx. 2 thick A4 folders) about the power plant, systems, components (Figure 2), including geometry materials, fabrications, as well as available calculations (Figure 5, including also the isometry of the piping system), etc. collected and structured as an ALIAS-tree.

Action 2:Monitoring data collected and made available for further analysis (Figure 6)

Action 3:TRD calculations for different nominal, operational and assumed combinations of parameters influencing stress and RL

For different assumed values of pressure, average temperature, wall thickness, diameter and material properties (within standard limits) various "what-if" scenaria have been analyzed (Figure 5).

Action 4:TRD calculations performed with standard monitoring data (Figure 6) assuming no influence of system stresses

Action 5:TRD calculations performed with standard monitoring data (Figure 6) assuming influence of system stresses

Using a finite element model of the piping isometry it was possible to calculate system stresses due to external forces and moments. The analysis was a linear one and before using ALGOR as a tool for parametric analysis its results were compared to those of other codes (ANSYS and ROHR2). The comparison has shown identical results in all load cases (Figure 9).

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00:07:30;1;     57.018;
00:08:00;1;     58.537;
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00:12:30;1;     59.924;
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00:07:30 1	58.129	-0.708	-1.099

Figure 6: Data from the monitoring system: time series of temperature, pressure, displacement and strain measurements.

Action 6:Monitoring displacements

The piping system was equipped with the displacement monitoring transducers as shown in Figure 12. Measured displacements deliver, an indication about real system stresses and about the correction to be introduced into the RLA-calculations. Furthermore, comparing the displacements directly to those obtained for the limit design conditions the monitoring delivers an additional indication "is the piping still in the design limits" (Figure 10).

In a similar way as displacements, monitoring of strains was performed on a selected position on the piping (Figure 12) using high-temperature capacitative strain gauges (Figure 11). However, a pre-condition for implementation of strain monitoring is availability of non-linear analysis. In this case it was done by ANSYS finite element code. The analysis enables to (a) reiterate in calculation the stress-strain situation corresponding to the measured one and (b) to perform the component remaining life analysis based on realistic time-dependent creep-fatigue behavior.

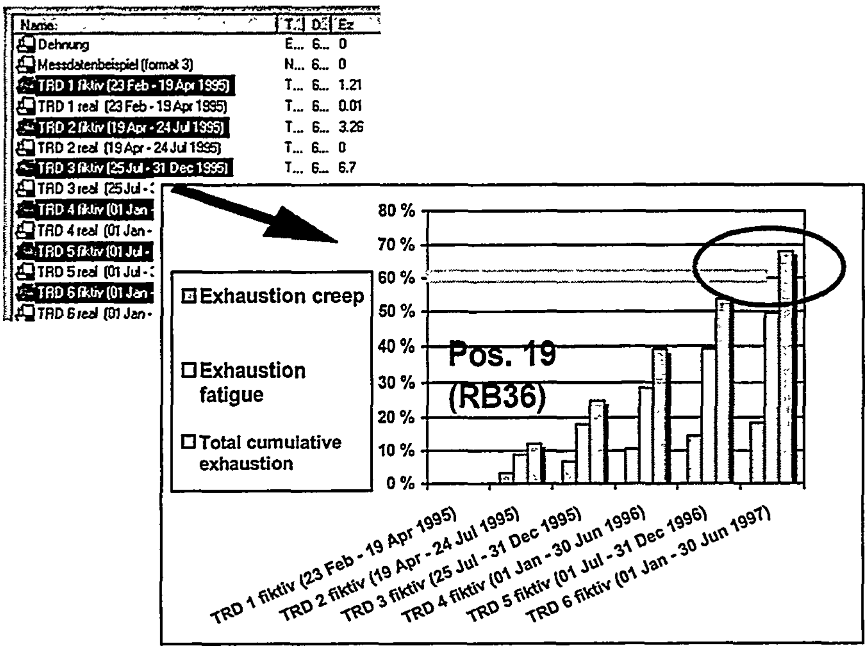

Figure 7: From monitoring data (Figure 6), over single RLA calculations, to the overview of damage development – 60% TRD-limit indicated,

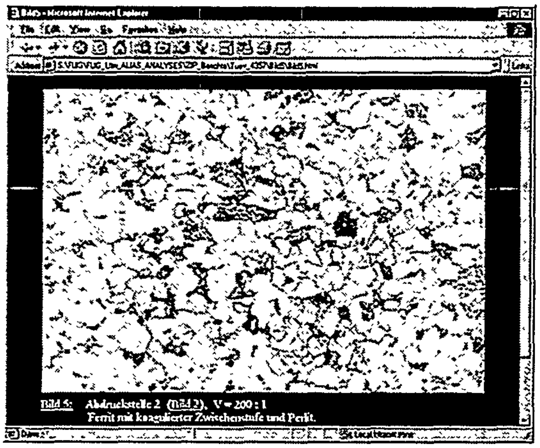

Figure 8: Linking NDT-data (replica) to RLA-calculations in ALIAS.

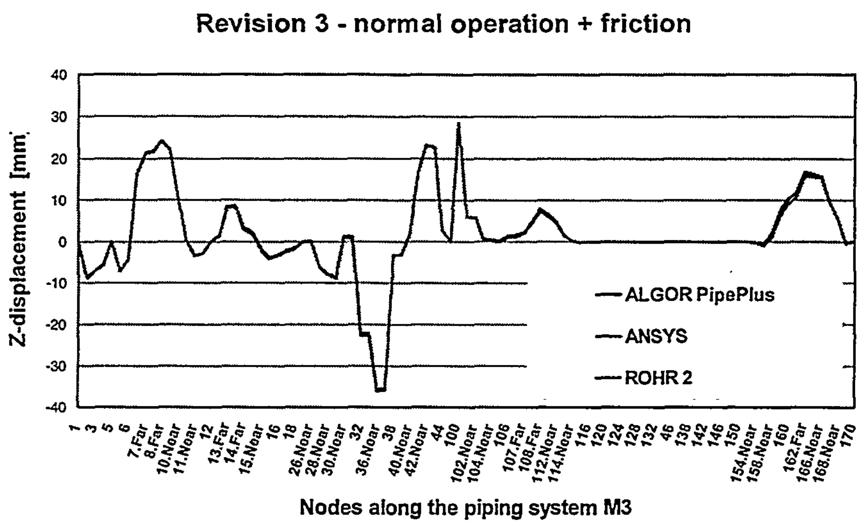

Figure 9: Displacements in z-direction as calculated by different tools for the same piping system in the selected example.

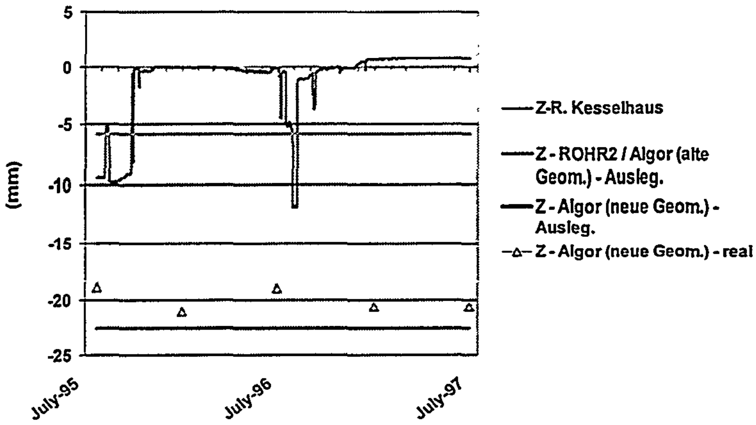

Figure 10: Displacement monitoring (monitoring in z-direction, position 32 as in Figure 12, straight lines displacements for design conditions, triangles displacements calculated for the measured operating conditions): overall result showing that measured displacements are within design limits.

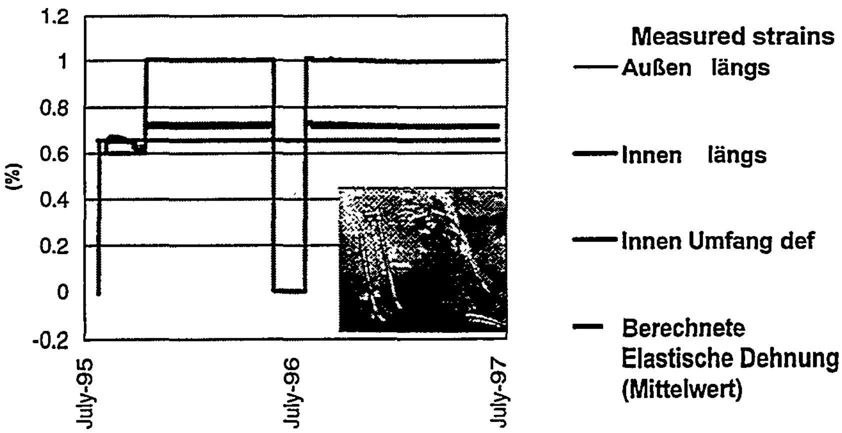

Figure 11: Measured strains using high-temperature capacitative strain gauges (position 36 in Figure 12, out- and inside, hoop, elastic strain).

Action 7:Monitoring strains

Action 8:TRD and RLA calculations performed with advanced monitoring data (displacements and strains)

Comparing the results of damage accumulation and remaining life consumption for the limited time of strain monitoring (approx. 2 years) one can see that in the given example a difference of over 100% was registered (Figure 13).

4 Conclusions

Out of the work presented here and performed by MPA and supporting German utilities in the area of targeted monitoring of high-temperature critical components, piping systems in particular, the following conclusions can be made:

1. Life monitoring is essential for the overall life management.
2. Besides the conventional monitoring based on global operational parameters, concentrated "targeted" monitoring should be made.
3. Selection of locations can be made according to experience (e. g. case histories) and results of global monitoring..
4. Monitoring of displacements and strains is essential for the better assessment of actual stress states and, consequently, life assessment.
5. Monitoring of displacements and strains can achieve its goal only if supported by powerful analysis tools, including the non-linear finite element analysis.
6. Monitoring as such just one of the elements of the comprehensive life assessment and management – only a system like ALIAS integrating parallel analyses and enabling permanent cross-checking and linking of monitoring results with other elements (e. .g NDT results and/or case histories and/or detailed off-line analyses), can assure the confidence needed: (a) that no "false alarms" are triggered, and (b) that no real damage location is overseen. Consequences of both can obviously be very serious.
7. Further link between monitoring and operation management system(s) is needed as shown by Farwick (1997).
8. Further work is needed in the areas like assessment of data on the non-monitored but anyway critical locations, reconstruction of the missing data (e. g. for the cases when monitoring was not available), and similar. Intelligent techniques (e. g. neural networks, fuzzy classification, etc.) can be useful for this purpose and MPA is currently working on this issue.
9. Further work is needed on the improvement of displacement and strain monitoring, i. e. remaining life monitoring and management based on result from strain and displacement monitoring.

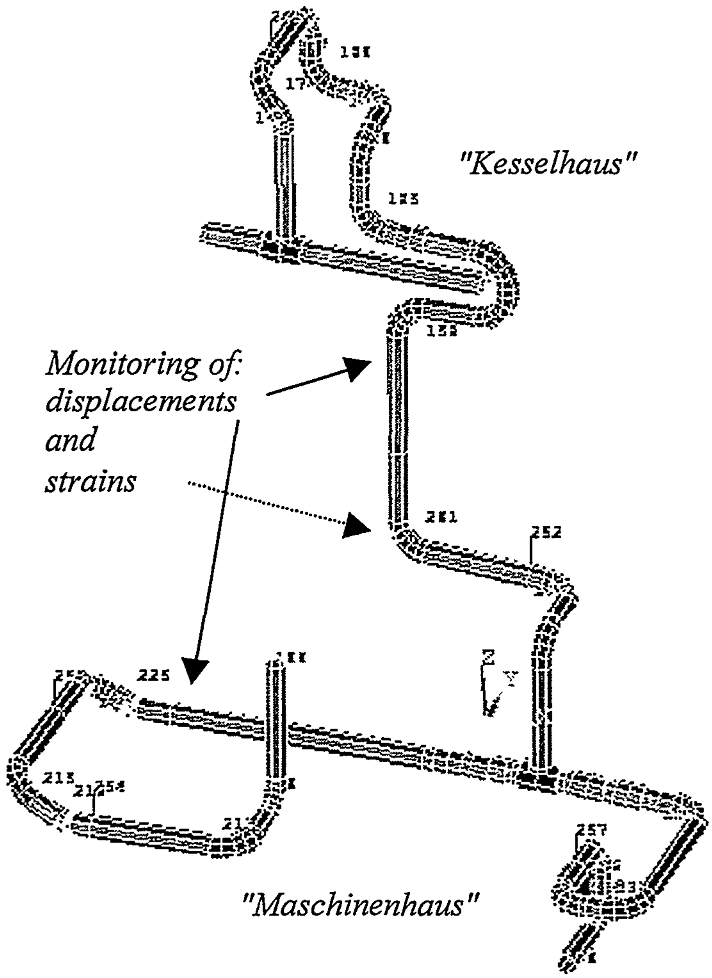

Figure 12: Positions of strain and displacement transducers on the piping (here: the finite element model used for non-linear analysis creep analysis in ANSYS).

10. Due to many uncertainties involved and the exponential character of the damage development processes it is essential to include risk assessment into the overall evaluation.

11. Intranet/Internet orientation of monitoring systems is not just a technical issue – all future developments of the systems must go in this direction in order to make monitoring results available across the company.

12. Virtually every monitoring solution is specific. It is, therefore, difficult to look for a monitoring system that would "fit all". Flexible and modular solutions are required instead (like ALIAS),

provided that the corresponding configuration management is available.

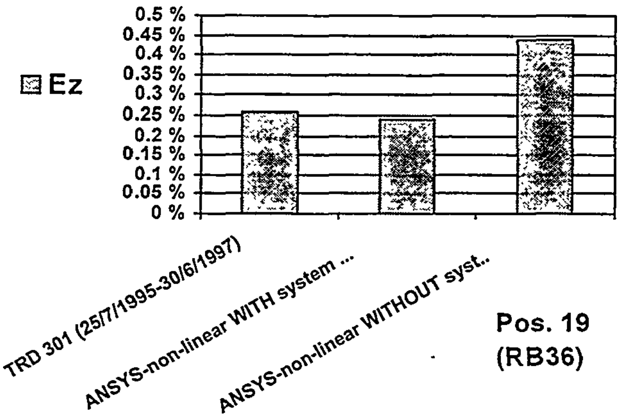

Figure 13:Influence of system stresses onto life exhaustion (Ez -creep) – according to TRD, ANSYS with and without system stresses.

ALIAS as the framework for the targeted monitoring presented in this paper offers a series of advantages as shown in Table 1. Except for the part regarding missing values and data mining, further work on ALIAS will not be aimed on introducing new features, but rather on consolidation and verification of the existing ones.

Acknowledgements

The support provided for this work by the utility companies EVS Stuttgart and FUG Ulm, Germany is gratefully acknowledged.

Table 1: Comparison of ALIAS with conventional monitoring systems.

Feature	ALIAS	Conventional systems	Remarks
p, T, ΔT monitoring	✓	✓	TRD and pair-range method for cycle counting
ovality	✓		
displacement monitoring	✓	(*)	*with 1 exception
management of RLA calculations	✓	partly	Easy overview, full flexibility
Intranet documentation base integrated	✓		
piping system analysis integrated	✓		ALGOR
non-linear system analysis	✓		ANSYS – off-line link
strain monitoring	✓	(*)	*only experimental
full-scale material database	✓		
case-history database integrated	✓		

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TRD – Technische Regeln für Dampfkessel:
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An Advanced Maintenance Advisory and Surveillance System for Boiler Tubes - AMASS

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Abstract

In a recently completed European collaborative project, the aim was to address the issue of boiler tube failures and thereby plant availability. The reduction of forced outages due to component failures and the reduction of planned outages for preventative maintenance can both contribute in this respect.

It has been possible to assess tube degradation due to erosion, corrosion and overheating through the use of on-line techniques (thin layer activation, corrosion probes and novel temperature sensors) and off-line techniques (cold air velocity measurements, laser shearography and measurements of steam side oxide) which have been developed in the project. These techniques have been demonstrated on an oil fired boiler in Portugal and a coal fired unit in Spain.

The output from the monitoring techniques has been integrated in the AMASS maintenance advisory and surveillance system. This is a computerised system comprising a spatial database with add-on tools designed to assess data from individual monitors and to provide the user with information on tube life utilisation rates and the probability of tube failure occurring.

A description of the monitoring techniques will be described along with some of the results of demonstrating them in the field. Also an overview of the computerised system and the way in which it works will be given along with examples of how it can be used to assist with preventative maintenance and to help avoid unplanned outages.

1. Introduction

The thrust of modern development in boiler tube maintenance philosophy, as with other industry sectors, has been driven by developments in computer systems and software. The ability to retain large quantities of data and to analyse it using complex algorithms can allow maintenance engineers to improve performance whilst reducing down time, thus increasing availability and reducing costs. Hence, there are two aspects to the use of computers with maintenance data: data processing and data storage.

In a recently completed European Community sponsored programme an advanced maintenance advisory and surveillance system has been developed for fossil fuel fired boilers for electricity generation. This comprised six monitoring techniques to gather tube data and a computer software system to store data and compute tube lives as an output. The monitoring techniques used were:

1. cold air velocity measurements - to determine areas of high gas flow in a boiler and thus indicate potential for high erosion,

2. laser shearography - to assess the presence of tube thinning or defects due to e.g. corrosion,
3. ultrasonic measurement of steam side oxide - to assess mean effective operation temperature,
4. thin layer activation - an on-line technique to measure tube wear/erosion,
5. resistance corrosion probe - for on-line corrosion loss measurements,
6. duplex stainless steel temperature monitor - an implant technique to report effective average temperature.

Monitoring techniques such as these can provide useful information which can aid decisions regarding maintenance activities. However, the raw data from sensors often requires further analysis (via suitable algorithms) to become useful, e.g. a steam side oxide thickness can provide a temperature indication, once a calculation has been performed. This can be simplified for the operator by computerising the algorithm and submitting files of information to be processed.

It has long been a problem for maintenance engineers to handle the large quantities of data which are accumulated during plant inspections. Data may exist in many different forms, it may be collected from all plant components and establishing relationships between disparate data is difficult. The use of more and newer sensor techniques with greater sophistication only adds to this problem by increasing the amount of data (and formats) available. Hence, there is a strong need to use a computer database to handle the data and the spatial relationships that are developed.

In the project described here a prototype computer system was designed to address both of the problems just described, i.e. the processing of data from sensors and the storage of data from different sources with spatial relationships.

2. Development of Sensors

The aim of the sensor development was to address the problems of erosion, corrosion and temperature measurement of boiler tubes with the emphasis on being able to make continuous (on-line) measurements during plant operation. Two sensor techniques were used to assess each of these aspects, one "off-line" and one "on-line". The intention was to use the "off-line" techniques to assess suitable locations at which to place the "on-line" sensors.

2.1. Off-Line Sensors

2.1.1. Cold Air Velocity

The cold air velocity (CAV) technique is used to assess which areas of a boiler are likely to be most susceptible to high rates of fly ash erosion. It is relatively simple to apply. During a shut down, before any scaffolding is erected in the boiler, an anemometer is used to measure the gas velocity distribution in the tube banks while the induction fans are running. The assessment of information is straight forward, i.e. where gas velocities are high the erosion rate is also likely to be high, and cannot provide any quantitative information on erosion rates. Figure 1 shows an example of some velocity measurements made during the project.

The technique was first investigated in the 1980's by Combustion Engineering (1,2) and was used in this project to determine a suitable location to install an "on-line" erosion sensor, thin layer activation (see section 2.2.1). Some novelty was introduced with the use of smoke generators to determine the fly ash distribution within the gas stream. This is clearly important, as a high gas velocity alone will not cause erosion, it must carry an erodent, fly ash.

2.1.2. Laser Shearography

This is a non-destructive technique used to detect defects in structures. It was first proposed as a technique for inspection of fossil fuel fired power generation plant by Bobo (3). The principle of the technique is that a shearing camera is used to obtain images of a component illuminated by monochromatic (laser) light in both the unstressed and stressed state. The two images are stored electronically and compared with each other in software form to produce interference fringes. An example is shown in figure 2. The fringe spacing is an indication of the strain caused by the applied stress: at greater strains the fringes become closer together. Defects in a component will give rise to different strain patterns and, hence, it is possible to determine the nature and size (semi-quantitatively) of defects.

In this programme it was intended to use the laser shearography technique to determine areas of tube thinning due to corrosion/erosion. During laboratory trials this was shown to be possible and, in addition, it was shown that the technique could also be used to detect defects such as cracking and pitting in tubes. Different fringe patterns were obtained with each type of defect. Unfortunately the technique has the disadvantage that only a relatively small area of the boiler can be imaged at one time, due to the limited area which can be viewed with the shearing camera, and a stress must be applied by partially pressurising the tubes for each image. This can make the technique time consuming, since many images must be taken to inspect a large area, and it prevents other work being done on the boiler, since the pressure circuit must be maintained. However, the technique was successfully demonstrated during field trials in two fossil fuel fired boilers and it is strongly believed that advances in the utility of the technique will be made in the future. This may be through camera improvements, allowing larger areas to be examined with each stress application, or through alternative methods of applying the stress.

2.1.3. Steam Side Oxide Measurements

This technique was used to determine distributions in boiler tube operating temperatures. The internal oxide thickness in ferritic steam tubes is a function of the time and temperature of exposure. Hence, if the operating hours and the oxide growth rate law for the metal are known, the operating temperature can be determined. The original intention was to use the technique simply to determine which were the hottest tubes, i.e. which had the thickest oxides, and thus the optimum locations for installing the temperature implant monitors (see section 2.2.3). However, in an extension of the original work programme, suitable algorithms were developed for relating the oxide thickness to time and temperature for three common boiler tube materials, 2¼Cr1Mo, 9Cr and 12 Cr (figure 3).

For steam side oxide measurements to be a practical route to temperature determination a fast, repeatable, non-destructive method for obtaining data must be used. Ultrasonic thickness measurements provide such a method. This technique was pioneered in the USA in the 1980s (4). However, since the oxides to be measured are relatively thin compared to the measurements normally made using ultrasonics, a high resolution ultrasonic instrument using a high frequency probe (>15 MHz) is required. A review of the literature and discussion with equipment vendors showed that, at the time when the project was starting, the lower threshold oxide thickness which could be measured was ~200 μm. However, it was necessary to achieve a significantly lower limit than this in order to make the technique practical. As a consequence, during the evaluation of the technique, a principal aim was to significantly improve the resolution achievable. Oxides as thin as 100 μm have been successfully measured and it is anticipated that with further developments its will be possible to measure oxides as thin as 50 μm.

2.2. On-Line Sensors

2.2.1. Thin Layer Activation

Thin layer activation (TLA) has been used to monitor wear and erosion processes in the laboratory for some years now (5,6,7). The technique requires that a thin layer at the surface of the component is activated with a low level of radioactivity. When material from the layer is lost there is a consequent reduction in the level of radioactivity detectable and the thickness of material loss can be determined.

Activations are carried out in an accelerator, where elements within the component surface are converted to radioactive isotopes when they are bombarded by high energy charged particles. The depth of activation is determined by the energy of the particles and the level of activation by the duration of bombardment, although it should be noted that the level necessary is extremely low (typically 10 μCi). When the radioactive isotopes decay, gamma radiation is emitted and this can be detected remotely, even through the walls of plant, up to a total distance of about 1.3 m. The level of radiation detected is reduced through natural radioactive decay (determined by the half life of the isotope) and through material loss. For continuous measurements the natural decay of the isotope can be built into the analysis system, but where measurements are discontinuous it is better to compare measurements with a calibration sample activated at the same time and with the same isotope as the component surface.

Gamma radiation is highly penetrating allowing measurements to be taken at some distance and through solid objects, while the sensitivity of detectors allows very low levels of activity to be used, typically 10 μCi. The technique has the advantages of being on-line and also allowing remote monitoring. Real components can be activated, provided that they can be fitted into the accelerator, ensuring that the plant remains unmodified. The limitations of the thin layer activation technique are the maximum depth of activation, which is usually <0.5 mm, the facilities required for activation, which can only be provided at a very limited number of sites, and the maximum distance from activated area to detector.

In the AMASS project TLA has been used to monitor tube erosion in a coal fired electricity boiler burning a very high ash burden coal. These trials demonstrated just how sensitive the technique can be in measuring erosion. In this case it was possible to detect a metal loss of just 1 μm in a 200 μm layer, sensitive enough to be able to show the reduced erosion rate when the plant load was reduced at weekends (Figure 4).

2.2.2. Corrosion Probe

In order to monitor boiler tube corrosion on-line, an electrical resistance probe has been developed to continuously monitor metal wastage. This technique was originally developed for monitoring corrosion at low temperatures but in recent years there have been attempts to adapt the technique to high temperature applications. The principle of the technique is that a metallic element, made of the same material as the component being monitored, is exposed in the environment and allowed to corrode. As it corrodes the element becomes thinner and the electrical resistance increases. Regular measurements of the resistance can provide valuable corrosion rate information on-line.

In applying the technique to heat exchanger applications there are two obvious requirements. The temperature of the corroding sensor element must be maintained at that of the component being monitored, e.g. a boiler tube, and must therefore have some form of cooling to maintain it at that temperature, rather than the temperature of the flue gas. Also, the temperature of the corroding element must be known, such that the variation in the metallic electrical resistance with temperature can be accounted for and will not affect the corrosion measurements made. These difficulties have restricted the use of this technology in heat exchangers in the past (8). Nevertheless, considerable effort has been devoted to solving the problems encountered and it is now believed that, as a result of the lessons learnt during the field trials of the technique, it will be possible to build a fully working probe.

2.2.3. Temperature Monitors

The final sensor technique evaluated during the project was an implant temperature monitor. This comprises a duplex stainless steel in which the ferrite content is only metastable and, as a consequence, will decay on exposure at high temperatures. After exposure the remaining ferrite content of the stainless steel is a function of exposure time and temperature. The remaining ferrite content may be measured quickly and easily with a hand held ferrite content meter, which measures the magnetic permeability of the metal.

This technique was first proposed by Lai at the City Polytechnic of Hong Kong (9,10) who established a selection of model alloys which were characterised for their time/temperature response. The work at ERA has been to investigate the time temperature response of a selection of commercial duplex stainless steels. This showed that the technique may be used to monitor temperature in the range 400 – 700°C, and algorithms for converting the ferrite contents measured to temperature were established for three materials.

However, the accuracy of the technique is not as good as had been hoped. This is believed to be due to several factors including: variability in the ferrite content of the material before exposure (±1-2%); the limited accuracy of the ferrite content measurements (typically ±0.1%); and the formation of para-magnetic secondary phases during ageing, such as sigma phase.

3. Development of Software System

The purpose of the AMASS software system is to collect and store plant data (boiler tube inspection and sensor data) and process it, in order to provide boiler tube life predictions which will assist with maintenance scheduling. However, because of the modular design, with a generic, spatial database at its core, the system is capable of being applied to other complex equipment, where large quantities of design and inspection data exist.

Associated with any high value, complex plant, where regular maintenance inspections are carried out and numerous sensors are installed, there will be a very large volume of historical data to store. The relationships between different data sets are often complex, but, where the relationships are known, inferences may be made for the benefit of the plant operator. The advent of powerful desktop computers, with large, fast access memories and fast processors, has made it possible to accelerate data storage and access and expand its utility by allowing full comparisons to be made. The AMASS software system was designed as a modular system with a topological or spatial database at its core, intended to establish and maintain complex data set relationships. To provide the life estimates, on which maintenance decisions can be based, "plug-in" tools (algorithms) have been designed and encoded for data processing.

3.1. Database System

At the core of the AMASS software system is a topological or spatial database with a user configurable graphical interface. The principle is that data files, which may be images, numerical or textual data, are all stored and accessed in the same way via a descriptor of the data. The descriptor contains information such as the type of data, date of creation, source, size etc. One of the most important pieces of information stored in the descriptor is the physical location of the data with respect to the plant. Remembering that data can be an image, this allows a hierarchical graphical interface to be developed, where images are linked together. A browser is provided such that the user may navigate through the interface to find the data that is required or the location against which to store new data. The browser relies on the locations within the plant being associated with a coding system, which may be the user's system or a proprietary system, such as KKS. The purpose of the coding system is ultimately to allow spatial relationships to be inferred between data sets and the graphical images, which represent the plant. Hence, data sets with related codes may be compared with each other or processed together, as appropriate.

In practice the system is user configurable with the benefit of flexibility and thus applicability to a wide range of plant. The user may import custom images into the system to create the graphical interface and apply the local plant coding system. The necessary component coding systems can be cumbersome, since they are generally complex, and therefore difficult to set up. However, once they have been established, i.e. the system has been configured, it is not necessary for the user to know them. It is then possible to browse through the database via the graphical interface. A hierarchy of images in the graphical interface, as illustrated in figure 5, will ultimately lead the user to the data that is required or the location to store new data.

A prototype of the database has been developed, which has served as an adequate demonstration of the basic principle. However, the scope for further development lies not only in productising the prototype, but also in introducing advanced software features, such as data mining and data fusion. By including advanced features it will be possible to either infer solutions, where there is a shortage of data, or provide complete solutions, where multiple sources of data are available. This is only possible if a location coding system has been fully implemented.

3.2. Modular Tools

The software tools were designed to process the data output from the sensors which were tested and developed during the project. Hence, there were tools developed to provide temperatures from steam side oxide measurements, metal loss rates from thin layer activation measurements, and temperature from feroplug measurements. Finally, and most importantly, a tool was also developed to provide estimates of tube life from geometry, operating pressure, metal temperature and metal loss rate, i.e. using the output of the sensors either directly or processed by the other software tools.

In practice the tools are treated in a similar way to data. The tools are modular, existing as standalone executable files which may be run separately from the database at the core of the software system. When the tools are registered in the database system it becomes possible to make permanent associations between them and the data files, such that data files may be recalled and processed with a few simple commands. This increases the flexibility of the system since, it is a relatively simple matter to incorporate new tools and associate them with data files as necessary.

4. Integrated Sensor and Software System

The successful integration of the sensors and software in the AMASS system depends on the primary data flow. A flow diagram showing the integrated data flow is shown in figure 6. The offline sensors, cold air velocity, laser shearography, and ultrasonic measurements of steam side oxide, are used to survey the boiler and determine which tubes are affected by high erosion and corrosion rates or exposure to excessive temperatures. The areas where these potentially life limiting degradation mechanisms are at their worst are the optimum locations for installation of the on-line sensors. If the on-line sensors, TLA, corrosion probes and Feroplug implants, are installed at or close to these positions then they can provide critical information regarding the rates of degradation in the most susceptible areas of the boiler. Hence, the life of the tubes which will fail first can be predicted and appropriate maintenance can be undertaken in a timely manner.

From the above, the primary data flow is from the off-line sensors to the on-line sensors, to determine their installation locations. The secondary data flow is then from the entire set the sensors (off-line and on-line) to the AMASS computer database system, i.e. all of the data collected is stored in the database with location and time and date information. This is supplemented by plant data from other sources, such as design data, including tube dimensions and operating pressures, and materials data, including tensile properties and creep parameters.

The next line of data flow is from the database to the software tools, steam side oxide, temperature implant and TLA. The database system stores the necessary information in the data descriptors to configure correctly the stored data for use with the appropriate tools. The outputs from these three tools provide suitable input values for use in the final tool, which produces tube life estimates. Hence the final line of data flow is from the steam side oxide, temperature implant and TLA tools and the AMASS database system, where materials information is stored, and other sources of information (as required) to the tube life tool. The output from this final tool is tube life estimates, which, as stated above, can be used to assist maintenance decisions.

5. Concluding Remarks

1) As part of a BriteEuram project a system of sensors for providing information on boiler tube failures has been investigated.

2) The sensors have all been demonstrated during plant trials with varying levels of success, nevertheless demonstrating proof of the concepts.

3) A modular software system incorporating a spatial database for storage of data and tools for data processing has been developed.

4) The software has been demonstrated as a prototype and the steps necessary for further development have been identified.

6. Acknowledgements

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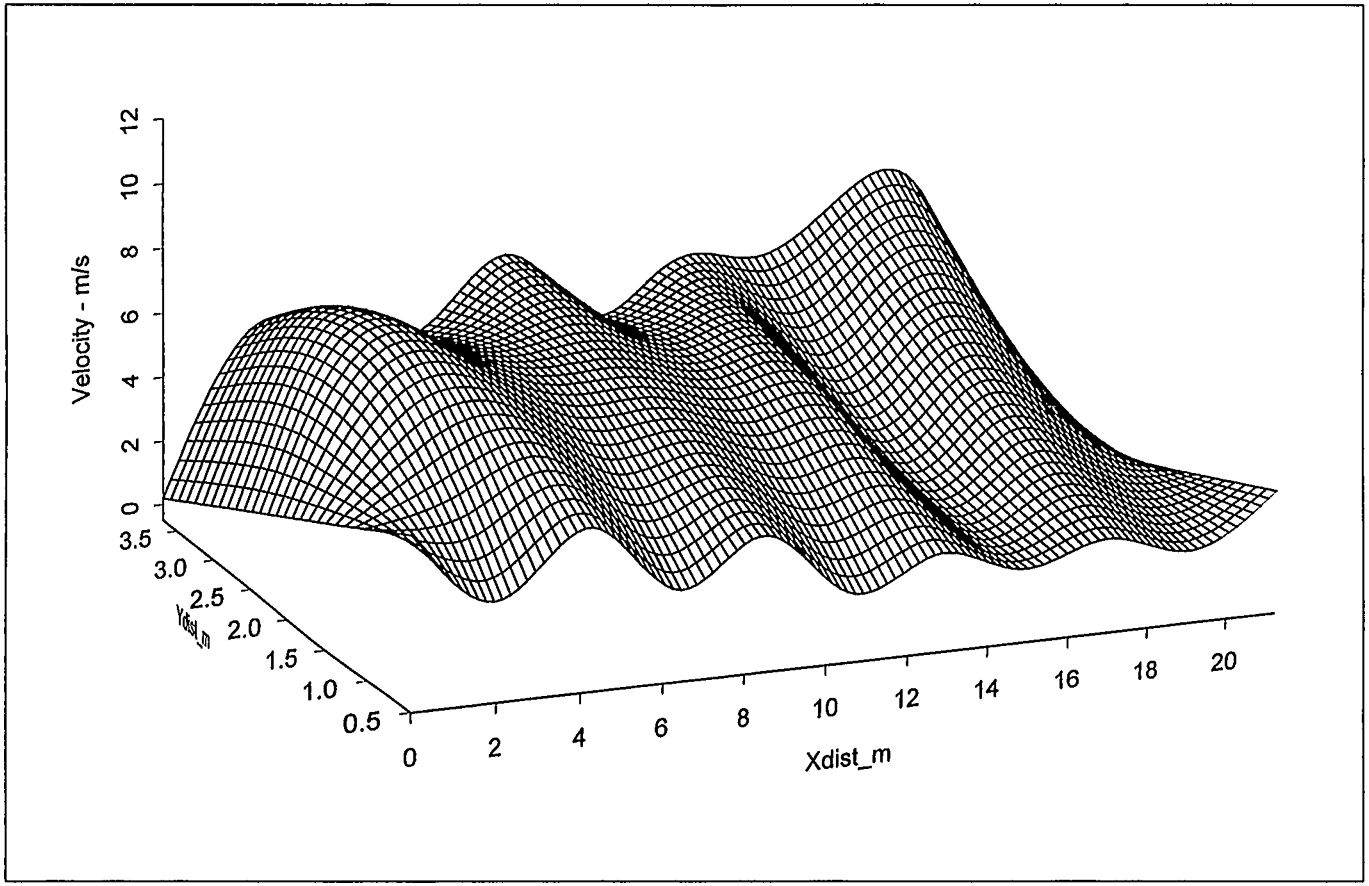

Figure 1. 3d plot of cold air velocity data.

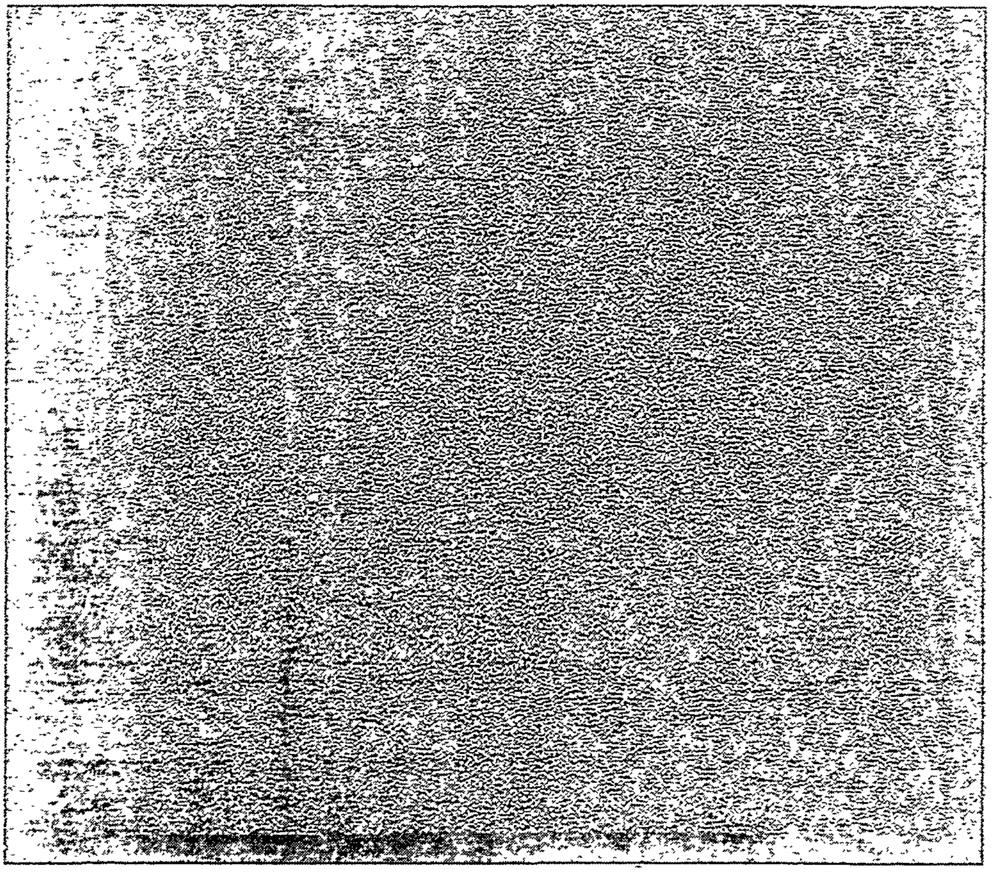

Figure 2. Example laser shearography image.

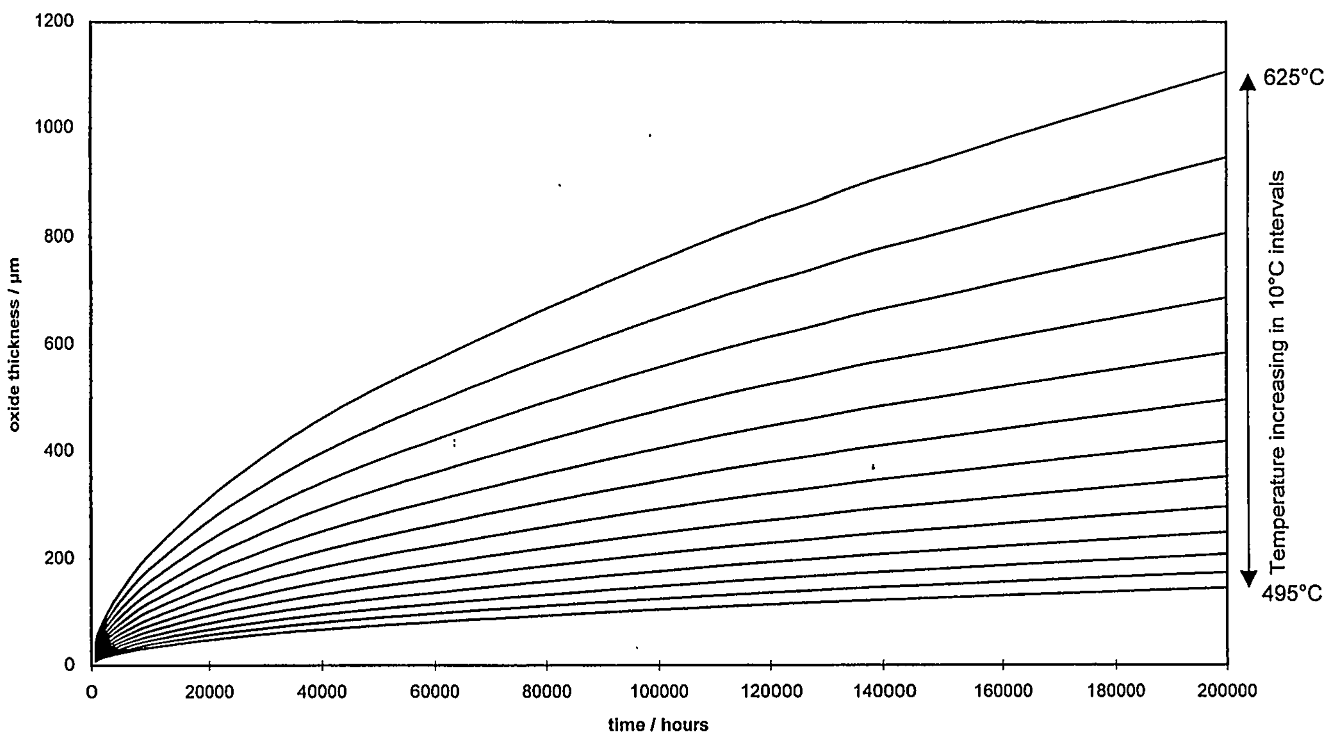

Figure 3. Model for steam side oxide growth derived for 2¼Cr1Mo.

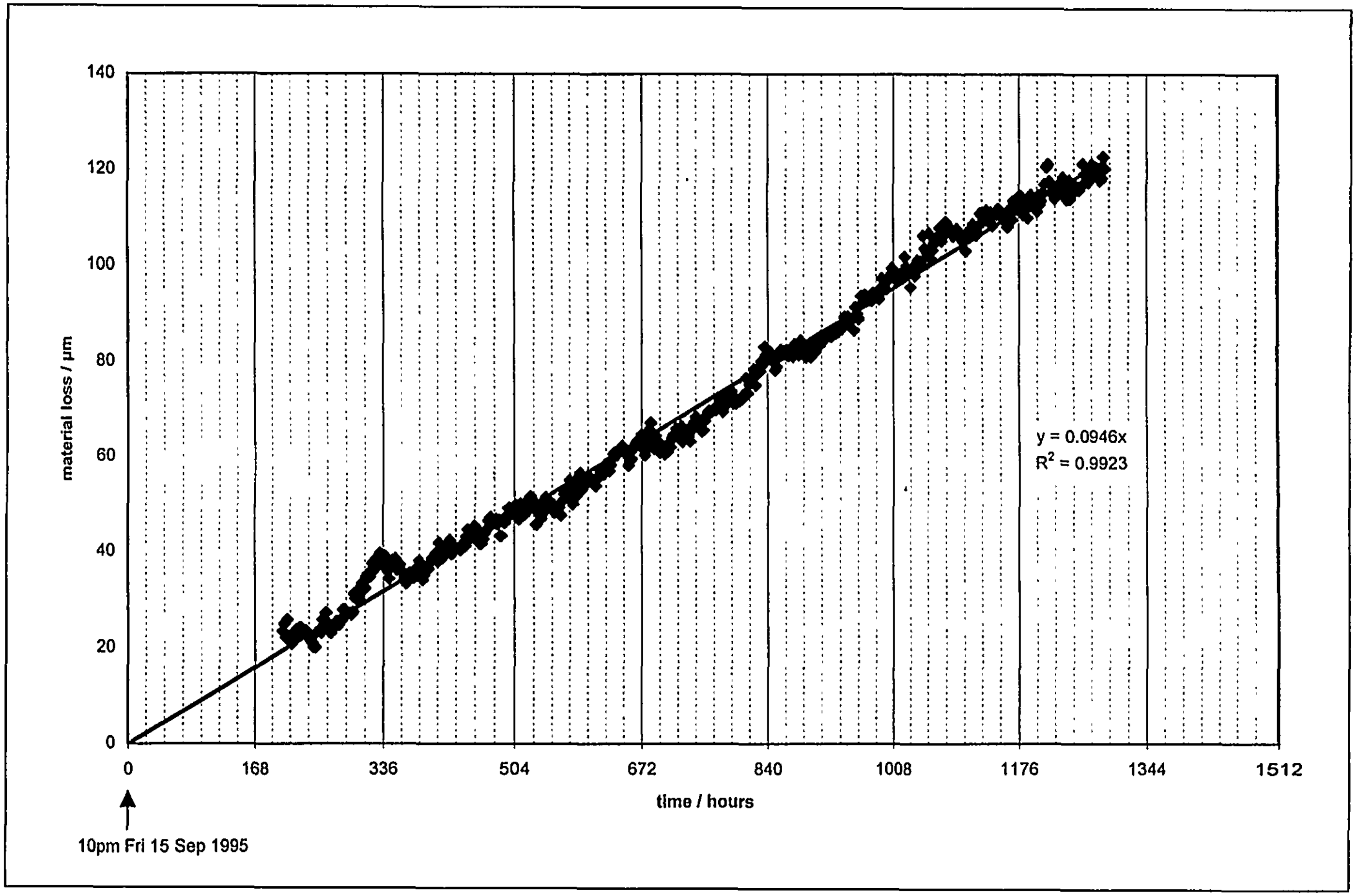

Figure 4. Metal loss with time as measured using thin layer activation on a boiler tube (grid lines at 1 day intervals).

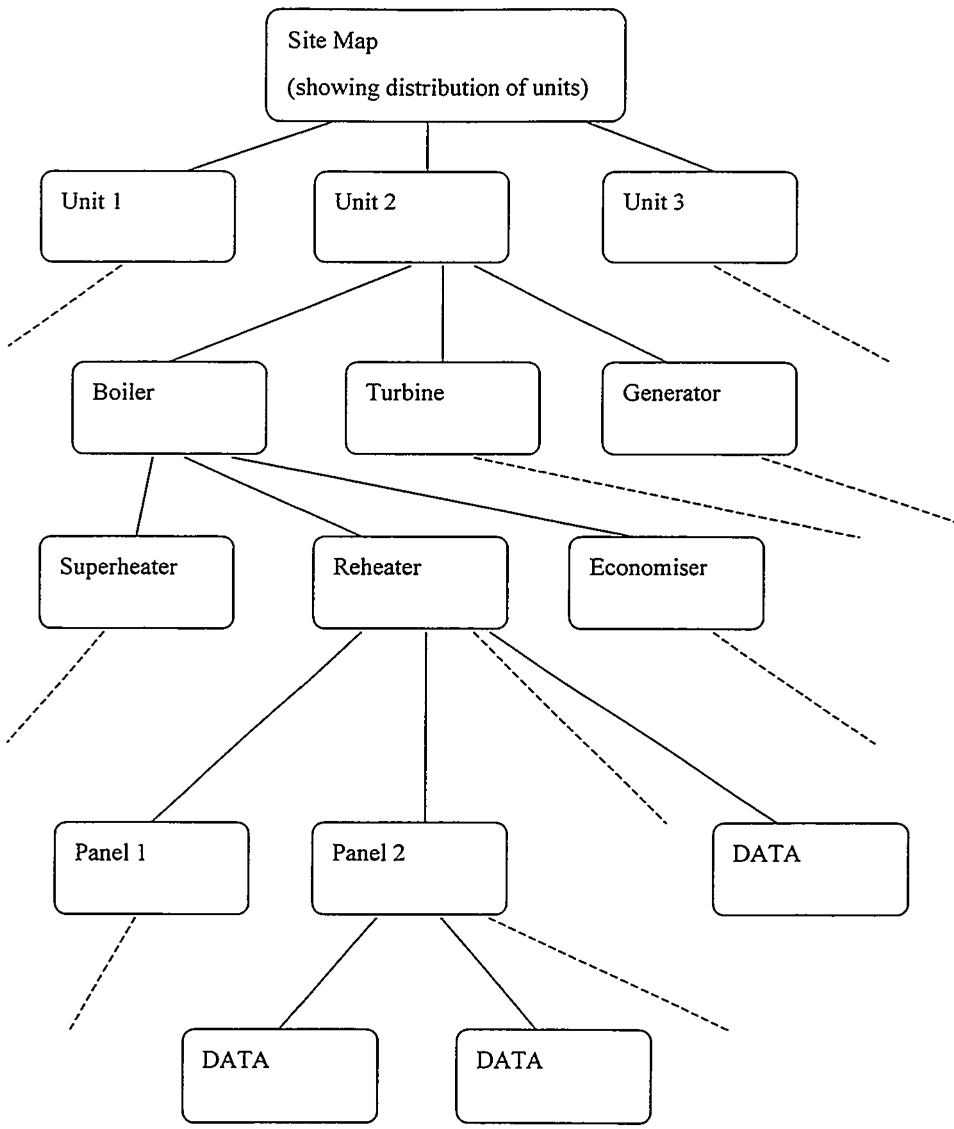

Figure 5. Hierarchical structure of images and data in the database system.

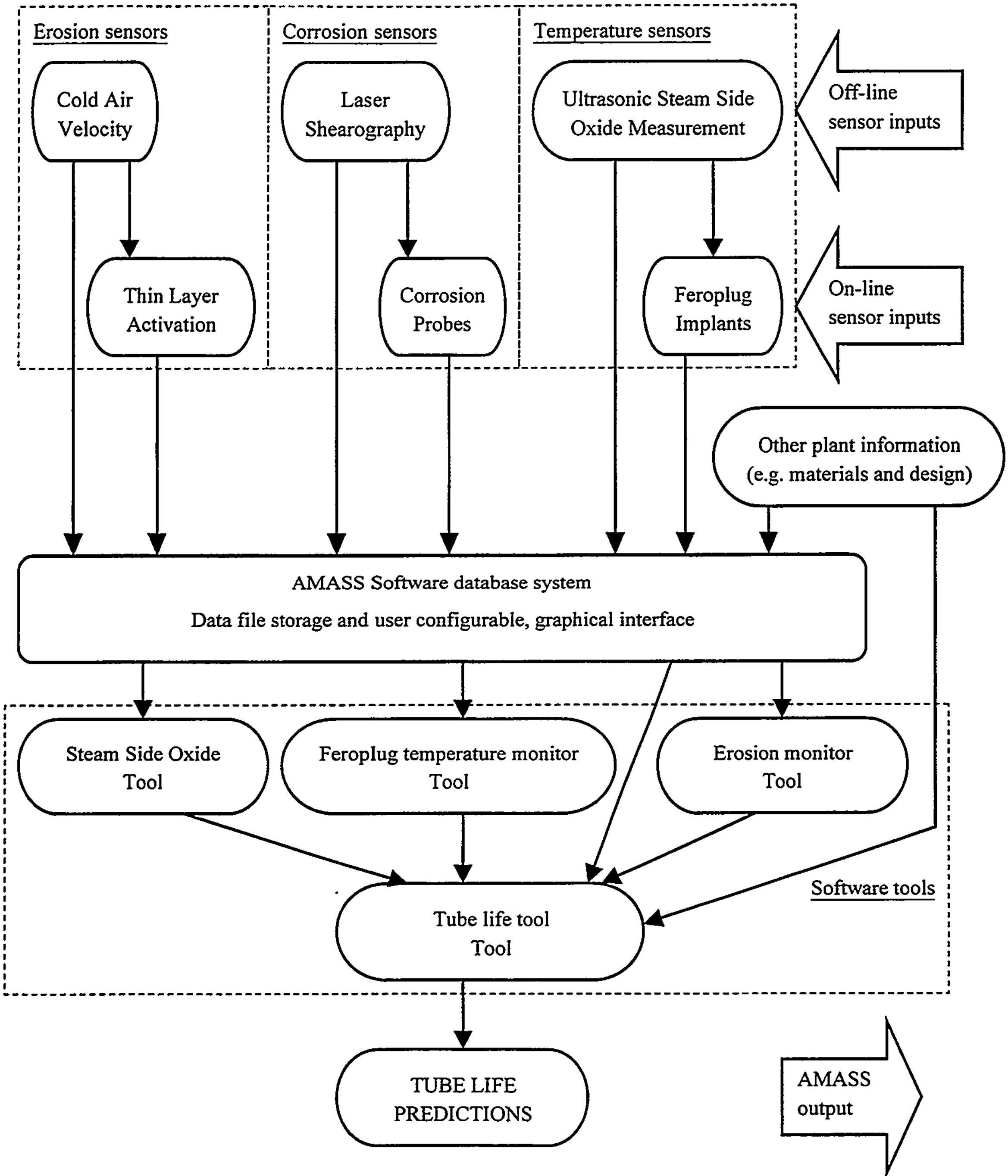

Figure 6. Flow diagram showing the integration of the sensors and software system.

The Role of Predictive On-Line Monitoring Systems in the Power Generation Industry

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Introduction

It is has been apparent in the power generation sector for some time that utilities are moving away from large scale, labour intensive, inspection and overhaul programmes. These are being replaced by targeted inspection and replacement programmes supported by engineering assessment. Such engineering assessments address the predominant long-term damage mechanisms and are aimed at predicting failure timescales based upon historic operating data. From these predictions extended inspection intervals can be justified and replacement schedules planned in advance, ensuring maximum plant availability and deferred capital expenditure. However, as these assessments are based upon an examination of past operating history they must be periodically re-visited and up-dated. The cost of such re-assessments is usually close to that performed initially, although cost savings can arise from reductions in work-scope which have been previously justified.

As computers have become more advanced (and significantly cheaper) some of the expertise used in these assessments has been transferred into software based products. However, these products are generally aimed at replacing specific parts of the desk-based analysis, necessitating a suite of products to be used in order to address all of the components and damage mechanisms, which must be assessed. As these products require specialised knowledge to be used effectively they are often employed by consultants and rarely by plant operators, except in the largest of organisations which can support an in-house team of 'experts'. This has in essence led to an increase in the number of companies capable of offering assessment services, but has maintained, in the majority of cases, the plant operators reliance upon external consultants. These software based assessment methods rely upon historic operating data (in the same manner as their desk-based counterparts) and hence also need to be periodically up-dated. However, as previous assessments can be retrieved electronically re-assessment costs are generally significantly less than that of the initial assessment.

On-Line Systems – The Benefits

On-line assessment systems, which constantly monitor plant operation, have recently been developed which are capable of updating analysis results as operating conditions vary. These systems represent a natural progression from their off-line predecessors, and a range of additional benefits, the more important being:

- **Extended run periods between turnarounds:** on-line life usage monitoring of critical components demonstrates a degree of vigilance which can persuade safety regulators and insurers that the interval between plant turnarounds may be extended, thus providing the opportunity for increased production, reduced costs and corresponding competitive edge.

- **Plant Life Extension:** the life of critical components of boilers is limited by time-dependent degradation processes. However, the actual life of these components invariably substantially exceeds the design life. The continuous life usage accountancy provided by on-line life usage monitoring which accommodates changes in operating regime and practices as they occur. Thus the life prediction is significantly more accurate and meaningful than off-line predictions based upon historic operation, thereby maximising the safe and economic life extension period. This provides economic benefit via (i) avoidance of plant failures and associated loss of generation revenues, and (ii) deferred capital expenditure on plant refurbishment or replacement.

- **Focused maintenance:** on-line life usage monitoring identifies developing integrity problems in advance of turnarounds, thereby allowing contingency repair, refurbishment or replacement plans to be made. Extended shutdowns due, for example, to procurement of long lead-time components such as boiler headers, are thereby avoided and production losses minimised.

- **On-line stress displays** allow plant operators to identify the effect of various operating practices on the life of headers and other thick-section boiler components during cyclic operation, and provide the opportunity to mitigate particularly damaging events, thereby facilitating further life extension.

The greatest driving force leading to the wider acceptance of such on-line systems relates to the last of the above key benefits, which is the increasing move toward cycling previously base loaded plant, in the form of 2-shift operation and load following. In the UK, generation over-capacity (and cheap imported electricity) has lead to an increasing number of stations; in particular older coal powered plant, regularly cycling in accordance with market requirements. This trend is spreading worldwide as electricity-generating industries are taken out of the public domain and privatised. This both introduces competition, reducing generation revenues and a need to increase fuel cost/generation revenue ratios, and generally leads to an expansion in generating capacity as private companies build new plant and increase the capacity of existing stations to increase efficiency.

This move from base load to cycled plant has two major implications for off-line assessment. As noted above off-line assessments are reliant upon historic data which it must be assumed is representative of future service to facilitate predictive analysis. Evidently, where plant is taken from base load to cyclic loading, this is not the case. Furthermore, it is difficult to predict the number of cycles which will occur in the future, as this is dependent upon changing market conditions. Consequently, the weighting of historic data to estimate future operation is fraught with uncertainties, necessitating the need for upper bound estimates of operational parameters to be assumed, resulting in inherently conservative estimates of plant life.

However, despite the benefits offered by on-line systems there still remains reluctance amongst many plant operators to install such systems on- plant. The most commonly cited reasons for this reluctance are cost (as always) but also a reluctance to accept the results of a computerised system which potentially could indicate that plant should be shut-down, replaced etc which has self evident economic consequences.

Key Issues

The cost issue is perhaps the more readily addressed of these two issues. Taking a short-term view, the purchase of an on-line system is often significantly greater than undertaking an off-line assessment. Although it can be argued that to provide sufficient operating data (by the provision of sensors on the plant) for an off-line assessment of comparable accuracy to that which can be offered by on-line systems would significantly reduce the cost difference. Taking a longer term economic view removing the reliance on repeated off-line assessments shows that on-line systems prove more cost effective, even ignoring the additional economic benefits that they offer. Thus taking the cost issue contracts for on-line systems are not won overnight. In general once a utility has been convinced of the need and benefit of an on-line system it may take several years for the appropriate budgets to be agreed before such a system can be purchased.

It is in overcoming utilities reluctance to put reliance on a computerised system to ensure plant integrity that has imposed the greatest restriction on the adoption of on-line systems. Although, the assessment methods used in these systems are directly related to those upon which the utilities rely for justifying targeted inspection and replacement programmes the removal of the human factor from the assessment process remains a matter for concern. Often this reluctance is not overcome by reasoned argument, but on the basis of example, by providing details of other utilities already using such systems. Fortunately, the former CEGB in the UK developed a number of on-line assessment systems which the privatised generating companies continue to use, and thus can be cited as a suitable example.

Available on-line systems can be divided into two groups, those that simply monitor operating conditions and report abnormal events, and those that use monitored data to predict remaining effective component life. As would be expected it is these latter systems which provide the greatest potential benefits and can be used to supplement (and in part replace) standard inspection and assessment activities. In the power generation industry the majority of these predictive (capable of estimating life consumption) on-line systems are targeted at steam generating boilers, with relatively few being available for the steam turbines which they power. There are a variety of reasons for this imbalance, of which some of the most significant are:

- Standard maintenance schedules require far more frequent boiler, than turbine, major inspections. Hence greater potential benefits can be derived in the boiler case.
- Turbines (or the sections thereof to which life prediction is applicable) are responsible for far less forced generation losses than boilers.
- Turbines generally have far more monitoring systems (non-predictive) installed as standard, to detect abnormal operation and aid the prevention of failure.

The following section of this paper provides an overview of a typical on-line predictive assessment system aimed at steam boiler plant, AEA Technology's Boiler Life Monitoring Software (BLMS).

Boiler Life Monitoring Software (BLMS)

Background

The principle purpose of BLMS is to provide on-line analysis of the life usage of identified at risk components, within large steam generating boilers. In the majority of cases it is used to monitor the following component types, and locations thereof:

Component Types	Examples	Monitored Locations	Damage Mechanisms
High temperature headers	Final superheater outlet header Reheater Outlet header	End cap Outlet branch External body Internal body	Creep Creep Creep Creep and fatigue
High temperature tube banks	Final superheater tube bank Reheater tube bank	Tubes	Creep and corrosion
Low temperature headers (and vessels)	Economiser inlet header Steam drum	Internal body Internal body	Fatigue Fatigue

The above list of typically monitored locations will be of no surprise to those familiar with the long- term integrity assessment of boilers. Of evident prime concern is the development of creep damage at the external surface of internally pressurised high temperature components. In addition for thick-section components, subject to transient temperatures, the development of fatigue damage at the component's inside surface must also be addressed. The latter gives rise to a phenomenon usually referred to as "inter-ligament" or star-burst" cracking, which in susceptible component types is often the predominant long-term integrity concern. There follows a brief description of the cause of this internal fatigue damage.

In the presence of significant thermal cycling, the principal damage mechanism which occurs in thick-section boiler components is either creep-fatigue (if operating within the creep temperature range of the material of construction) or high strain fatigue due to the through-wall temperature gradients which occur during operating transients i.e. start ups, shut-downs, load changes etc. For components operating within the creep temperature range, creep damage also accumulates during steady load operation due to internal pressure stresses.

Fatigue damage develops in the bore of thick-section components due to thermal gradients established through the wall during operating transients. Fatigue damage is concentrated in areas of high local stress concentration at the internal surface, such as the ligaments between tube stubs in headers. Damaging transients are generally those where hot or cool steam (or water) enters thick-section components (from tubes), thereby producing a sufficient down-shock locally in the bore that a high strain fatigue cycle is generated. If the component is operating below the creep temperature range, the damage will accrue by high strain (low cycle) fatigue. If it is operating within the creep temperature range, damage will accrue by creep-fatigue, the creep component being the result of relaxation of the displacement controlled thermally induced stresses during the operating period following the thermal cycle.

BLMS logs data from sensors (thermocouples and pressure transmitters) installed on the components of interest, from which information stress levels are calculated (due to internal pressure and where applicable through-wall temperature gradients). This information is subsequently used to determine life consumption and thereby to estimate remaining life.

The methodology used to determine life consumption evidently varies depending upon the damage mechanism(s) being addressed. For locations subject solely to pressure stress dominated creep damage accumulation assessment is made on the basis of pressure-driven creep using a creep-rupture assessment procedure. This utilises a time-based description of damage accumulation, where the material's behaviour is described by a parametric equation relating temperature and stress to rupture life.

For locations subject to fatigue or creep-fatigue, a strain based assessment procedure is used based upon the principles of R5, using a ductility exhaustion description of damage accumulation. For operation in the creep range, the life fraction consumed due to damage generated by pressure stresses during steady load operation is summed with that due to creep-fatigue damage using a linear damage summation rule. BLMS identifies peaks and troughs in the operating stress to discriminate cycles using a forward time stepping protocol such that life usage is calculated on-line. The calculated elastic stresses are corrected for plasticity and the magnitude of each strain cycle is compared with the fatigue endurance threshold for the material and either discounted as non-damaging, or used to calculate the life usage. The creep damage associated with relaxation of the peak tensile stress in each cycle during the subsequent dwell is also assessed where appropriate.

In the case of tube banks, the analysis of individual tubes is impractical, consequently a statistical approach is adopted whereby tubes are grouped into populations of common dimensions, material and duty.

Boiler tubes undergo long term thinning as a consequence of external and internal corrosion during operation. Since they are thin-walled components, such thinning is significant and typically can reduce tube thickness by 50% within 5-10 years. The dominating stress in such tubes is the hoop stress (due to internal pressure) which is inversely proportional to tube thickness. Accordingly, tube wall stresses can increase significantly over this time frame and resistance to creep damage accumulation decrease. To reflect this process, BLMS utilises an analysis procedure which takes full account of the synergistic effect of wall thinning on creep life. Creep damage accumulation is assessed on the basis of a time-based assessment procedure as in the general pressure-creep case.

Within each of the tube populations there will be both physical and service related variations in the key inputs required to the assessment algorithms, in particular thickness, temperature, material properties and thinning rate, it generally being assumed pressure is constant throughout the tube bank. A statistical description of the variation of these parameters is contained within the LMS tube module, based upon various empirical and service experience based sources. The assessment algorithm samples each of these distributions and calculates the associated life consumption. This process is repeated 10,000 times and the results of these individual assessments assembled to provide a cumulative failure probability for any given time. In general life management is based upon a failure probability of 1/n where n is the number of tube sections within the tube population, hence this represents the time at which there is a 100% probability that one tube within the population group will have failed.

Software Aspects

The LMS software is configured as a client/server application running on suitably specified PC's, operating under Microsoft Windows NT V4.0, and forms part of the overall monitoring system. The LMS core software is generic to all boiler plant, the product delivered to customers being tailored to reflect the actual boiler design and data acquisition system (DAS) of the plant it is monitoring.

In order to minimise the cost of this tailoring (referred to as customisation) all of the plant specific information is contained within a single (SQL server) database. This same database is also used to store the monitored and calculated data. BLMS monitors temperatures and pressures at critical locations on selected components and convert these on-line to stresses, life consumed and remaining life on-line.

The software displays the measured temperatures and pressure, the computed stress and the cumulative life fraction consumed and remaining life for each monitored location. All significant data are stored and can be recalled for review. Display and data selection is via a graphical and intuitive user interface, using familiar Windows icons and drop-down menus, providing a simple route to the considerable amount of data generated each minute. BLMS utilises a main display to provide an overview of the calculated remaining life of the components being monitored augmented by supplementary text and graphical displays, which provide more detailed information.

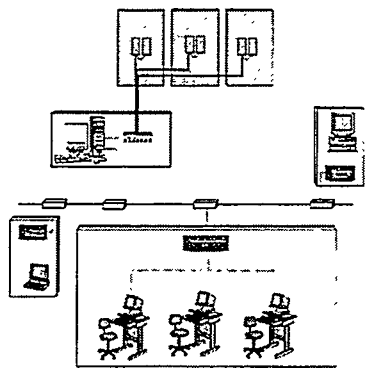
The main display area comprises a series of user selectable displays, arranged in a hierarchical order. Each layer of the hierarchy representing an increased level of detail. As such the user navigates from the top level (least detail) station overview display, through boiler overview to displays depicting each individual component (most detail).

The 'Station Overview Screen' displays for each boiler, the maximum life usage and remaining life for any of the component locations being monitored on each boiler. In addition it allows the operator to select more detailed displays either at boiler level or location level, the latter via the 'Boiler Overview ' and 'Component Overview' screens.

System Aspects

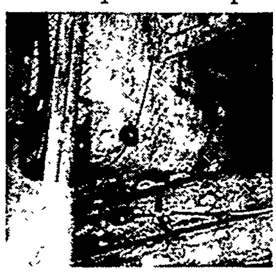
The BLMS software forms the core of the overall BLMS system, the key common components of which are as follows:

- Sensors
- Data acquisition system
- LMS server computers
- LMS client computers
- Ethernet network



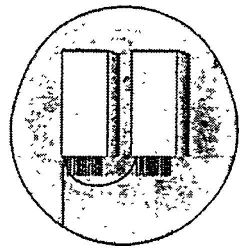
Sensors

LMS requires both pressure and temperature data specific to the components being monitored. This is provided by thermocouples and pressure transmitters located at key plant locations. In general, there will be only one pressure sensor associated with each component. However, there are usually multipul thermocouples per component. These thermocouples being located at various locations corresponding to the locations of interest (generally the locations with the highest potential for damage accumulation).



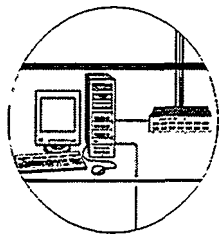
In addition to the physical sensors on the plant LMS also utilises so-called "virtual" sensors. These, as the name would suggest, are not physical sensors but calculated values derived from the value of one or more physical sensors. These virtual sensors make use of mathematical modelling techniques to simulate sensors at locations where no physical sensor exists. This both reduces the number of real sensors required and allows temperatures to be monitored at locations where the installation of a physical sensor is in impractical (e.g. on the inside surface of a header).

Data Acquisition System



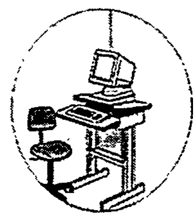
The data acquisition system provides the link between BLMS and the plant sensors. It can take many forms depending upon local circumstances, ranging from a stand-alone system controlled by BLMS, to a pre-existing station DAS from which LMS retrieves the required data.

LMS Server Computer



The BLMS server computer(s) provide the BLMS data-logging functions and act as the interface between the DAS and client computers. As such it is the server computers which retrieve data from (and control) the DAS and log (store in the BLMS database) the sensor data. In addition, all of the calculations required in predicting remaining life are carried out by, and stored in the database by, the server computer(s).

LMS Client Computers



Although the server computer(s) are capable of displaying the BLMS data, because of their key role in the BLMS system they are generally not used for this purpose. Instead client computers (which do not carry out any data logging or calculation duties) are used as the primary user interface to the BLMS data.

As the purpose of the client computers is to display the data produced by BLMS (by the server(s)) they are usually located in the control room and various key office locations as required. In addition to providing access to data, important events/alarms identified by the server(s) are automatically displayed on the client machines

Requests for data made from the client machines are processed by the server(s) and the results returned to the client. Thus if on-line data is to be displayed on the client it must be connected to an active server (via the ethernet network)

Ethernet Network

The ethernet network provides the link between the client and server machines. All BLMS networks utilise TCP/IP protocols although the actual topology of the network can take virtually any form. In addition to connecting the server(s) and client(s) the network also links printers and remote access devices (providing connection to corporate WANS).

All on-line systems take a similar form to that of BLMS described above, varying only in scope and complexity. The system requirements are also generic as all systems require access to plant data and some means of storing and disseminating this data to users together with the results of the analysis undertaken.

Future Development

Steam Plant

As this paper is predominantly aimed at those concerned with the power generation industry, the majority of this discussion will reflect this bias, and look at other areas within the industry. However, it is certain that the move to on-line monitoring systems will increase in all sectors of industry. As the problems of creep and fatigue damage are not unique to the power industry, a couple of examples of where this technology can be expanded beyond the power generation industry will also be examined.

As mentioned in the introduction to this paper, the majority of predictive on-line monitoring systems are targeted at large steam raising boilers. However, for every boiler there is a corresponding steam turbine, for which there are very few predictive systems. The current concentration on boilers centres around two aspects :

- Standard maintenance schedules require far more frequent boiler than turbine inspections
- Turbines generally have far more monitoring systems installed as standard to detect abnormal operation and hence prevent failure, although not forced downtime.

For these reasons it is generally difficult to justify a turbine only monitoring system, unless a significant integrity issue has been identified. However, the provision of a combined boiler and turbine system is a more viable prospect as it would allow the management of the total power producing unit (boiler and turbine) and not just a part thereof.

The development of predictive steam turbine monitoring systems is only a short step from boiler systems as the majority of the required assessment routines required are the same in both cases, albeit that in the turbine case stresses produced by rotation must be considered in addition to pressure and thermal stresses. In the case of older vintage rotors, particularly of mono-block un-bored construction there is also a strong case for monitoring bore stresses during transients in the context of fast (brittle) failure originating from bore defects contained in low fracture toughness material

Currently of particular concern in many UK power stations is the presence of internal ligament cracking in high temperature headers. Currently the majority of on-line systems address crack initiation (for instance BLMS predicts the initiation of cracks up to 5mm in size), but do not address subsequent crack growth. The CEGB recognising this problem developed a system which was integrated into the data acquisition system of a number of power stations. However, difficulties in 'tuning' this package to reflect crack dimensions and growth rates observed on plant has continued reliance upon inspection based assessment methods. Currently the requirement for crack growth monitoring systems remains relatively small, predominantly consisting of the older UK power stations owned by the smaller generation companies. However, it is anticipated that overseas markets will expand as the population of older (and importantly cycled) plant increases and the problems experienced in the UK become more wide spread.

In mitigation against the wide-spread development of such systems are two key factors however. The reluctance to rely upon a computer based system to ensure the integrity of components known to be cracked is far greater than that in the un-cracked case. Indeed, in some countries legislative bodies will not even allow operation if there are cracks present in critical components. The second factor is that to a large extent inter-ligament cracking can be designed-out, by adopting higher creep strength materials, for instance by using 9Cr rather than 21/4 Cr steels, which allows for thinner sections and hence lower through-wall temperature gradients. Adoption of a policy of selective header re-design and replacement in smaller stations with only a relatively few at-risk headers will almost certainly prove more cost-effective than installing a suitable monitoring system.

Gas Turbines

The use of gas turbines in the power industry is steadily increasing as a result of low gas prices and the increased availability of larger (higher generating capacity) turbine units. The popularity of gas turbines is to some extent also attributable to the very low manning levels required to run gas turbine, as opposed to traditional steam turbine, plant. Gas turbines are also being increasingly utilised as part of combined cycle plant, which increases efficiency and thereby potential profit margins.

At the present time there are no widely accepted non-destructive inspection methods suitable for assessing the condition of many of the critical gas turbine hot section components, such as the blading. Inspection intervals are based upon simple formulae (usually provided by the OEM) and assessment usually made on the basis of destructive sampling. Even in the light of test results component replacement is generally made at OEM recommended intervals.

In view of the above the potential market for on-line systems targeted at gas turbines is both large and potentially of high value to users. However, there are two major obstacles, which thus far have limited the development of viable on-line monitoring systems.

The first such concerns the availability of materials data. The development of gas turbine technology (particularly that geared toward the production of higher capacity plant) is to a major extent constrained by the availability of suitable blade materials and developments in blade design. As a consequence, manufactures are constantly developing new materials, often using novel production methods. In addition, many blades are coated by various methods to provide improved corrosion resistance at the blade surface. Many of the materials employed are therefore proprietary to the various turbine manufacturers who are naturally reluctant to disseminate key blade material data.

Consequently, if a generic on-line monitoring system were to be developed a considerable amount of creep/fatigue materials testing (at very high temperatures) would be required to derive the necessary materials data. It is unlikely that these costs could be recovered, considering the constant revision of the blade materials themselves, through the sale of an affordable system. An alternative approach of passing the cost of materials characterisation to individual power stations for the materials used in the construction of individual turbines would also effectively price a system out of the market. It is likely therefore that this problem will only be overcome by the targeting of the required materials characterisation at those materials used only in the most popular gas turbine designs. This would result in a system, which although not universally applicable to all turbine designs, would have a potential market of sufficient size to allow an effective pricing level.

The second limitation to producing a gas turbine system is the effective measurement of temperatures at key points of interest. The majority of gas turbines have very few (if any) temperature sensors in the higher temperature regions in which the critical blading is located. It is probable that this problem will be addressed through the use of thermal dynamic modelling aimed at predicting the temperatures in the regions of interest on the basis of inlet and exhaust gas temperatures. Although the cost of such modelling will no doubt be high it is almost certainly a more cost effective (and more easily maintained) approach than the installation of sensors in the high temperature zones.

The development of gas turbine on-line systems could be readily expanded beyond the power generation industry and be expanded to turbines used in the aviation industry, both civil and military. The number of gas turbines currently in-service in the aviation industry is evidently far larger than those used in power production. Furthermore, there are relatively few turbine designs and materials in use, this effectively minimises the range of designs to be thermally modelled and materials to be characterised. These limits on the range of designs and materials to be modelled would allow such a system to be offered at sufficiently low cost (potentially) to ensure wide acceptance. In terms of market need, considering the civil aviation industry, the potential cost savings arising from extending inspection, overhaul and replacement intervals are obvious. In addition, it may be that the comparison of flight profiles (particularly during taking-off and landing) may show significant life benefits can be attained from minor changes in operating practice.

Concluding Remarks

On-line predictive systems capable of monitoring the life usage of critical boiler components offer significant benefits to plant operators. It is evident that such systems will become increasingly common in the Power Generation Industry, in response to the economic pressures resulting from privatisation and changes in operating practice from base load to cyclic operation. Furthermore, it is probable that these systems will increase in scope being able to address not only conventional steam plant but potentially also to gas turbines, as the benefits of these systems are transferred to all types of power generation plant.

Acknowledgements

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Reference

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A Solution for Maintenance-Related Problems in the Power Generating Industry

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Abstract

Important political, social and economic changes in the Europe of the end of the century have had important repercussions in the field of energy generation. A general trend to an opened energy market was encountered not only in the East European (former communist) countries, but also in other West European and overseas countries.

Since the continuous aging equipment is far away to be renewed (mainly because of financial reasons), people charged with maintenance responsibilities in power plants are facing with increasing problems. A solution to these problems was developed in the last years within the framework of a cooperation project between ISIM (Institute of Welding and Material Testing) of Timisoara, Romania and GKM (Mannheim Central Power Plant), Germany, represented by Prof. Dr.-Ing. habil. H.R. Kautz.
A project was developed to support the O&M activities in the field of energy generation. The idea, the way of development and implementation, and estimated results will be presented in this paper.

1 Background

Important political, social and economic changes in the Europe of the end of the century have had important repercussions in the field of energy generation. A general trend to an opened energy market was encountered not only in the East European (former communist) countries, but also in other West European and overseas countries. As a result of this situation the best solution to be selected by energy producers is to reduce the energy costs in order to become competitive. There are many alternatives to reduce this price, but the best results were obtained by reducing O&M (operation and maintenance) costs. This alternative does not require significant investments, as the alternative to increase the plant efficiency.

A solution to these problems was developed in the last years within the framework of a cooperation project between ISIM (Institute of Welding and Material Testing) of Timisoara, Romania and GKM (Mannheim Central Power Plant), Germany, represented by Prof. Dr.-Ing. habil. H.R. Kautz. The structure of this project will be further detailed.

This project was aimed to solve some stringent power plant maintenance problems. A "Manual for maintenance and retrofit of conventional power plants" [1] was developed to fit with common types of equipment in Europe and not only. The next step was to create an informational support for this Manual, namely a knowledge-based system (a set of databases and calculation modules). The third step is to implement these final products within the power industry by means of an interactive computerized network. The last step that shall ensure a technical and scientific support for the proper utilization of this network is a training program that shall be performed for all end-users of the network and of the Manual.

2 Manual for Maintenance and Retrofit of Conventional Power Plants

This manual was initially thought to fit the Romanian energy industry requirements. As the work evolved, a more general orientation was given to this manual in order to fit general requirements and to reach a wider applicability. The final version of this manual has the following structure:

a) **Inspection recommendations for power plant components** - in this section some recommendations regarding the inspection procedure of four classes of power plant components are presented. These classes are:
   - i) Boiler tubes
   - ii) pipe lines
   - iii) large boiler components (headers and drums)
   - iv) turbines

   The inspection procedure includes three levels of approach depending on the component condition, method initially developed in EPRI and applied in U.S.A. The application of the latest methods of examination is considered in order to reduce the overall costs, to increase the confidence level and to decrease the time of inspection.

b) **Maintenance recommendations classified by failure mechanisms** - this section introduces into the maintenance activity of power plant components the decision-making principle based on the expertise obtained in this field up to date, or, in other words, the knowledge-based system concept. Within this section about 24 failure mechanisms identified in boiler tubes are presented and classified in six classes:

i) Stress rupture failures
ii) Inner tube surface corrosion
iii) Outer tube surface corrosion
iv) Erosion
v) Fatigue
vi) Other failure mechanisms

For each failure mechanism the following information is listed:

i) Typical location
ii) Probable root causes
iii) Determination of root causes
iv) Typical appearance
v) Non-destructive examination methods
vi) Corrective actions
vii) Preventive actions
viii) Control actions

c) **Recommendations for welding repair of power plant equipment** - the maintenance of power plant equipment includes as one alternative the repair in order to extend its life. The current section offers some technical solutions of welding repair of power plant components operating at high pressures and elevated temperatures. Bellow, some welding techniques recommended within this section are presented:

i) Weld metal overlay
ii) Metal spraying
iii) Cold-welding, etc.

d) **Condition Assessment Methods of Creep- and Fatigue-Exposed Materials of Pipes and Boiler Components** - this section includes some practical as well as theoretical methods of power plant equipment life assessment. They will support the strategic task of the maintenance activity, namely the one to increase the confidence level of the inspection procedure. Some of the proposed methods are:

i) Creep-fatigue cumulative damage assessment based on different mathematical relations;
ii) Replica method as an alternative to creep destructive tests;
iii) Component remaining life assessment based on the level of material microstructure degradation, etc.

e) **Off-line operating temperature estimation of power plant components** - a high by accurate estimation of the operating temperature of a component is a critical prerequisite in establishing an approach for identifying a specific failure cause. Some off-line temperature estimation methods are offered as an alternative to establish this data if monitoring systems are not available or were installed only later.

Notes:

1. The references used within this Manual are only European or international standards such as ISO or EN. No references are made to specific standards or regulations with a narrow area of application.
2. The structure of the Manual allows further updates to be made without major changes of the contents. Thus, future sections or guidelines can be easily added.
3. It was developed in an electronic format for an easy future update and an easy way of transfer.
4. The electronic format (HTML files) provides an easy to use multilevel structure with a simple browsing system.
5. The knowledge base includes the latest state of the art in the field of maintenance available in Germany and the U.S.A. at the moment when the Manual was published.
6. Knowledge transfer is based on agreements with each institution, project manager, or organization where from particular knowledge was obtained.
7. Cross-references will be developed with respect to other tables from supporting databases (e.g. tables of case studies, material characteristics, standards, etc.), see Heading 3 of this paper.
8. Computation modules based on mathematical relations recommended within the Manual were developed and shall be connected to it in order to make them easy to apply when necessary, see Heading 3of this paper.
9. The Manual represents a tool in supporting the decision-making process related to maintenance matters of power plant equipment (i.e. leave as it is, repair, replace).

3 An intelligent system in supporting the Manual's utilization

An intelligent system was developed in order to ensure a proper Manual's utilization. This system includes databases, computational modules and an intelligent browsing system. Database system includes information related to materials for power plant components, case studies, standards, laws and regulations with respect to the environment protection and preservation in power industry, etc.

Case studies are classified according to the following criteria: Component type, operating conditions, location inside the power plant, materials issues, damage mechanisms, etc. Choosing some branches in a classification tree, the end-user of the system will receive a list of case studies referring to circumstances that match the given criteria. For instance: for a pipe line specific component all related cases included into the database shall be listed, the information provided being oriented on the following topics: failure circumstances, investigations performed, conclusions, arguments, recommendations for avoiding further similar failures, eventually design- or material-related recommenadtions. For a refined search, a further in-depth browsing may be done by continuing the selection of different more specific characteristics of the case studied by the end-user (e.g. material type, operating conditions, etc.).

Efforts have been made to gather as much as possible information on materials for Eastern and Western Europe, as well as for the United States into a unique database. Within this project, as information becomes available, it will be further included into the database. End-users shall provide a feedback to project staff by disposing lists with materials currently used in their plants, so that the database shall fit their needs.

Again, the user will have the possibility to obtain material-specific characteristics as they are described in materials standards. Such a database shall be useful in cases when damage mechanisms are studied — on exposed components, when replacements are considered, etc. This information is also interesting during the design phase, when the best material must be selected, from a technical and economic point of view, in order to fit with the designer requirements. Also, in cases when retrofit of old equipment is considered, and new materials must be selected for specific operation circumstances, such a database is highly useful and recommended to be used, if available.

The section of the database related to standards will contain a collection of references to standards and regulations that must be available when the Manual is used (references within the Manual). Such standards and regulations are for instance non-destructive examination and material testing standards, environment protection and preservation regulations, etc.

4 A computerized connection in the field of power generating industry

A very modern way was chosen for the intelligent system implementation in the power generating industry: A computerized network between companies with interests in this field. A short description of this idea, of the potential customers, market, and potential benefits will be briefly described in this section.

The most of today's valuable product is the information or, more exactly, the adequate information at the right moment. There are a lot of money and energy involved in specialized services that provide information in different fields of activity. Also many profitable businesses are developing around this activity.

This project being developed in the framework of a private company intends to offer information service to power plants. Main topics of interest covered by this information service will be the power plant maintenance and retrofit activities. The most attractive ideas of this project are:

- State of the art information on topics related to the energy-generating field shall be offered by this system.
- Information will be continuously updated from sources of high scientific and technical level, and worldwide suitable information will be included only.
- A mechanism of distributing this information to many users with low costs is involved (distribution over the Internet), which will make the price of information quite accessible for everyone.
- By gathering various information about different case studies occurred in power plant operation, *expertise* will be offered through this information service.
- By making the information available in electronic format and by organizing it into a structure that particularly fits the given field of interest (a dedicated structure), topics of interest can be found faster and easier.
- Additional supporting tools (computational modules) will be included, so that the users should be able to immediately apply information gained from the system on their particular data. By creating these tools also adapted to the particular field of interest, the value of the system is further increased (by making it more comprehensible to specialists).

The idea is to build up and sell a complex information structure, which will contain two main components: a database component and a computational component as they were described earlier in this paper. In the future, an expert system (knowledge-based system) will be developed which will provide more detailed and specific information — i.e., it will minimize the end-user's effort to search for and exploit the information.

4.1 Operational structure of the network

Since the service/product to be offered will be quite valuable, it cannot be offered for free. Another reason for this is that each component of the information model needs upgrade and maintenance, and those operations will be cost-intensive, if the result is to be of a high quality. This is why all customers that intend to use these services/products will have to pay a specific fee. On the other hand, if each power plant would develop and maintain such a system by itself, the costs would be prohibitive.

These fees can be lowered if another source of money can be found. This alternative source, in the project staff conception, consists of two sources for additional income. They are described below, in the order of importance. First, advertising facilities will be provided for all parties interested in presenting targeted-advertising spots to the group of customers that we will address (mainly to power plants). Such parties might be in the first line providers of services, power plant component manufacturers, assurance companies, etc.

A second source of income will be data warehousing. By statistically examining the activity of the web site that shall be build, it will be possible to provide the above-mentioned companies and any other institution that has something to offer to power plants with valuable data about the regional profile of their customers. Such data is very important for marketing reasons.

These auxiliary sources of income, together with the large audience expected, will make it possible to offer services/products at a very low price, worldwide accessible. This will lead to a general improvement of the activity of the power plants that will make use of these services, with quite affordable costs. Therefore, this activity shall become in a short time also a profitable business.

Essentially, this project will lead to the implementation of an affordable source of information for any party involved with power plants. The only product/service to which it can be compared is counseling services in this field. But, while a specialized counselor is a quite expensive person to employ, this offer will have a much lower price, with no reduction of quality. Also, a counselor does not contribute to the increase of knowledge of the personnel of a power plant, while the information system to be built up does. This will lead to a safer, more cost-effective activity in thermal power plants that will use the informational system. Of course, on the other hand, a counselor can take decisions and give advice on-site. This system, being accessed through a laptop can provide also an on-site information practically anywhere on the world.

4.2 Customers

This product shall be offered to all people charged with power plant maintenance activities in order to support their decisions on matters related to this topic. Other potential customers of this product shall be companies developing activities connected to the energy generating field, such as: Power plant component producers, power plant design institutes, services providers, research institutes in the field, universities, etc.

Once the system will develop, the customer type and number shall increase. It is planned to extend the Manual's orientation on additional fields such as nuclear power generation, chemical and petrochemical industry, etc. Basically, in a couple of years all users of pressure vessels operating at elevated temperatures shall be included on the list of potential customers. Simultaneously, the number of sponsoring companies shall increase including companies with interests in the additional fields.

4.3 Market

Market will be for all three products: information system, advertising and data warehousing the same: the energy field.

As the project will develop, the market will increase. In order to fit the market requirements, software as well as the information from the database will be translated to different other languages, based on cooperation agreements with specialized partners that may perform such a work (e.g. universities, profile institutes, etc.). It is planned that after the first 12 months of operation the Manual, the software and the information contained in the database will be made available in three languages (English, German and Romanian).

For the beginning, the East European countries are considered as the first targeted customers of this project. Among the countries of interest are ***Romania*** as the first customer country, ***Bosnia Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Poland, Russia, Slovakia, Slovenia, Ukraine, other former SU countries,*** etc.

Simultaneously, the development of this project will be focus also on the direction of the West European countries, such as ***Belgium, Finland, French, Germany, Italy, Norway, Portugal, Spain, Sweden, UK,*** etc., including whatever company regardless its geographic or political situation.

There will be considered also overseas countries such as ***Canada, China, Japan, South Africa, U.S.A., South American countries,*** etc.

Additional languages will be considered during the following stages of project development: Russian, French, Spanish, Portugal, etc., the decisive criteria being the extension of the network on different countries or energy markets and the spoken languages of customers.

The market extension shall consider not only the language diversification, but also the direction mentioned above. Other customers and consequently a growing market mean a diversification of the sponsor profile and number and, therefore, an increase of income sources.

5 Training courses of the end-users

The last stage of development of this project (so far is currently considered) includes yearly training courses to be hold by the project leader and his collaborators for each project end-user (power plant). Thus, training courses shall be organize for representatives of all power plants (people charged with decision making tasks and maintenance responsibilities in power plants) in order to:

- update the latest information that was made available through this system,
- explain the utilization of the new software modules developed in the time between two recurrent training courses,
- make these people aware about the latest developments in the field of power plant components and services,
- make them aware about the environmental protection and preservation policy at the global level.

Training courses shall encourage young people to become involved in this project, will bring valuable information and highly interested issues in the attention of power plant managers, will bring solutions for technical problems, etc. The main advantage to be gained through these training courses shall be the development and improvement of the feedback procedure from end-users to the project staff. Thus, the further development of the software shall take into account the requirements and necessities of the customers of this product. It shall be ensured in this way a suitable development of the products, as the customers require it.

6 Conclusion

This project intends to bring a modern way of thinking in the field of power generating industry regarding maintenance as well as environmental issues. The energy generation is currently becoming a business (that should be profitable as any other business) all over the world. The reduction of O&M costs should be therefore one of the main issues of interest of the people charged with decision making responsibilities in this field. Also, the environmental problems should not be neglected. It is foreseen that in the near future this issue will be a governing issue in all sectors of human activity (power generation not making an exception). Knowledge-based systems, accessible through a computerized network, virtually all over the world and all around the clock will bring many advantages to end users (power plants).

In the second line, all energy buyers will take advantages of it by means of long-term repercussions of the utilization of this system by the energy producers on the energy price.

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Integrated Vibration-Based Maintenance: An Approach for Continuous Reduction in LCC, A Case Study

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Abstract

The biggest thread in achieving and maintaining high equipment effectiveness can be stated as: whether the improved manufacturing processes capable of producing quality products at a competitive cost. The effect of a new vibration-based maintenance concept, called Total Quality Maintenance (TQMain), is introduced. It aims to make intensive use of the real-time data acquisition and analysis to detect causes behind product quality deviation and failures in machinery, and following defect development at an early stage to increase machine mean effective life and improve company's economics. The effect of TQMain on LCC of machinery and company's economics is discussed. A case study to reveal savings in maintenance cost when a vibration-based policy involved, is presented. Using TQMain, company's economics can be improved effectively through continuous improvement of the technical and economic effectiveness of production processes.
Keywords: Failure causes, Condition control, Integration of vibration-based maintenance with IT-System, Life Cycle Cost, Cost effectiveness.

1 Introduction

In Sweden, the cost of maintenance and operational safety was about US\$ $23x10^9$ during 1991, in most cases the total losses which arise because of maintenance omission or ineffectiveness exceeds the purchase price of the equipment, see Ahlmann (1994). In Blanchard (1994), from 15 to 40% (with an average of 28%) of the total cost of finished goods can be attributed to maintenance activities in factory. Preventive maintenance, i.e. statistically-based policies, aim to reduce the number of failures, failure cost and the cost of associated repair. The use of vibration-based (VB) maintenance policy provides possibilities for acquiring early indications of changes of machinery state, see Al-Najjar (1996). These indications could be of great importance also in detecting deviations in the product quality early and before they show on quality control charts. Cost-effectiveness is one of the criteria which should be used to select a suitable maintenance policy. Condition-based maintenance (CBM) lets the machine run until just before failure, and it may be defined by two defence lines which are proactive maintenance, i.e. the activities and efforts of detecting and correcting failure causes, and predictive maintenance, i.e. monitoring symptomatic conditions. Condition monitoring (CM) programs, especially VB programs, became popular in many industries, e.g. paper mills, refineries, power stations and recently in manufacturing industry. In application, these programs are, in general, not integrated with programs for production/operation, quality control, environmental condition or cost accountancy. The information in the databases of CM programs is limited. A database for a wider range of information is required for effective diagnosis and prognosis of machinery condition. The aim of this paper is to discuss the effect of TQMain on LCC of machinery and company's economics.

2 Integrated Vibration-based maintenance

Operating and environmental conditions such as machine speed and load, operator, maintenance staff, production plan, etc., often influence the time to failure of a machine. Therefore, the assessment of the machine condition and improvements in maintenance effectiveness and accuracy would be achieved effectively if the information from the surroundings is considered. Improvements, in machine productivity and performance efficiency, product quality, etc. may, in many cases, be performed effectively when considering the maintenance policy involved. For example, high vibration levels in the press and drying cylinders of a paper machine can reduce the quality of the paper surface which is very important.

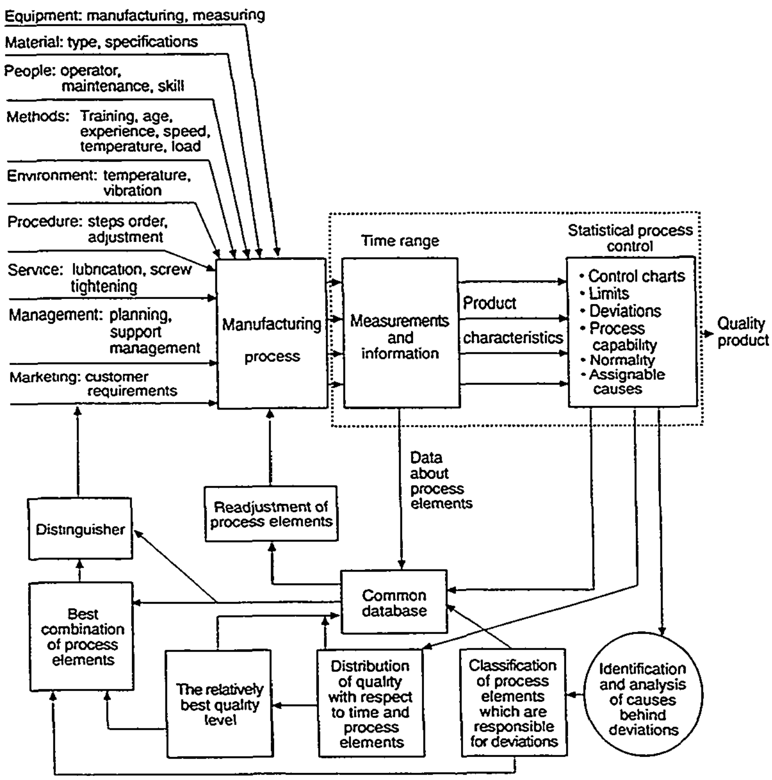

Fig. 1. The concept of Total Quality maintenance, (TQMain).

In many cases, it is impossible for the operator to run a machine at its maximum speed because of high vibration level due to resonance. Overestimation and underestimation of the defect development rate and severity cause the user to lose some of the machine life or some extra production, due to bad quality products, and sometimes to production stopping at an inconvenient time, respectively.

The basic elements constituting a manufacturing process may be summarised as: Manufacturing machines and equipment, monitoring and maintenance policy, environmental condition, operating and maintenance staff, manufacturing methods and procedures, quality control methods and procedures, materials, managerial functions such as spare parts stores, purchasing and marketing, services such as lubrication and screw tightening, etc., see Fig. 1. TQMain is to sustain not only machinery but the essential elements constituting a manufacturing process, such as production/operation, environmental condition, quality control, personnel, methods and material. It is based on making intensive use of the real-time data acquisition and analysis to detect causes behind product quality deviation and failures in machinery, and following defect development at an early stage to increase the machine mean effective life. TQMain is developed to overcome some of the limitations of TPM and RCM, see Al-Najjar (1996), and is based upon the Deming managerial feedback cycle [Plan-Do-Check-Act], see Fig. 1. It is a methodology which enables the user to maintain and improve continuously the technical and economic effectiveness of process elements.

The state of manufacturing process is considered to be assessed by monitoring both the process elements and product characteristics. TQMain`s role is defined as: A means for monitoring and controlling deviations in a process condition and product quality, and for detecting failure causes and potential failures in order to interfere when it is possible to arrest or reduce machine deterioration rate before the product characteristics are intolerably affected and to perform the required action to restore the considered part of a machine to good as new. All these should be performed at a continuously reducing cost per unit of good quality product.

2.1 Common Database and Integration of Plant Activities

A common database is one of the essential features of integrating plant operations for maximum economy because it will ease the identification and elimination of both quality deviations and failure causes at an early stage. The required data will be gathered into the common database without the duplication that usually occurs when each department collects its own data. The analysis and assessment of, e.g. the machine condition or product quality will be performed much easier if the required information is easily accessible. We believe, but without a very long experiment cannot demonstrate, that besides the obvious advantages, a common database, together with an integrated company-wide IT-system would probably be cheaper in the long-term than keeping maintenance data separately, and controlling the maintenance function without co-optimising with other activities. The integration of the plant activities may be achieved in different ways based on which activity is considered to be the backbone of this integration. The backbone activity is defined as the activity which plays the central role in improving the whole process. In Al-Najjar (1996), the integration is proposed to be performed by locating the VB maintenance at the core between the integrated activities, i.e. being the backbone activity, see Fig. 2. This is because the companies using this policy, in general, establish one of the best data acquisition and analysis systems which is a prerequisite to build a common database. Also, vibration spectral analysis provides a reliable basis for identification of failure causes and defect development mechanisms in rotating and reciprocating machines, see Collacott (1979), and Bloch and Geitner (1994). Further, detecting the relevant vibration frequencies early would lead to keeping the quality within its specified limits for longer, and in more time to plan the eventual repairs. But, TQMain is not limited to the activities mentioned in Fig. 2. The decision to expand the integration to include new activities is a function of many factors such as the business strategy,

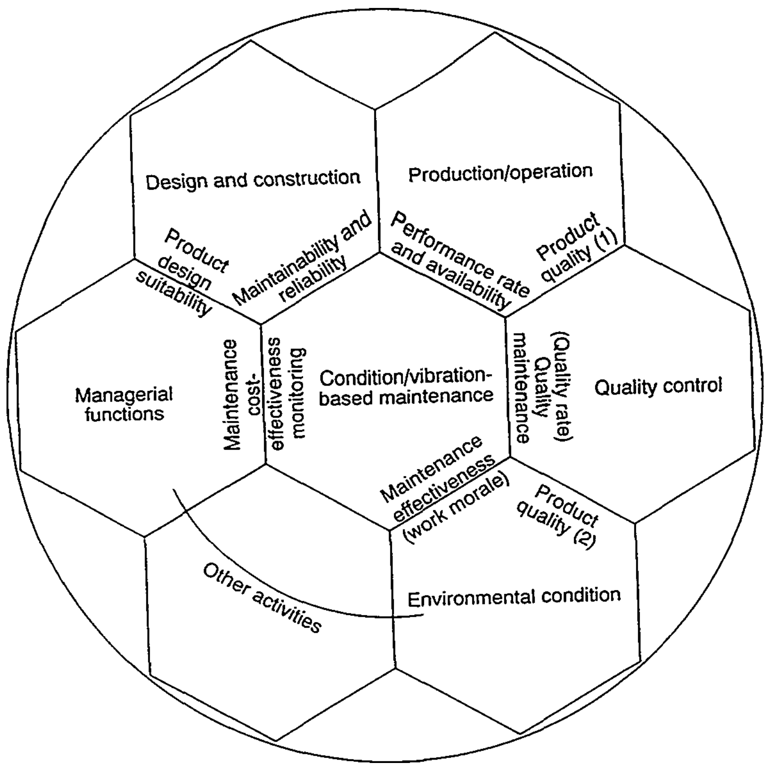

Fig. 2. Integrated activities from the view point of condition-based maintenance.

manager or maintenance engineer request. In VB maintenance, operating and environmental conditions such as loading, temperature, lubricant, production plan, machine speeds, etc., often influence vibration signature. The technical and statistical analysis should be considered an effective tool to identify failure causes and their vibration frequencies and criticality. These vibration frequencies can be utilised to monitor the machine condition and product quality, and consequently which element in the process these causes are related to. The best product quality may also be distinguished through selecting the suitable combination of the process elements, see Fig. 1. For example, the common database can be utilised to distinguish the actual reasons behind defect initiation and development whether the usual operation, repair/replacement quality, operator's misuse, faulty design in the machine, harsh operating or environment conditions or the replaced component quality. Systematic and continuous identification of these reasons would result in improvements to avoid their recurrence. Technically, the integration of the databases of, e.g. VB monitoring program, operation and quality control, to build the common database can be achieved using the techniques and experience known within information technology, e.g. Heterogeneous database management system, (DBMS), see Thomas et al (1990) and Litwin et al (1990). The features which characterise TQMain and distinguish it from RCM and TPM are: (1) It advocates the use of a common database, which would be updated by real-time measurements of the essential parameters, for real-time monitoring and assessment of the machine condition and manufacturing process technical and economic effectiveness. (2) It is based on making intensive use of the real-time data acquisition and analysis to detect causes behind quality deviation and machinery failure, and following defect development at an early stage to increase the component mean effective life and to improve company's economic. (3) Using VB monitoring system, it is possible to improve the VB maintenance policy after each renewal through confronting database history, including vibration measurements, with the replaced component.

The extensive use of data feedback is considered essential to accomplish continuous improvements, to assure high quality products and to enable the user, on demand and at all levels to get reliable information on: (1) Detection of deviations in the state of a machine at an early stage in order to control its condition, when possible by arresting or reducing the speed of damage development. (2) The most cost-effective vibration level at which to replace components suffering deterioration. (3) The acceptable deterioration rate to 'guarantee' no sudden failure during the lead time, (time between detecting a defect and action to repair it). (4) Detection of defects and prediction of remaining useful working life. (5) Condition-dependent failure rate of the component during the lead time. (6) Identification of failure mechanisms, failure causes and failure modes and increasing diagnosis and prognosis precision by relating past readings to damage subsequently found and safe lead time achieved.

3 Life Cycle Cost, LCC

Life cycle cost is defined in BS 3811:1993 as the total cost of ownership of an item taking into account all the costs of acquisition, personnel training, operation, maintenance, modification and disposal. The analysis of LCC of a machine can be used for different goals. In this paper, we focus more on identifying the cost factors constitute LCC and on describing their behaviour during equipment life, so that it will be possible to localise the causes behind changes in LCC. This will enable the user as well as manufacturer to improve machine construction and operation, environmental conditions and maintenance in order to reduce increasing cost factors and treating problem areas effectively. The goal of using

LCC, in general, decides the level to which the total cost should be broken down.

To evaluate the economic importance of a particular investment in production or maintenance, it is always required to assess Life Cycle Income, (LCI). In many cases, this assessment seems to be very difficult to achieve. For example, it is often easier to assess the savings achieved by reducing failures and downtime, through using more accurate maintenance policy, than to assess LCI of this investment because there exist many cost factors which can not be assessed accurately such as better sales and income which may happen due external factors as well. LCC can be divided into the following major parts:

1. Life acquisition cost, LAC; the capital invested in the machine, support equipment, installation, systems, building, training, etc.
2. Life operative cost, LOC; the cost incurred by the operation of a machine including operator, fuel and power, insurance and taxes, etc.
3. Life support cost, LSC; the maintenance cost such as maintenance staff, spare parts, storage expenses, measuring instrument, etc.
4. Life unavailability cost, LUC; the cost of down time, (the time which should be utilised for production).
5. Life indirect losses, LIL; the losses arise due to bad quality products and/or lower equipment efficiency due to, e.g. lower production speed, caused by an ineffective maintenance policy.
6. Life modification cost, LMC; the cost incurred in modifying the machine or equipment during its operating life.
7. Life termination cost, LTC; the cost paid to scrape the equipment or that gained by selling it. Thus, LCC may be expressed as

$$LCC = LAC + LOC + LSC + LUC + LIL + LMC \pm LTC \qquad (1)$$

see Dhillon (1989), Fabrycky and Blanchard (1990) and Ahlmann (1994). If we consider a machine, LAC can be assumed unvarying when the investments in machine modifications, i.e. LMC, is treated separately. LOC may be considered increasing during machine operating life due to machine ageing and deterioration which may cause, among other, e.g. more fuel consumption. LCS is usually considered reducing at the wear in phase, constant during the normal operating phase and increasing at the wear out phase, see Ahlmann (1994). In Sweden, the mean value of the proportion of the maintenance direct cost to the added values in the product is about 8%, (varies from 5 to 18%). But, in the case when the total maintenance costs are considered, this mean value increases to 15%, (varies from 11 to 30%), the same reference. These figures reveal the economic importance of any reduction in maintenance total cost. The quality index increases by 23% and scraped items reduced by about 18% when the number of stoppages reduced to the half. These figures display the relation between the failures and losses due to bad quality arise because of machine degradation which can be expressed as a polynomial of the second degree, the same reference.

3.1 The Effect of the Common Database on LCC

Using a common database makes it possible to access the required information easily especially when evaluating the condition of a machine or component. Improvement in the knowledge and experience of how to use VB monitoring system would consequently be achieved. This means that the failure causes which make a bearing deteriorate faster than the usual and result into an unplanned-but-before replacement, (UPBFR), can be avoided in the future. UPBFRs are performed at unplanned but before failure stoppages to prevent the occurrence of failures. Note that this situation arises because of a sudden increment in the measured variable(s), e.g. the vibration level, due to undetected defect causes at an early stage. Better data coverage and quality will give reliable opportunities to distinguish the reasons behind increments in the vibration level(s) such as increment in the operating conditions, operator, repair team, environment.

Table. 1. Qualitative analysis of the effect of the features of a VBM system.

Better feature	**Produ -ction losses**	**Storage value**	**Mainte-nance staff**	**Prod -uct quality**	**Acci-dents**	**Instru-ments**	**Repa -ir**	**Trai ning**	**Consu l-tancy**
Alarm level	-	-	-	+	-	0	-	0	0
Analysis band	-	-	-	+	-	-	-	+	-
Resolution	-	-	-	+	-	-	-	+	-
Multi-check	-	-	- or +	+	-	- or +	-	+	-
Speed of the VBM program	0	0	-	0	0	0	0	0	0
Estimation of time to action	-	-	-	+	-	-	-	0 or +	-
Continuous Monitoring	-	-	-	+	-	+	-	+	-

Identification of the basic reasons behind damage in a bearing helps maintenance engineer to monitor deterioration development and control the condition of the bearing. Also, contrasting the damage in the bearing replaced with its vibration history improves the user's experience in identifying the relevant frequencies which should be monitored and their significant amplitudes. Improvement of the features of a VB monitoring system to achieve the above mentioned requirements has its impact on several activities such as production, quality, maintenance and storing. In Table 1, a qualitative analysis demonstrates the effect of these features when they are improved, where -, + and 0 mean reducing, increasing and no effect, respectively. For example, a Multi-check feature may be achieved through using Shock Pulse Measurement (SPM) technique in addition to VB monitoring program, i.e. +, or through another processing technique of the vibration signal such as Enveloping technique to be used together with overall RMS vibration level. Thus, monitoring two parameters such as SPM and vibration usually increases the maintenance staff and cost. Prolonging the mean effective life length of bearings means a direct reduction in the number of condition-based replacement, (CBR), and failures. The machine availability will increase and the production losses will decrease. Less CBR and failures reduces the number of spare parts consumed which leads to smaller storage and less storing cost. Less failures leads to increase the faith in the CM system and maintenance policy. This would result in reduction in the redundancies in spare parts, equipment and personnel, i.e. less capital tied up.

When establishing a common database, it would be easy to prepare documents convincing the manufacturer to perform the required modifications in the next generation of the machine. Better diagnosis and prognosis is possible to be achieved when a cyclic improvement for the maintenance policy is established. This results into less time for repair, adjustment and service. For example detecting high operating or environmental temperature which reduces lubricant viscosity and results in rapid wear helps to avoid damage initiation and reduces maintenance costs. In order to consider maintenance as a profit centre we should identify the effect of the improvements in the maintenance policy on the plant's activities.

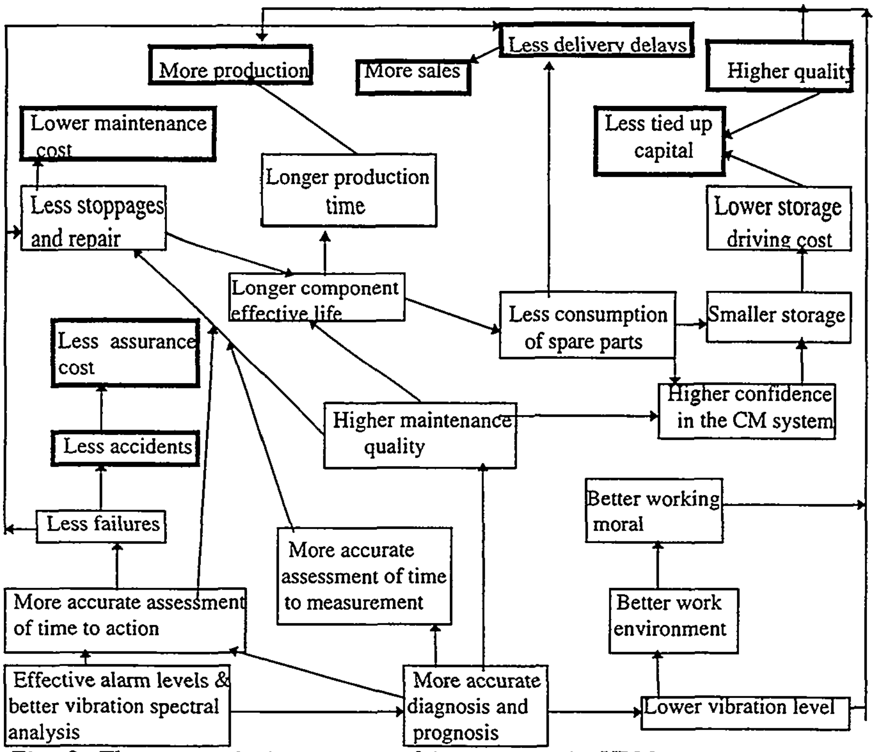

Fig. 3. The economic importance of investments in VBM systems to improve vibration spectral analysis.

More accurate diagnosis and prognosis, and lower vibration level are the direct results of better vibration spectral analysis which should be improved continuously, see Al-Najjar (1998). Using an effective VB monitoring system it is possible to control the condition of an equipment and to reduce the vibration level. Better working environment can be achieved which in its turn gives more production and better quality. Finally, the analysis shown in Fig. 3 reveals how better diagnosis and prognosis, when using VB monitoring system, may influence the costs incurred by production, maintenance, quality, capital tied up and other expenses such as insurance and compensations for accidents.

Keeping the machine operating at specified conditions will reduce operation costs, for example solving the problem of high vibration level due to resonance will enable the operator to increase machine speed to its maximum capacity. Low vibration level results into better quality. Better and reliable service concerning lubricant, grease, tightening lose screws, cleaning, etc. reduce the probability of damage in the machine and bearings. Lower vibration level results into lower energy losses and less operation cost. When operation costs and scraped product are reduced the capital tied up for operation is consequently reduced, see Fig. 3. The effect of using VB maintenance integrated in a common database are:

1. Total capital invested to modify a production line decreases in time.
2. Operation cost required to keep the machine running according to the specified operating conditions will not be increasing when a cost-effective VB policy is used and improved continuously.
3. Maintenance cost reduces in time and better data coverage and quality.
4. Keeping the condition of an equipment well during its effective operating life, enables the company to sell it instead of paying LTC.
5. The cost of down time, i.e. Life unavailability cost, can be reduced based on the reduction in the failures and total number of stoppages.
6. The cost incurred by manufacturing defective items would be reduced in the continuous improvement of VB maintenance policy, see Al-Najjar (1996), (1997) and (1998) and, Al-Najjar and Kumar (1997).

3.2 A Conceptual LCC Model

LCC of a machine is, in general, reduced by the improvements in the efficiency of the maintenance policy being used. The efficiency of a maintenance policy represents its ability in determining the replacement moment so that as much as possible of the component mean effective life is utilised. Let the terms in (1) be functions of the operating time t. Thus, along the machine life, these functions would vary unlikely with respect to the efficiency of the maintenance policy used. This variation can be measured along the downtime and time used to manufacture defective products. The effectiveness of monitoring and controlling these time losses is related to the maintenance efficiency. The number of CBR and failures, and how long of the components' mean effective life is used until replacement are the most interesting measurements needed for monitoring the efficiency of a maintenance policy. An accurate maintenance policy with high efficiency results in continuous reduction in the replacements and losses in the mean effective life of the replaced components. Denote the function describes the ith cost factor in (1) and variation in the cost factor by $Y_i(t)$ and $G_i(a_\pi)$, respectively, i.e.
i = LAC, LSC, LOC, LUC, LMC or LTC , then (1) can now be written as:

$$LCC = Y_{LAC} + G_{LSC}(a_\pi)*Y_{LSC}(t) + G_{LOC}(a_\pi)*Y_{LOC}(t) + G_{LUC}(a_\pi)*Y_{LUC}(t) + G_{LMC}(a_\pi)*Y_{LMC}(t) \pm G_{LTC}(a_\pi)*Y_{LTC}(t) \qquad (2)$$

The relation between the functions $G_i(a_\pi)$ and $Y_i(t)$ is considered multiplicative to avoid negative values. For easiness, the changes expressed by the function $G_i(a_\pi)$ are all assumed linear in time except those for maintenance and profits which are represented by a polynomial of second degree. Such assumptions need more justification than just convenience. A conceptual model representing the behaviour of cost factors of LCC of a machine can now be constructed, see Fig. 4.

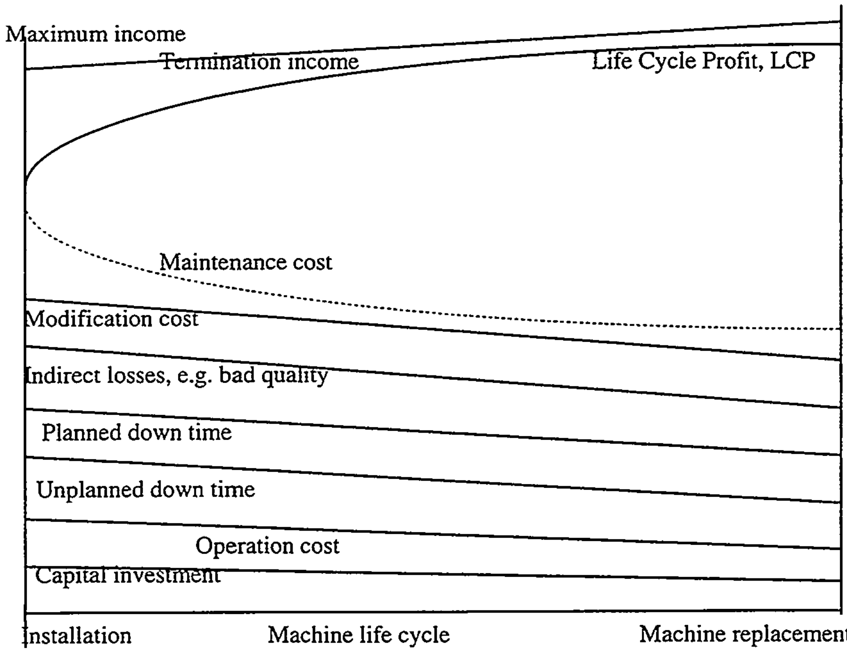

Fig. 4. Conceptual model of LCC when implementing TQMain.

4 A Case Study

The companies with expensive down time such as paper mills are more sensitive to improvements in their maintenance policy. Divsalar and Karlsson (1997) presented in their MSc thesis data which have been collected over one year from a Swedish paper mill company called Stora Hylte AB. The company has a turnover equal to 3,5 billion SEK during 1995. The mean product of the company is pulp and paper for newspaper and about 85% of its product is usually exported. The total number of employee is about 900. The company has 4 paper machines. The study is focused only on one paper machine called PM1. The reason is the database of this machine contains much more data than the other machines. The machine is operating 24 hours daily and it has a production capacity of 500 tons per day. The company plan is to stop the machine 8 hours each other week to perform some actions recommended by the production department. The vibration was the main parameter used for monitoring the machine. The failures in the company are divided into seven categories, see table 2. The losses and savings in Table 2 are calculated on the basis that the company's losses is about 30 000 SEK per hour. It is clear that the savings during only one year and for three major failure categories were about two millions SEK. Almost all failure categories reduced during 1996 except the category called others. The use of VB monitoring system can be improved gradually based on new experience and knowledge, see Al-Najjar (1998). These savings accumulated mostly due the reduction in mechanical failures. Table 2 reveals clearly that an appreciable reduction in the mean time to repair, MTTR is achieved. Better diagnosis of the condition of a machine enables the user to identify failure causes and mechanism and consequently the assets, spare parts and expertise required to perform the action needed. The mean time between failure is increase by about 184,4% during 1996. This is a good evidence of the efficiency of VB maintenance policy being used. The increase in MTBF and reduction in MTTR increases the production time. Less failures results in less product of low quality so that the overall equipment effectiveness, OEE, could be improved clearly during 1996.

Table 2. The economic benefits of using VBM system.

Failure categor	% Failures		MTBF		MTTR		Downtime		Losses		Savings
	1995	1996	1995	1996	1995	1996	1995	1996	1995	1996	
			hour		hour		$x10^4$ SEK		$x10^3$ SEK		
Mechanical	19	8	553	1020	5,3	2,1	74	18	2220	540	1680
Electrica l	15	13	213	155	1,7	0,8	60	30	180	90	90
Hydraulic	5	5	-	-	-	-	-	-	-	-	-
Caleaning	10	8	75	59	0,41	0,3	89	50	267	150	117
Transport	9	6	-	-	-	-	-	-	-	-	-
Covering	23	22	258	230	3,0	1,6	41	41	123	123	0
others.	19	28	-	-	-	-	-	-	-	-	-

Conclusions

Detecting and eliminating common and special causes of problems at an early stage, the quality and reliability of products and processes will be improved. Integrated activities give more effective diagnosis and prognosis which leads to another reduction in the efforts needed to interpret data, and fewer failures means fewer man-hours required to repair. At companies with an established IT system, the cost of integrating additional activities is negligible compared with the cost of the system.

TQMain provides a basis to find true optima or best approximations in more realistic situations for continuous reduction in the cost per unit of product. Improvements in the features of VB monitoring systems result in less failures and CBR, less maintenance cost, more production, higher quality and finally better company's economic. Integrating relevant activities such as VB maintenance, quality, production and accountancy gives unique opportunity to reduce the cost of maintenance, machine modification, unavailability, indirect losses and to keep the machine in a good form, so that its value at the end of its operating life is increased. The profits of investment increases in time and in continuous improvement in the efficiency of VB maintenance policy.

Using an effective VB maintenance policy, reduced the cost incurred by mechanical and electrical failures by about two millions SEK during only one year. Insufficient data made it impossible to demonstrate the changes in all cost factors constituting LCC.

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Performance Measures for World Class Maintenance

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Abstract

A main problem in maintenance in general, and in power plants and related equipment in particular, is the lack of a practical, consistent, and adaptive performance measure that provides a focused feedback and integrates preventive and corrective modes of maintenance. The paper defines concepts of world class and benchmarking. Desirable features in an appropriate performance measure are identified. It then, demonstrates current practices in maintenance and criticises their shortcomings. An alternative model is presented through a case study. The model monitors performance from a general view, and then offers a focused analysis. The main conclusion is that the proposed model offers an adaptive and a dynamic framework, and hence production and maintenance are integrated in a 'real time' environment. The system is also flexible in working with any other criteria whether they are of a quantitative or a qualitative nature.

1 Introduction

The competitiveness of any organisation relies on its performance, which enables it to achieve its objectives through appropriate decision making. Unfortunately, maintenance engineering is still one of the "Cinderellas" of the organisational world, yet it has a crucial role to play in minimising process variability and sustaining process stability - the essential ingredients of product quality. In Computer Integrated Manufacture (CIM) "everything" is integrated except maintenance" (Al-Najjar, 1996).

The aim of this paper's to propose a methodology for integrating corrective and preventive maintenance through a decision analysis process. Figure (1) summarises the concept of the paper where the aim is to establish a link between corrective and preventive maintenance.

The purpose of this paper is to propose a new concept of World Class Maintenance (W.C.Main) that relies on multiple criteria decision analysis. This aim is achieved by presenting a systematic method for implementing a consistent performance system for maintenance.

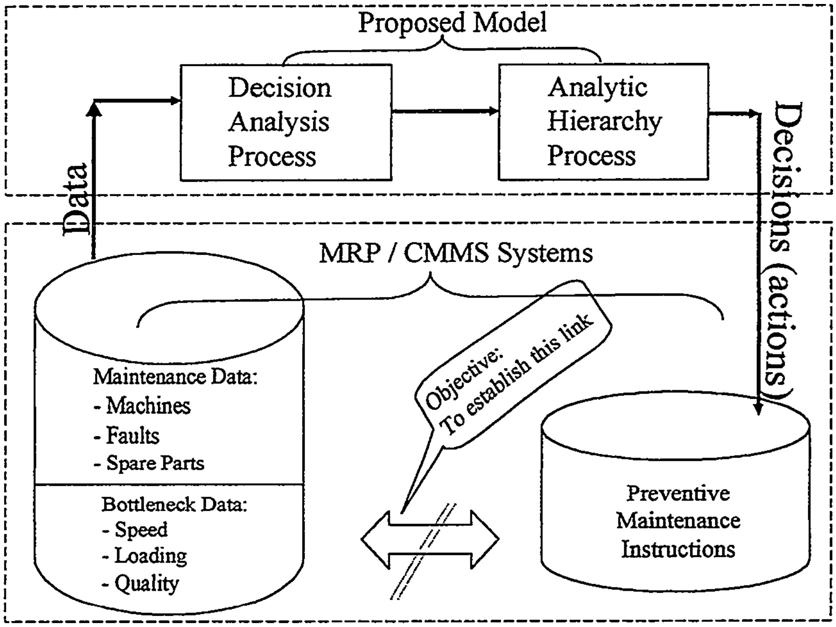

Fig. 1. The proposed model.

2 World Class Maintenance & Performance Measures

It is useful to use the plant as the level of analysis because, although World Class Maintenance (WCMaint) is a strategic approach, many of its measurable improvements initiatives have occurred at the plant level. Strategic considerations and operational decisions are influenced by other corporate functions such as production, finance, quality, and human resources [Labib, et.al, 1996], [Labib, et.al, 1997]. It is true that the information gathered by these systems at the operational level and actions taken are in fact strategic - improved asset availability, productivity, and quality, as well as resource management, inventory control, planning, and so on. It is also true that the adoption of advanced and appropriate practices such as the ones presented in this paper can show remarkable benefits that they too could be regarded as strategic.

Many indices in maintenance have been published over the years by a large number of authors each claiming that his particular index (or set of indices) is a measure of maintenance performance. Most of these indices are of limited value to the decision-maker. They only indicate that some action may be necessary, but seldom, if ever, indicate what this action should be. In addition, the true value of maintenance is given in terms of events that do not occur (like a machine not breaking down), which makes the assessment of the value of these measures a pure speculative task.

This section discusses the limitations of different existing methods of measuring maintenance performance, and attempts to identify the useful applications of measures in the decision analysis process of maintenance strategy formulation and implementation. The purposes of this section are three fold. The first task is to examine some typical measures of maintenance performance and their effect on decision analysis. The second is to identify means of measuring the appropriateness of these indices. The final task is to formulate and to implement maintenance strategy based on performance measures.

There are a number of desirable properties that a measure of performance should possess and these are listed below.
i. The measure should be relatively easy to calculate and use otherwise the cost in time and effort in evaluating the measure of performance may eliminate any potential benefits that the measure may afford. Clearly, if the measure is relatively complex this factor cannot be ignored in assessing the usefulness of the measure.
ii. The measure should accurately reflect management's' subjective notions of what constitutes maintenance performance especially with respect to the organisational objectives as a whole. This requirement ensures that compatibility between the maintenance performance objectives and the organisation's overall objective is observed.
iii. Ideally the measure, in addition to indicating that something has gone wrong, should indicate what remedial action is necessary to correct the error which has been observed. This is, probably, the most important practical function that a measure of performance should perform. If the measure of performance fails to indicate what remedial action is necessary then its value to management is limited to the role of being a consequence variable that, in some way, summarises the effect of past decisions.

Nowadays fully integrated computerised maintenance management systems (CMMSs) provide the on-line ability to track a broad range of indicators, many of them user-definable. The talent is now to equip these systems to monitor performance indicators that most appropriately measure the organisation's effectiveness.

3 Traditional Maintenance Practices

Traditional maintenance practice promotes the application of TPM (Total Productive Maintenance) and its main performance measure that is called the OEE (Overall Equipment Effectiveness). Both TPM in general, and OEE in particular, have shortcomings. The main idea of TPM is to bring maintenance and production together through small groups, to exchange skills, and take specific actions. Blending maintenance and production, is the core philosophy of TPM. There are three main concepts of TPM which have been promoted by Seichii Nakajima [Nakajima, 1988], and the Japan Institute for Plant Maintenance. These concepts are related to improving equipment to its highest performance level (by achieving no losses), maintaining equipment at its highest level (by applying autonomous maintenance), and procuring new equipment with a defined level of high performance and low life-cycle cost (through small groups).

3.1 Shortcomings of TPM

The TPM concept is simple and obvious, but the challenge is to answer important questions, such as: How to implement in a different culture, or environment? Is the methodology generic? These questions will be highlighted and investigated in the paper. Whilst its philosophy is sound, its implementation lacks focus, and systems approach that is compatible with different environments. Hence, an appropriate approach is presented. This approach is aimed at extending TPM rather than contradicting it. The trend in recent maintenance literature seems to emphasise on the cultural difference between the Japanese culture and the Western. It has been pointed out by [Hartmann, 1992] the impact of the cultural differences between the Japanese and the West, stressing the Japanese affinity for small groups and consensus decisions. Also, [Willmott, 1992] confirms this and emphasises that the work ethic is very strong in Japan, coming before self and family. In addition, [Kelly and Harris, 1993] identify uses and limits of TPM, and conclude that TPM succeeds not because of its systems or engineering techniques but because of its attention to the management of human factors. Through personal experience, industrial collaboration, and research, the author has formulated the opinion that whilst TPM is obviously a step in the right direction, it is clear that there is a need for a revised, 'appropriate', approach regarding TPM. This approach should be dynamic, practical, focused, adaptable, and integrated with other functions of the organisation.

3.2 Shortcomings of OEE

The OEE (Overall Equipment Effectiveness) can be summarised as shown in figure (2). Its traditional formula is as follows:

$$OEE = Availability \times Productivity \times Quality \qquad (1)$$

The shortcomings of TPM have subsequently affected its main performance measure that is the OEE. A review of the academic and professional literature has indicated that OEE has problems regarding its ease of use and mathematical formulation. This argument is emphasised with paper titled - *"Use OEE; Don't Let OEE Use You"* by [Murphy, et.al, 1996] as well as the work of [Flapper, et.al, 1996], [Leachman, 1997], and others. The other limitation associated with OEE is that it indicates that something may be wrong. It may even identify where the error lies but it does not, in general, indicate what action is necessary to rectify the observed error. This index may indicate that something has gone wrong if the value of the index decrease from one year to the next. But OEE neither indicates what actions are necessary to rectify the position, nor in which priority.

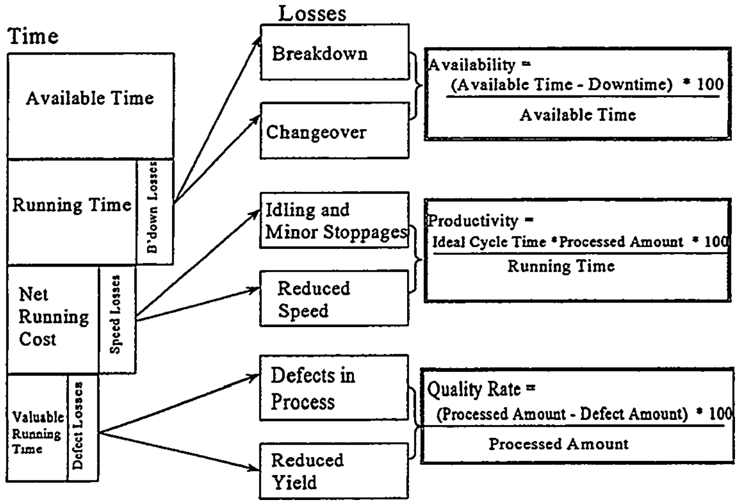

Fig. 2. The OEE model.

3.3 Need for a revised, appropriate, approach

The above literature survey shows that TPM in its pure form is not totally applicable to Western industry. TPM and OEE as well, appear to be in danger of being just an activity-centred management theory rather that a result-driven approach. Therefore, there is a need for a revised approach to TPM, an appropriate one. The revised approach is intended to be keyed to specific results, rather than to too large scale and diffused objectives. An approach that is a management thought process rather than a thing unto itself. It is not intended to contradict TPM philosophy, but to complement it. The proposed approach is a further step that puts a concept into practice. This revised approach is intended to account for differences from the ideal case, which embodies 'best' practices yet which can be 'tailored' to yield an appropriate system.

4 Proposed Model

The proposed model consists of two inter-related models: The first model is a *decision analysis process* that gives a total picture of performance in the form of a grid. This grid acts as a map where the performances of the worst machines are placed based on multiple criteria. The objective is to implement appropriate actions that will lead to the movement of machines towards a favourable position on the map. The second model is an *analytic hierarchy process* where machines chosen from the first model are analysed in the form of prioritising specific focused alternative actions related to the faults.

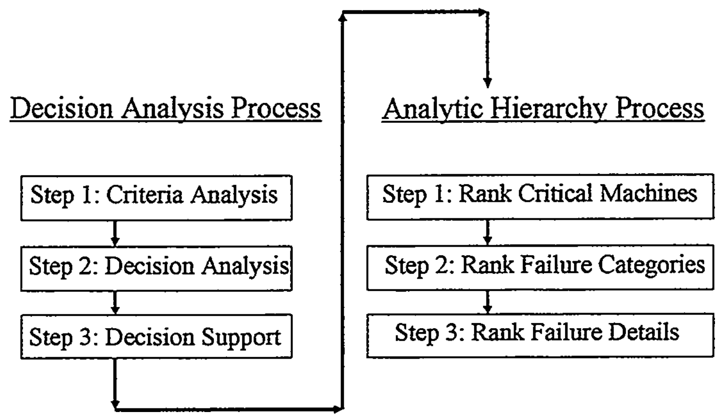

Figure 3. The proposed model.

5 An Industrial Case Study

This case study demonstrates the application of the proposed model and its effect on maintenance performance. The application of the model is shown through the experience of a company seeking to achieve World-Class status in maintenance. The company has implemented the proposed model which has had the effect of reducing total downtime from 800 hours per month to less than 100 hours per month as shown in figure (4).

5.1 Company Background and Methodology

In this particular company there are 130 machines, varying from robots, and machine centres, to manually operated assembly tables. Notice that in this case study, only two criteria are used (frequency, and downtime). However, if more criteria are included such as spare parts cost and scrap rate, the model becomes multi dimensional, with low, medium, and high ranges for each identified criterion. The methodology implemented in this case was to follow three steps. These steps are i. Criteria Analysis, ii. Decision Mapping, and iii. Decision Support.

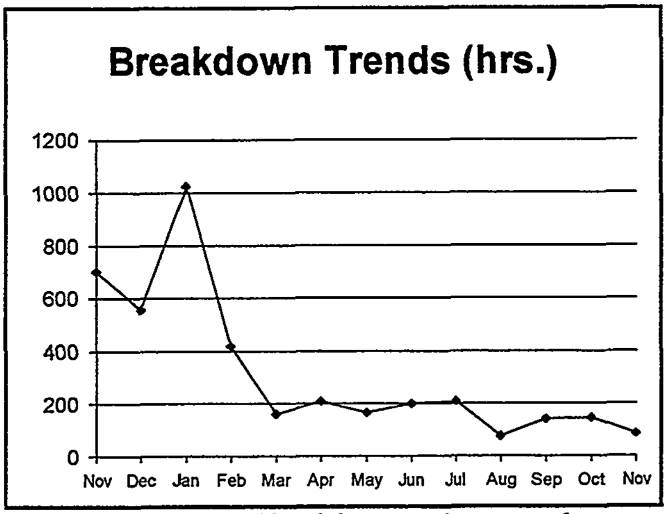

Figure 4. Total breakdown trends per month.

5.1.1 Step 1: Criteria Analysis

As indicated earlier the aim of this phase is to establish a Pareto analysis of two important criteria Downtime; the main concern of production, and Frequency of Calls; the main concern of maintenance. The objective of this phase is to assess how bad are the worst performing machines for a certain period of time, say one month. The worst performers in both criteria are sorted and grouped into High, Medium, and Low sub-groups. This is presented in figure (5).

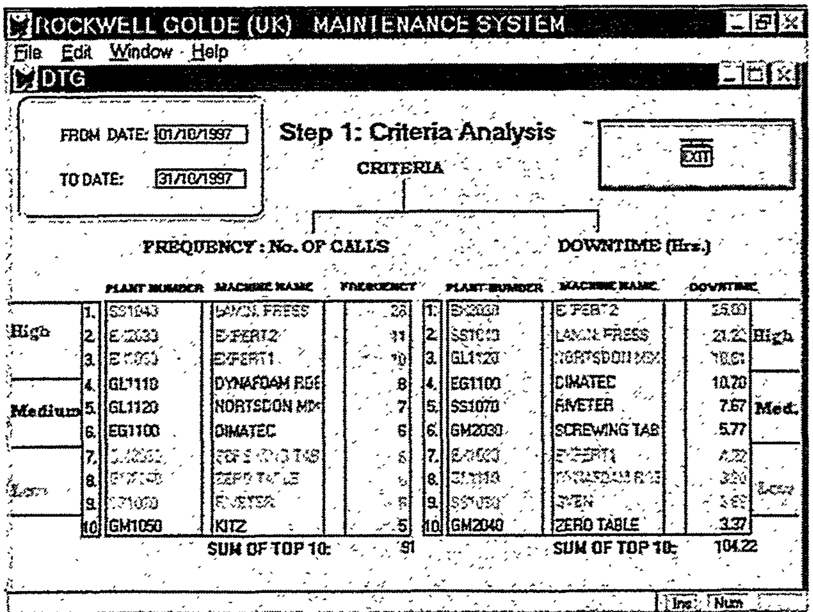

Figure 5. Step1: Criteria Analysis.

5.1.2 Step 2: Decision Mapping

The aim of this step is twofold; it scales High, Medium, and Low groups and hence genuine worst machines in both criteria can be monitored on this grid. It also monitors the performance of different machines and suggests appropriate actions. The next step is to place the machines in the "Decision Making Grid" shown in figure (6), and accordingly, to recommend maintenance decisions to management. This grid acts as a map where the performances of the worst machines are placed based on multiple criteria. The objective is to implement appropriate actions that will lead to the movement of machines towards the north - west section of low downtime, and low frequency. In the top-left region, the action to implement, or the rule that applies, is OTF (operate to failure). The rule that applies for the bottom-left region is SLU (skill level upgrade) because data collected from breakdowns - attended by maintenance engineers - indicates that machine [G] has been visited many times (high frequency) for limited periods (low downtime). In other words maintaining this machine is a relatively easy task that can be passed to operators after upgrading their skill levels.

Machines that are located in the top-right region, such as machine [B], is a problematic machine, in maintenance words "a killer". It does not breakdown frequently (low frequency), but when it stops it is usually a big problem that lasts for a long time (high downtime). In this case the appropriate action to take is to analyse the breakdown events and closely monitor its condition, i.e. condition base monitoring (CBM).

A machine that enters the bottom-right region is considered to be one of the worst performing machines based on both criteria. It is a machine that maintenance engineers are used to seeing it not working rather than performing normal operating duty. A machine of this category, such as machine [C], will need to be structurally modified and major design out projects need to be considered, and hence the appropriate rule to implement will be design out maintenance (DOM).

If one of the antecedents is a medium downtime or a medium frequency, then the rule to apply is to carry on with the preventive maintenance schedules. However, not all of the mediums are the same. There are some regions that are near to the top left corner where it is "easy" TPM because it is near to the OTF region and it requires re-addressing issues regarding who will perform the instruction or when will the instruction be implemented. For example, in case of machines [I] and [J], they are situated in region between OTF and SLU and the question is about who will do the instruction - operator, maintenance engineer, or sub-contractor. Also, a machine such as machine [F] has been shifted from the OTF region due to its relatively higher downtime and hence the timing of instructions needs to be addressed.

Other preventive maintenance schedules need to be addressed in a different manner. The "difficult" TPM issues are the ones related to the contents of the instruction itself. It might be the case that the wrong problem is being solved or the right one is not being solved adequately. In this case machines such as [A] and [D] need to be investigated in terms of the contents of their preventive instructions and an expert advice is needed.

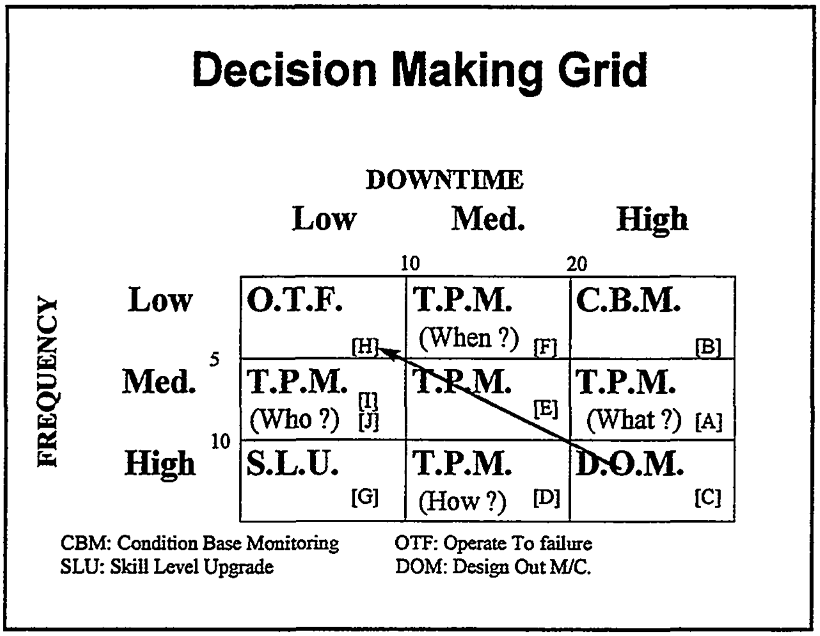

Figure 6. Step2: Decision Mapping.

5.1.3 Step 3: Decision Support

Once the worst performing machines are identified and the appropriate action is suggested, it is now a case of identifying the cost of each action, or the amount of money expected to be saved if the appropriate action is implemented. This is achieved by multiplying the hourly rate of production hours, by the number of production operators allocated on those machines, by the hours wasted in each machine and then averaging the value for each category. This step is shown in figure (7). This completes the first model, which is the decision analysis process. In the next section the model comprising the analytic hierarchy process is presented.

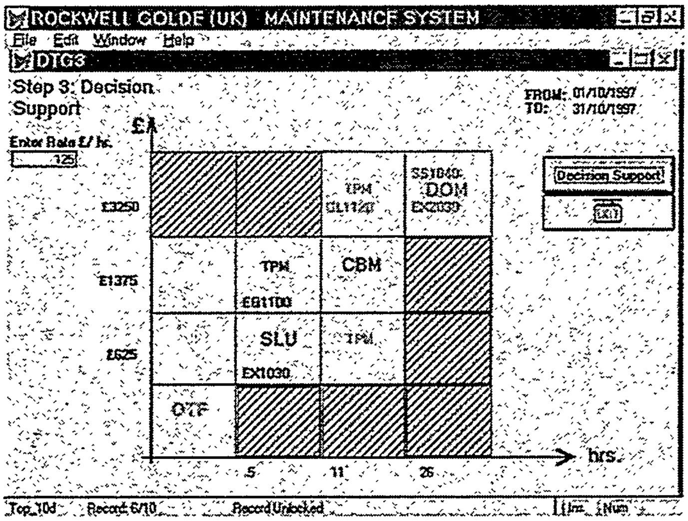

Figure 7. Step3: Decision Support.

5.1.4 Analytic Hierarchy Process

This model provides an analytic approach that prioritises fault categories and fault details based on a multiple criteria theory called the Analytic Hierarchy Process (AHP). The model is based on formulating the problem into a hierarchical structure of criteria, sub-criteria, and alternatives. A full detail of the model is described in detail in [Labib, et.al, 1998]. Figures 8-10 give a broad idea about the concept of the model. As shown in figure (8), the hierarchy is structured in the form of different criteria, which can be downtime, frequency, spare parts,..etc. This level is followed by a level of prioritised machines based on the upper level of criteria. Finally, last levels are standard failure trees of these machines.

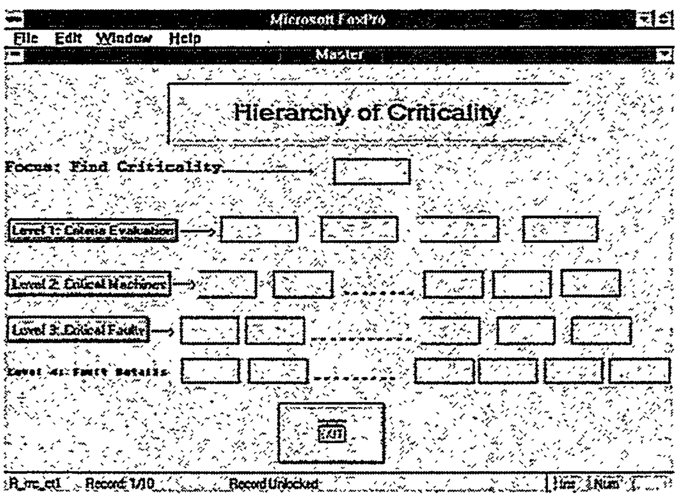

Figure 8. The AHP model.

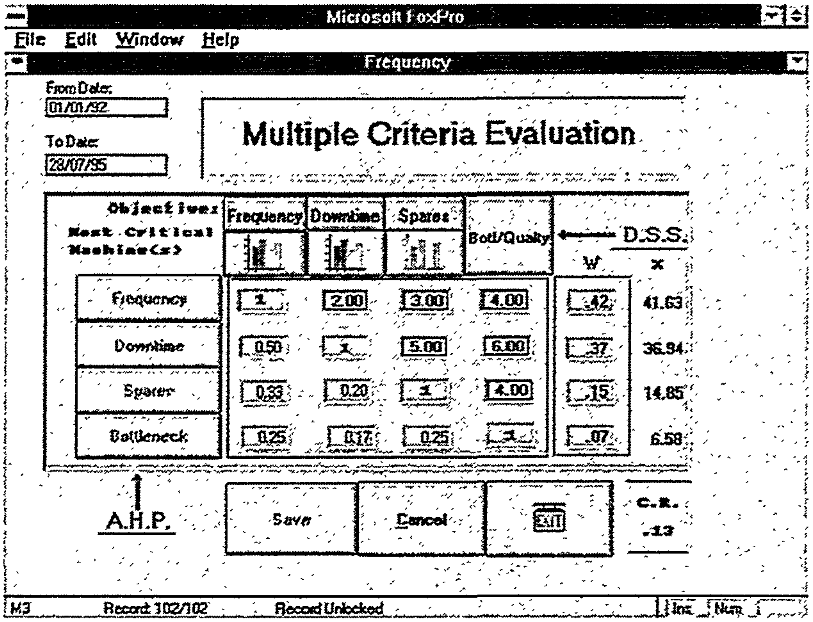

Figure 9. Criteria evaluation.

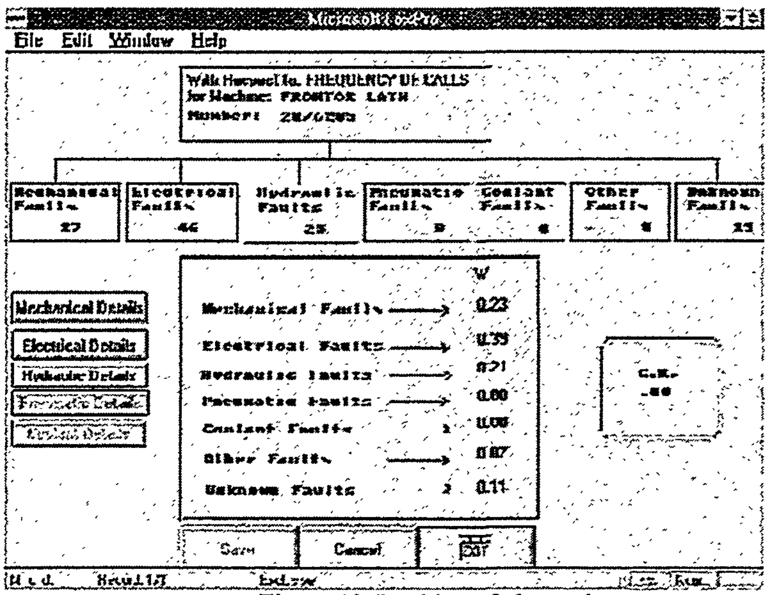

Figure 10. Ranking of alternatives.

5.1.5 Results

The results of implementing the decision-making grid have been a continuous reduction in total downtime, as indicated in breakdown trend in figure (4). Notice that although the same grid is used every month, the range of the scales differs. Since breakdown duration have been reduced, accordingly the scale had to be altered. For example, what used to be considered a "Low" downtime (5 hours or less) is now considered a "Medium" range, and what used to be considered "Medium", is now a "High" value. When big problems are dealt with, the attention is focused on smaller ones and they are treated as major problems. This shows that a process of continuous improvement is being implemented. In addition, even when the scale is tightened, there is seldom any machine in the DOM region which shows that a total shift towards the favourable north-west zone of the grid is being achieved.

6 Conclusions

The combination of the overall picture approach followed by a focused analysis ensures an adaptable and optimum methodology. Finding and improving the worst machines is not a new concept, as it is the core concept of TPM. However, using a formalised decision analysis approach based on multiple criteria and rule-based system is the contribution of the presented model.

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Methodology for Quantitative Assessment of Technical Condition in Industrial Systems

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Abstract

As part of the Eureka project *Ageing Management* a methodology has been developed to assess the technical condition of industrial systems. The first part of the paper argues for the use of technical condition parameters in the context of maintenance strategies. Thereafter the term 'technical condition' is defined more thoroughly as it is used within the project. It is claimed that the technical condition of a system – such as a feed water system of a nuclear power plant, or a water injection system on an oil platform – may be determined by aggregating the condition of its smaller components using a hierarchic approach. The hierarchy has to be defined in co-operation with experienced personnel and reflects the impact of degradation of elements on a lower level to nodes higher in the hierarchy. The impact is divided into five categories with respect to safety, environment, availability, costs and man-hours. To determine the technical condition of the bottom elements of the hierarchy, available data is used from both an on-line condition monitoring system and maintenance history. The second part of the paper introduces the prototype software tool TeCoMan which utilises the theory and applies it to installations of the participating companies. First results and gained experiences with the method and tool are discussed.

Introduction

In the increasingly competitive environment, the process industry has to focus on safety, environmental emissions, availability and operational costs. This influences the way the organisations handle the long-term management of operations and maintenance of their process plants.

It is the objective of the EUREKA project "AGEING MANAGEMENT" to develop a method to assess a quantitative measure of a plant's technical condition, taking into account the long-term degradation of the plant and the influences of operation and maintenance.

The development of systematic methods, which enable personnel to measure and predict technical condition, is a key issue for the project. The aim is to improve decision support for long term ageing management, and thereby increase the re-

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turn on investment through improved cost effectiveness, plant availability and safety levels.

The project started in 1996 as part of the Norwegian Research Council funded research programme PROSMAT 2000 - a national research programme for the process and alloy industry.

Four of the larger industrial groups within the process industry in Scandinavia are represented in the project: Elkem (N), Kvaerner (N), Statoil (N) and Forsmark Kraftgrupp (S). The Norwegian Marine Technology Research Institute (MARINTEK) and Norwegian University of Science and Technology (NTNU) are the research institute and university representatives. They are responsible for the models and development of generic methods.

Use of technical condition in an ageing management context

Traditional, executive key indicators used at management level are typically:

- Regularity
- Budgets and accounts
- Accident and incident statistics
- Environmental emissions.

The common characteristic of all these indicators is that they do not distinguish a development caused directly by the organisation (human factors) from a degraded plant (low technical condition). As far as the technical condition is regarded, these variables are burdened with a low sensitivity, i.e. there may be a long period between the point where the technical integrity of the plant is substantially reduced and when the parameters above alert the organisation. This is illustrated in Figure 1. The project's hypothesis is; by developing a new, reliable variable, named Technical Condition (TC), which is only affected by changes in the plant's technical integrity, the organisation will be alerted much earlier of developing problems than by using only traditional indicators. Thereby management is given the ability to take the necessary proactive actions.

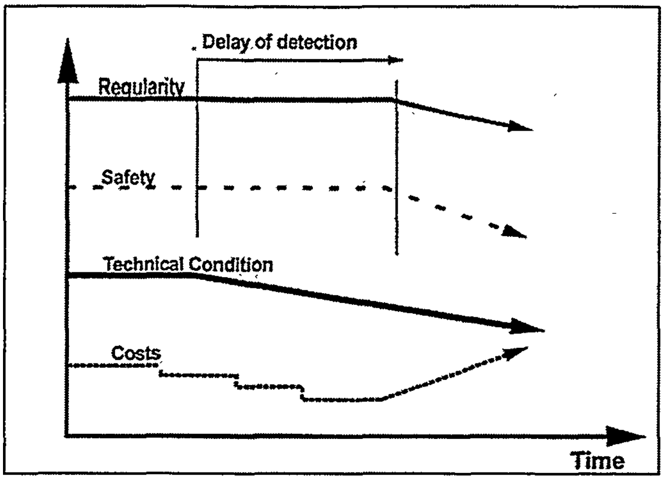

Figure 1. Traditional key indicators used at management level (with Technical Condition included).

Looking back in history, there are many cases described where enterprises were predominately focused on short-term costs. They eventually ended up with tremendous investment needs to catch up for a worn-down plant. Alternatively the plant was shut down. Often, the strategic decisions taken on cost reductions lack a proper assessment of consequences on the plant's technical integrity. Or, if the assessment has been made, it has been poorly communicated by the technical stuff.

Many enterprises are under constant pressure from low profit margins. Others experience a decision to prolong the lives of their process facilities by another 10 to 20 years, far beyond the original design life (e.g. production platforms in the North Sea). In both cases there is a need for a more systematic approach to handle the technical integrity and system degradation in a safe and efficient manner.

During its life, an industrial system's technical condition is under the influence of many factors, the main being:

- Initial quality as a result of the fabrication of components and installation
- Operational load, such as production rate, process medium characteristics, flow speed etc.
- Maintenance actions, i.e. the repair/overhaul actions, which ideally should bring the technical condition back to a "as good as new" condition.

The calculation of the TC value within the project is based on an aggregation method. In short, it comprises the following steps:

- Establish a hierarchy of objects which represents the actual industrial system
- Denote a weight to each of the objects according to their criticality
- Assign relevant input variables, which characterise the technical condition, to the objects (mainly at the bottom level)
- Based on the input variable values (e.g. maintenance statistics, process data, condition variables monitoring and inspection data), the TC values are then aggregated upwards the hierarchy.

The methodology for calculating the Technical Condition and the software based aggregation tool "TeCoMan" developed for this purpose is described in the next chapters.

The general management loop, the 'quality ring', comprises typically four phases as shown in Figure 2.

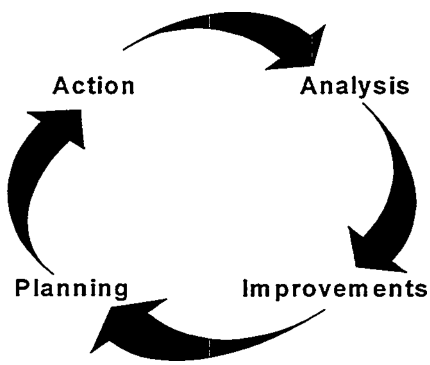

Figure 2. The quality ring.

This representation is valid for any level of action, from the maintenance action on a component to major decisions at strategic levels. The last two phases, effect analysis and improvements, are seldom performed in today's industry. If they are, it is occasionally and individually triggered.

The TC variable has its role in the third phase of the quality ring; i.e. it will show the effect of the actions on the plant's technical integrity. Thereby it becomes part of the effect analysis and may possibly lead to a compensating or improving action. This is illustrated in Figure 3.

The main objective is that the TC variable shall support the decision-maker in the long-term loop. The existing maintenance management systems, as well as condition monitoring systems (vibration analysis, material inspection and performance monitoring systems) generally take care of the effect analysis on the short-term loop.

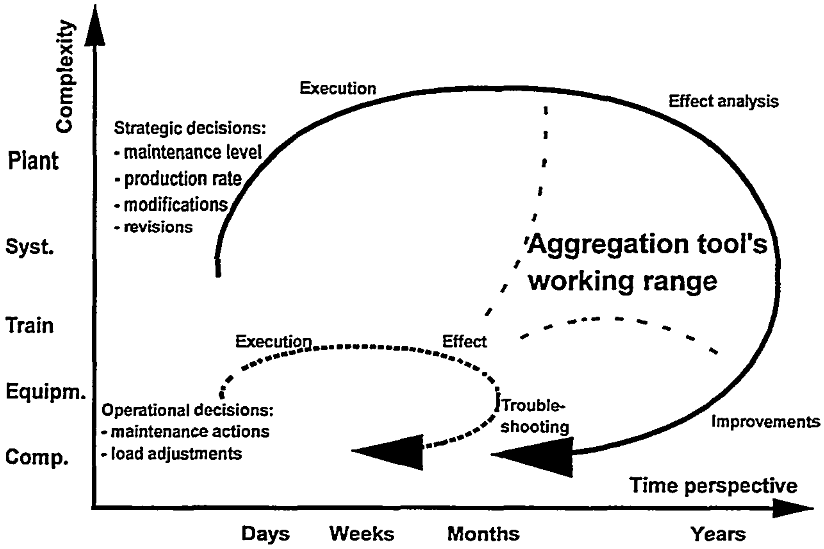

Figure 3. TeCoMan's position in the quality ring.

On the other hand, the systematic approach and coherent tools are lacking in the long-term loop, leaving it open. The aggregation tool will contribute in closing it.

Definition of technical condition

'Technical condition' is used as a term in various situations. Machinery is equipped with condition monitoring systems; a car is said to be in a good/poor technical condition etc. But, although the term is in daily use a proper definition is lacking. To be able to quantify and calculate the condition of an item the following definition is used:

> The technical condition, denoted TC, is defined as the degree of degradation relative to the design condition. It may take values between a maximum and minimum value, where the maximum value describes the design condition and the minimum value describes the state of total degradation.

In the following the minimum and maximum values are set to 0 and 100, respectively, but they could take any value. The design condition is taken as a reference in order to make the technical condition independent of the demands of the system in question. The design is fixed, whereas usage might change over time, making comparisons of TCs difficult.

As easy it is to define the perfect condition as difficult it is to define an item's 'state of total degradation'. The evaluation of technical conditions depends very much on the applied context. An engine, for example, might deliver sufficient horsepower but is completely degraded if the evaluation is done within an environmental context, because the NOX or CO values are too high and it might even break tomorrow. Therefore it was chosen to relate technical condition to a certain context rather than to use an absolute technical condition. Five principal contexts were identified:

1. Safety
2. Environment
3. Availability
4. Man-hours
5. Costs.

In other words, not the technical condition in itself is evaluated but its importance in the respective context.

Technical condition is not an equivalent to the residual lifetime. Residual lifetime is dependent on load, usage patterns etc. whereas a current technical condition should be independent of these parameters.

Determination of an item's condition from available data

To make decisions on maintenance strategies for the strategic or tactical time horizon, it is not necessary to determine an item's exact technical condition. The fuzziness of the subject may be compared to knowledge based diagnostic systems. Although those systems will seldom conclude with 100 % certainty, they have proved to be very useful.

Another important argument against exact determination of technical condition is the enormous amount of work that had to be done to study all the relevant degradation mechanisms. A combination of expert knowledge (gained by interviewing personnel working with the equipment) and available data from existing condition monitoring and maintenance management systems is sufficient to determine an item's technical condition. The item should be sufficiently simple in a sense that only little input data is needed to describe its condition. How simple depends on the system, the wanted degree of accuracy and the availability of relevant data. If the system is a gas turbine, the comprising elements of a gas turbine (for example compressor, combustion chamber and turbine) might be used. If the system under consideration is a power plant, a steam turbine might count as one item.

Three principally different types of information may be used to describe the technical condition of an item

1. Maintenance history
2. Traditional condition monitoring data, including manual inspection
3. Given the correlation between load and degradation mechanisms, process data may be used analytically to calculate a technical condition.

Maintenance history comprises various types of information. The project concentrates on use of statistics related to corrective actions. Periodic overhaul is less relevant. It is common practice to assume that during an overhaul the condition is restored to a level of "as good as new". This is not always the case. An overhaul will, however, reduce the number of necessary corrective actions. This in term will lead to an improved TC value when applying the above outlined line of reasoning.

History of corrective maintenance actions is available from maintenance management systems. Typical data includes

- Number of maintenance actions
- Man-hours spent on repair
- Direct costs, i.e. spare parts, tools, consumables etc.

When using such statistical data it is often useful to look at a group of comparable items, such as all shutdown valves or all pipes in a piping system. Levels have to be defined in order to convert between these parameters and the actual technical condition. An example: A group of 100 valves required 10 hours of corrective maintenance per month. This was said to be an acceptable level. A level of 50 man-hours per month, however, would indicate a severe degradation of the technical condition. The obtained TC value describes the technical condition of the valves as a group and not the condition of every individual within the group.

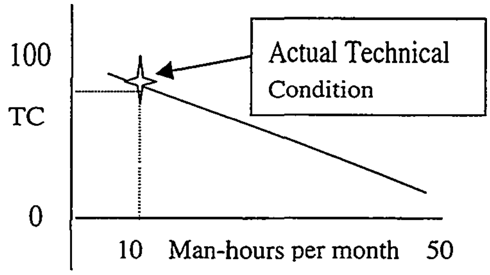

Figure 4. Linear relation between an input variable (man-hours spent per month) and the coherent technical condition TC.

This information can be used to describe a linear relation between used man-hours per month and the resulting technical condition as shown in Figure 4.

Traditional condition monitoring and process data may be used in a similar way. The gas generator exhaust temperature of a gas turbine indicates its technical condition with respect to the environment and probably costs as well. An increased temperature leads to higher fuel costs and higher CO2 penalties (as experienced in the Norwegian sector of the North Sea).

In some cases an analytical determination of the technical condition from load and usage patterns may be used. An example is the general corrosion of pipes. The medium, pressure, temperature and time of exposure lead to a predictable reduction of the wall thickness. Unfortunately, general corrosion is seldom the predominant degradation process.

In order to assist in determining relations between influencing parameters and resulting degradation of an artefact the project gathers knowledge about degradation mechanisms. Experiences so far indicate that known degradation models only address relations at a very low level and cannot be applied to more complex equipment.

Hierarchical aggregation of technical condition

Technical condition values of smaller building blocks of a system may be aggregated to a higher level. Figure 5 gives an example of how technical condition may be aggregated using weighted sums. The hierarchy represents a feed water system train as it is found in a power plant. Only those items, which are relevant when looking at environmental consequences, are shown.

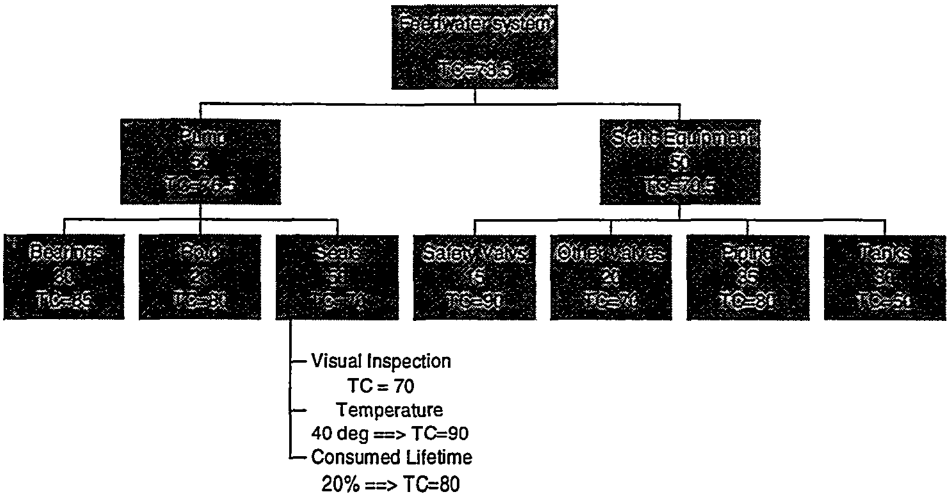

Figure 5. Example of a hierarchy to determine technical condition with respect to environmental consequences.

The numbers below the box titles denote the relative weights. Resulting condition values (TC) are shown below the weights. For the seals three input parameters are shown, visual inspection, temperature and consumed lifetime. The worst case philosophy is applied resulting in an TC value of 70 for seals. TCs from temperature and lifetime are obtained using similar relations as shown in Figure 4. As aggregation method the weighted sum method is applied. Equation 1 is the general formula used to calculate a parent's technical conditions from its children's values. In addition to the method of *weighted sum*, *worst case* and *mean* are implemented in the prototype (see the following chapter).

$$TC_{Parent} = \frac{\sum_{i=1}^{n} TC_i \cdot w_i}{\sum_{i=1}^{n} w_i}$$

where TC_i technical condition of child i

w_i weight of child i

n number of child nodes

Equation 1

The establishment of the hierarchy is an important task, which should be done in co-operation with operational and maintenance personnel. Two principal approaches may be used:

- Functional breakdown
- System breakdown.

The approach of functional breakdown is used, for example, in criticality analyses (in the context of reliability centred maintenance). An advantage is the ability to be able to see more easily influences of degradation at lower levels on the functional availability at a higher level. The hierarchy will, however, contain many levels, which in turn may make it difficult to follow the branches. Another disadvantage is the fact that equipment often provides more than one function, i.e. functions are not defined as a strict hierarchy, but as a functional net. If a net is converted to a hierarchy one item may occur several times in that hierarchy.

A system breakdown is easier to establish down to any desired level by answering the question: 'What parts does this equipment consist of?'. How to define a hierarchy. A disadvantage is the lack of link to the functions provided by machinery.

Therefore neither a strict functional nor a strict physical breakdown is usually used, but both forms are applied where appropriate. Another constraint is to allow for an existing tag system to be reflected in the hierarchy used for technical condition.

A technical condition manager, TeCoMan

In order to be able to test the aggregation method, a prototype system, the *Technical Condition Manager* (TeCoMan) has been developed. TeCoMan runs under Microsoft Windows NT and Windows 95. The prototype may receive data by polling a database server and data also may be imported from local databases or put in directly by the user.

Figure 6 shows a screen dump of the main window. The hierarchy is shown in the top left corner. Additional information on nodes is given in the top left panel. A graph, showing the development of a technical condition over time is presented in the lower panel. In TeCoMan all hierarchies are based on one common system hierarchy, which contains all items of the system. In the system hierarchy measurement points are connected to the bottoms nodes. Further configuration is done in the other hierarchies (safety, environment, man-hours and cost).

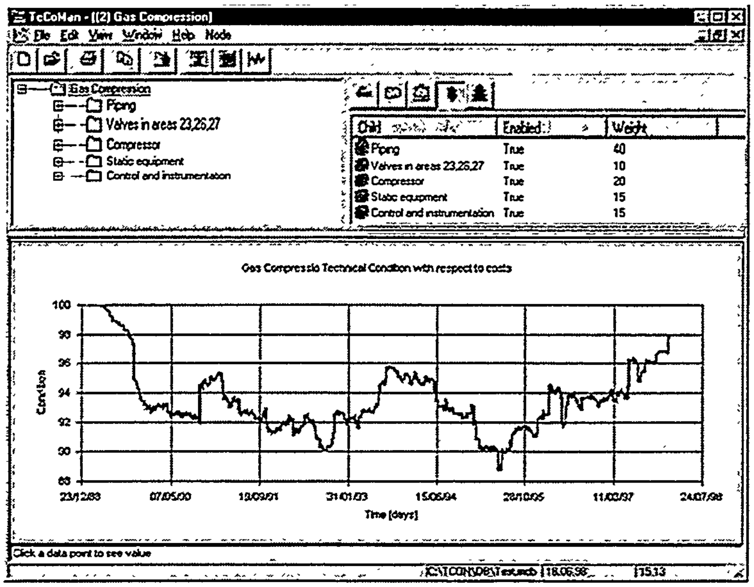

Figure 6. Main screen of TeCoMan.

Figure 7 shows the configuration dialog for a node within the hierarchy. Configuration is done with respect to costs. The question the user has to ask is:

If any of the nodes degrades substantially, which impact will that have in terms of costs on the parent node compared to all other nodes on the same level?"

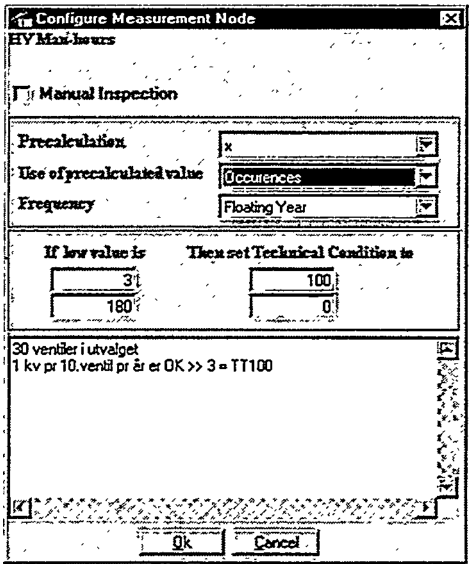

Figure 7. Configuration of a node in the hierarchy.

The answer to this question results in weights applied to the various children nodes. The user may choose to use only a subset of the available number of children nodes by using the check box left to the name of the child node. In addition to the method of 'weighted sum', 'worst case' and 'mean' methods to calculate a node's resulting technical condition are available.

Figure 8 shows the configuration dialog for converting measurements into technical conditions. The conversion is divided into four steps:

1. Pre-calculation, i.e. optionally relating the measurement value to some baseline value
2. Optional calculation of mean, sum over time, worst case.
3. Optional calculation of frequencies
4. Linear conversion of the obtained value to a technical condition.

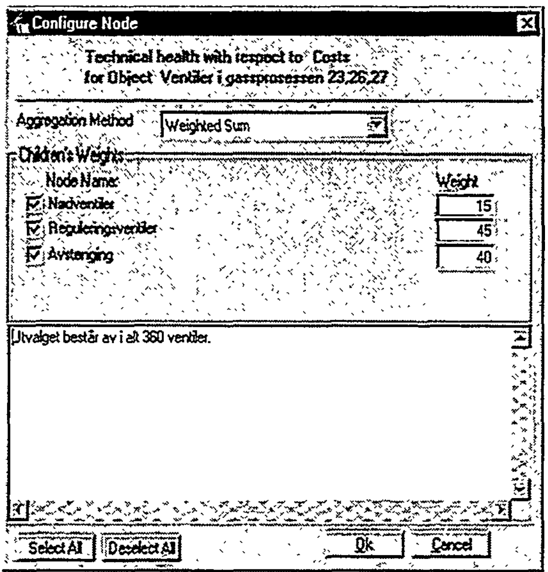

Figure 8. Measurement configuration.

Figure 9 shows the children's contribution to the technical condition of their parent node. The figure has to be studied together with Figure 6, where the parent's technical condition over time is displayed. The relative contribution helps identifying the effects of lower nodes on a parent node, including their weighting factors (if the method of 'weighted sum' is used). Figure 9 does not give any hint about the absolute technical condition of the gas compression system (the parent node, see hierarchy in Figure 6).

The trends of technical condition have to be analysed thoroughly in conjunction with other available data, for example the production profile in order to develop a trust in the obtained figures. So far the absolute values of technical condition are of less interest than their development over time. Site testing will help in developing a 'feeling' for the technical condition as a key indicator. Another important task is the development of graphical representations to ease the interpretation of results.

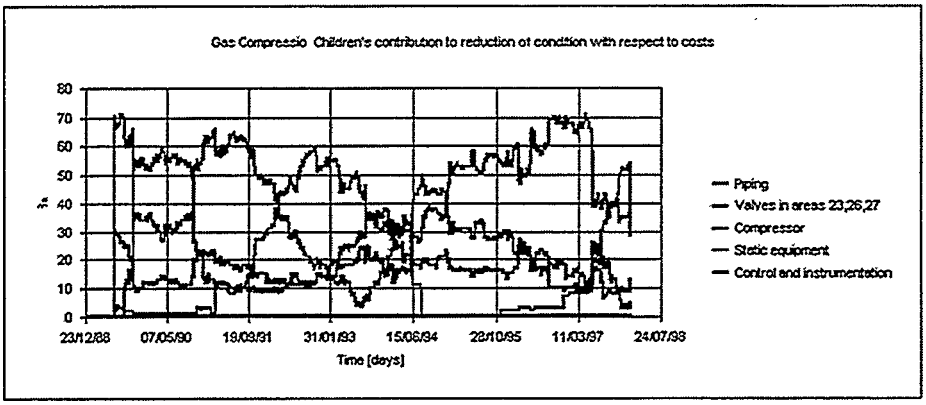

Figure 9. Relative contribution of nodes' technical conditions to their parent.

Site testing and user response

The project has to a large extent adopted the "learning by doing" approach. Therefore, a primary task throughout the project has been and still is the qualification of the models/methods developed in pilot projects at the participants' sites.

Introduction of this type of tool into an organisation is a time-consuming and long lasting activity. It is, least of all, a matter of technology. A major part of the effort to introduce the concept is related to a necessary change in attitude of the people engaged in operation and maintenance; only a minor part concerns technology (software and hardware).

The pilot project teams from each industry partner have been deeply involved in both methodology development and software tool testing. In the first case, contributing to making it feasible for industrial use. In the other case, providing real test data from the IT systems on site and commenting on the tools' user friendliness and functionality.

Some of the pilots could connect TeCoMan with online interfaces to their maintenance management and condition monitoring systems. In other pilots there is direct access to the process control and data acquisition database (PCDA) and non-destructive testing (NDT) databases (x-ray, ultrasound measurements and visual inspections). The first trend plots (see example in Figure 6) have been presented to the maintenance management group and the response is positive. This will continue on a monthly basis throughout the project period. Typically, the discipline leaders welcome the ability of communicating the technical condition trends to the rest of the organisation using a common, easily interpretable format.

Their response, however, is dependent on which type of maintenance strategy is favoured by the management. Companies using a reactive (fireman) approach are more reserved than the more proactive (reliability focused) ones.

A general observation, which is common for all the industry partners, concerns the enormous amount of data which is collected by various database systems. Little or no use is made of this data for analysis purposes. Maintenance personnel spend a lot of time and money with feeding the databases with reports without being able to harvest the fruits of their efforts. This has a demoralising effect on a proper reporting discipline, which is also reflected in the data quality.

Conclusions

The project has developed a method for aggregation of the technical condition of industrial systems or use in long-term management. Initial evaluations and experiences from site testing are:

- The method is feasible for use in industry
- It will contribute to closing the process in the continuous improvement loop.
- It will be a key indicator common for a whole organisation.
- The organisation will have a common, overall key indicator for the plant's technical integrity, more sensitive for changes than indicators used today.
- The method exploits historical data from maintenance and operation in a continuous, systematic manner for improved management and continuous improvement.

The method will be thoroughly tested and refined during the project's last year.

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The Application of Miniature Disc Testing for the Assessment of Creep Damage in CrMoV Rotor Steel

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Abstract

A range of critical experiments has been performed studying the creep and fracture behaviour of a typical CrMoV rotor steel. Initially, uniaxial tests were carried out to provide material with a predetermined level of creep damage. Then, miniature disc tests were undertaken under accelerated conditions in a similar manner to procedures used for post-exposure uniaxial testing of service components. Data analysis demonstrates that the miniature tests accurately reflect the damage present so that this approach can be used to support run/repair/replace decisions.

1 Introduction

Turbine rotors operating in the creep range are normally designed using conservative approaches. Thus, components which are properly operated and maintained will generally have operating lives significantly in excess of minimum estimates. However, as rotor lives approach and exceed design lives, methodologies which permit the actual creep strength and/or remanent life of specific components to be determined are required to allow realistic assessment of the safe operating life.

Frequently it is not possible to remove sufficient material for conventional uniaxial creep testing and decision making is based on non-destructive techniques such as metallurgical replication (1) or hardness testing (2). However, these approaches do not provide a direct measurement of creep strength or remanent life. Test methodologies based on miniature specimens offer the potential to increase the confidence in assessments provided material can be removed from a component without affecting its structural integrity, and the data produced are meaningful. This paper presents results from uniaxial and disc testing programmes on a CrMoV rotor steel and examines the ability of the miniature samples to measure creep damage.

2 Experimental Methods

The selected CrMoV steel exhibited a composition typical of these rotors, Table 1. The heat treatment schedule of normalising at 950°C for 14 hours, oil quenching followed by tempering for 18 hours at 700°C resulted in a tempered bainite structure. The measured hardness of 234H_v, 0.2% proof stress of 589 MPa and ultimate tensile strength of 743MPa are in reasonable agreement with the mechanical properties expected for 1CrMoV rotor steels.

2.1 Uniaxial Creep Testing

Uniaxial creep tests were carried out at 550°C and 585°C for stresses in the range 150 to 330 MPa. The bulk of these tests were performed to establish material specific creep and fracture properties. These tests therefore used specimens with a cylindrical gauge length of 40 mm and 8 mm diameter. Limited testing was also performed to provide material with a pre-selected level of creep damage. Since this material was required for subsequent post exposure disc testing, the specimens were of 50 mm gauge length with a square cross section of 10 mm each side. This square cross section was required

i. to facilitate surface preparation and metallographic examination of the sample to evaluate the level of creep cavitation present after an interruption, and
ii. to allow manufacture of disc specimens of the required size at different orientations.

The specimens used for these specific creep tests are shown in Figure 1. In the present phase of the research, it was desirable for the strain developed in the post-exposure disc test to be in the same direction as the tensile axis of the uniaxial test. Thus, the disc specimens were fabricated normal to the gauge length of the uniaxial samples, Figure 1. After manufacture the disc samples were hand-lapped to ensure a uniform surface finish with a uniform thickness.

Table 1. Composition of the Test Material.

Element	C	Si	Mn	S	P	Ni	Cr	Mo	V
wt%	0.25	0.21	0.81	0.014	0.009	0.71	0.99	0.65	0.28

2.2 Disc Testing

High sensitivity creep machines have been developed for disc testing. This equipment applies a constant load to the centre of the sample through a hemispherically-tipped punch. The specimen was located in a recess on a stainless steel die and clamped around the edges by a stainless steel sheath. The punch was constructed from a creep resistant nimonic alloy and was machined by CNC technology to have a perfectly hemispherical tip. Inspection of the punch tip was carried out between tests to ensure that there was no distortion present. A stainless steel rod connected the punch to the load pan at the top of the machine, and a system was incorporated whereby the punch could be aligned with the centre of the specimen at the start of each test. A circular hole was located in the die below the specimen centre, into which the sample would bulge under the action of the punch at the specified load.

To maintain the specimen at the desired temperature, the whole of the die/specimen/sheath/punch arrangement was enclosed in a cylindrical furnace which could be controlled to within ± 1°C by a thermocouple mounted next to the wall of the furnace.

Measurement of deformation of the specimen during the tests was carried out using two capacitance transducers linked to a computer controlled data acquisition system which could record displacements at any desired interval of time. The first transducer was connected by a ceramic rod to the lower surface of the specimen. The second transducer measured the distance moved by the stainless steel rod attached to the punch.

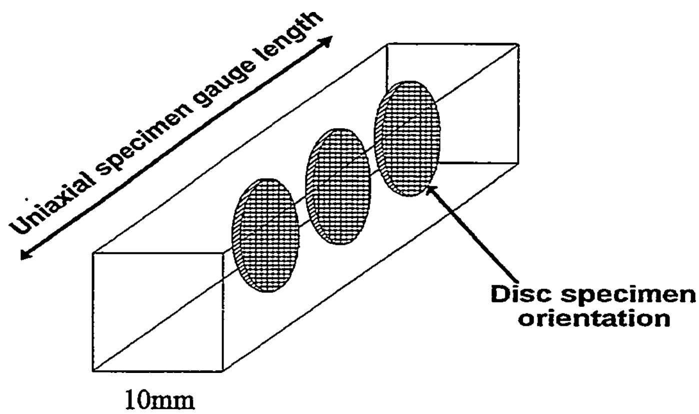

Fig. 1. Schematic diagram showing the gauge length of a uniaxial specimen with detail of the disc samples removed for post-exposure testing.

3 Results

3.1 Uniaxial Behaviour

The general shape of the strain:time curves noted was similar for all test conditions. Thus, after the initial extension on loading the strain rate decayed during primary creep before tertiary creep processes lead to an increase in deformation rate until fracture occurred. For tests at one temperature the creep rupture life increased with decreasing applied stress, and, as expected, test lives at 585°C were lower than those at 550°C. The longest life recorded in the present programme was 18740 hours for the test at 150 MPa and 550°C.

The stress, σ, and temperature, T, dependence of the rupture life, t_f, shown in Figure 2, could be described by an equation of the form

$$\frac{1}{t_f} = A\sigma^n \exp\left(-\frac{Q_c}{RT}\right) \qquad (1)$$

where A and R are constants, n is the stress exponent and Q_c the activation energy for fracture. The trends in rupture life with stress at each temperature indicated a slight curve. However, a value of stress exponent, n, of 6.5 provided a reasonable representation of the bulk of the results at both 550°C and 585°C. Moreover, for a given applied stress the lives observed at 550°C were approximately 6.5 times those at 585°C indicating that the activation energy for fracture was about 315 kJ/mol. The values of n and Q_c noted were in good agreement with published data for the stress and temperature dependence of fracture for similar creep resistant low alloys steels (3).

The tests at the greatest applied stresses resulted in the shortest lives and highest failure strains. Thus, for example, for tests up to about 1000 hours duration the reductions in cross-sectional area observed were greater than 60%, Figure 3. However, as rupture life increased the failure strain decreased with ductilities of only about 3% measured in tests of the longest duration. This trend in behaviour is consistent with the fracture behaviour under these conditions being documented by the nucleation, growth and link-up of cavities on prior austenite grain boundaries. Thus, it is apparent that in these laboratory tests, the damage developed is similar to that reported for long term service behaviour of rotors (1).

Having characterised the stress and dependence of deformation and fracture, further uniaxial tests were required to provide creep damaged material for post-exposure disc testing. For these post-exposure tests, it was

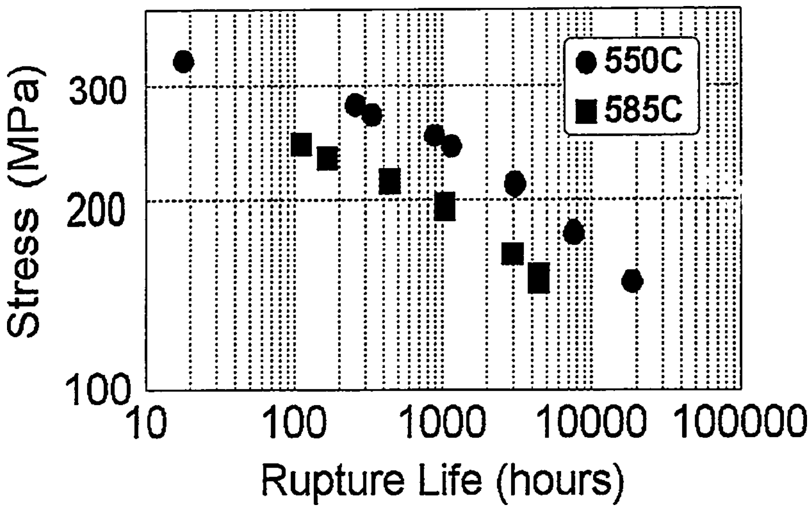

Fig. 2. Stress dependence of the rupture life after uniaxial tests at 550℃ and 585℃.

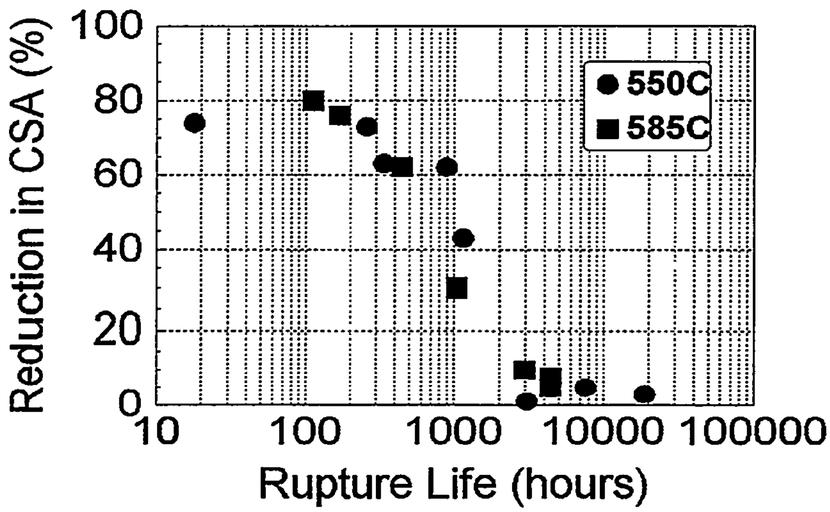

Fig. 3. Variation in reduction of area with creep life for uniaxial tests at 550℃ and 585℃.

important to ensure that the damage developed was relevant to service components. Uniaxial conditions of 585°C and 154 MPa were selected for these tests since

i. failure occurred predominantly as a consequence of creep cavitation, and
ii. the rupture life was less than 5000 hours so that material would be available relatively rapidly.

The creep and rupture data exhibited relatively low scatter consistent with high sensitivity testing of homogeneous parent material. However, to further ensure that a reproducible level of creep damage would be present in any interrupted tests, a test with a square cross-section was taken to failure at 585°C and 154 MPa. As shown in Figure 4, the agreement with the previous data recorded using a specimen with the cylindrical cross-section was excellent. Thus, as reported previously (4), provided creep samples are fabricated with dimensions complying with the appropriate standard (5) data are similar for both square and cylindrical test pieces. An additional test was conducted under these conditions to provide damaged material for disc testing. The strain:time data for this test again indicated excellent agreement with previous results, Figure 4. The test was terminated at 3077 hours after an accumulation of 1.24% strain. Thus, compared to the full creep curves under these conditions, the test was interrupted after a life fraction of 69% and a strain fraction of 52%.

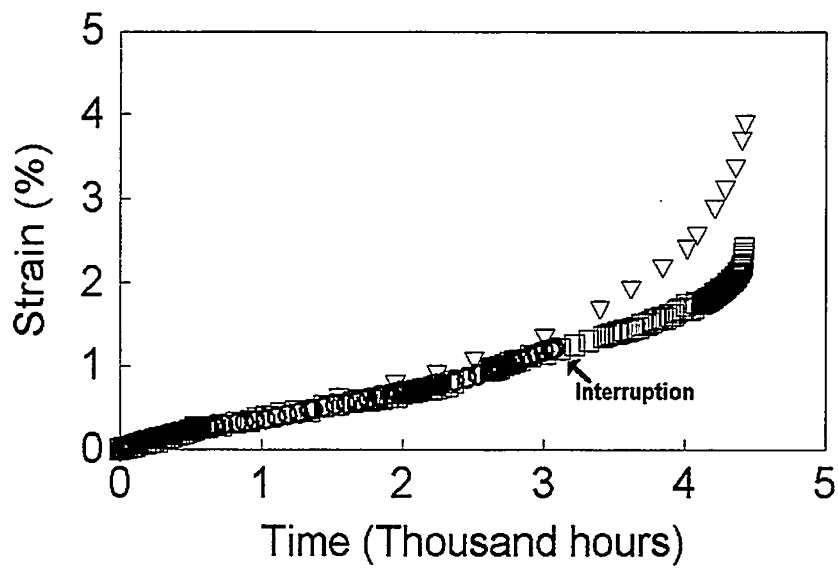

Fig. 4. Reproducibility in uniaxial tests performed at 585 °C and 154MPa.

As a further assessment of the damage level, the surface of the sample was prepared using techniques similar to those for replication of service components(6). Metallographic evaluation revealed that cavities were present on prior austenite grain boundaries, Figure 5. The density of these cavities was in reasonable agreement with established A-parameter values for 69% damage in these materials (7).

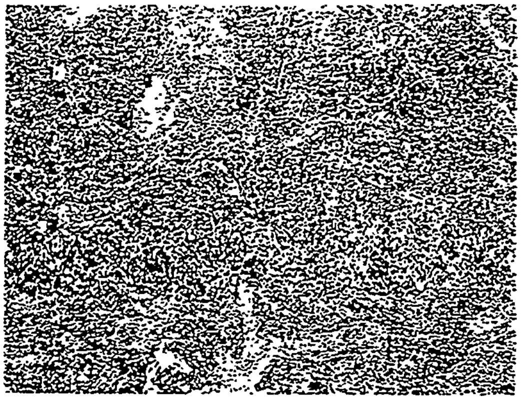

Fig. 5. Cavitation on the surface of the specimen crept to 69% life fraction (250x).

3.2 Creep and Fracture of Discs

Disc testing was carried out at 550°C and 585°C for loads from 250 to 600N. The rupture lives observed were in the range 20 to 4600 hours. After the initial deformation noted on loading the displacement:time behaviour exhibited a "primary" region of decreasing rate, Figure 6. The deformation rate was approximately constant for a significant region of the curve before the deformation rate increased leading to failure. Tests under the same conditions indicated very good reproducibility, Figure 6.

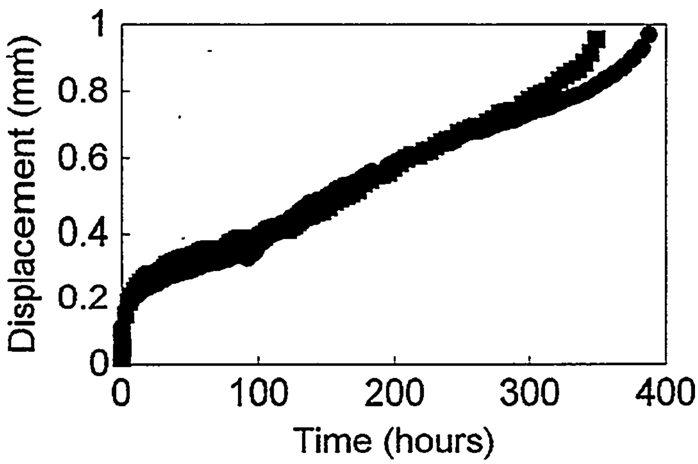

Fig. 6. Reproducibility of disc tests at 550°C and 585°C.

For a given test temperature, the rupture life increased sensibly as applied load decreased, Figure 7. Moreover, the data at 550°C and 585°C exhibited similar trends with results at the lower temperature being about 6 times the lives noted at 585°C. The results obtained could therefore be described using a relationship of similar form to equation 1, i.e.

$$\frac{1}{t_f} = B(Load)^m \exp\left(-\frac{Q_c}{RT}\right) \quad \text{..............................(2)}$$

where B is a constant and m is the load exponent of failure life. For the current rotor steel the data could be represented by an m value of 6.5 and Q_c of 330 kJ/mol. As would be expected for tests performed using the same geometry, the applied load in the disc tests is proportional to stress in a conventional uniaxial creep experiment. Moreover, the values of Q_c were similar for disc and uniaxial tests indicating that the rate determining damage processes were the same in both cases.

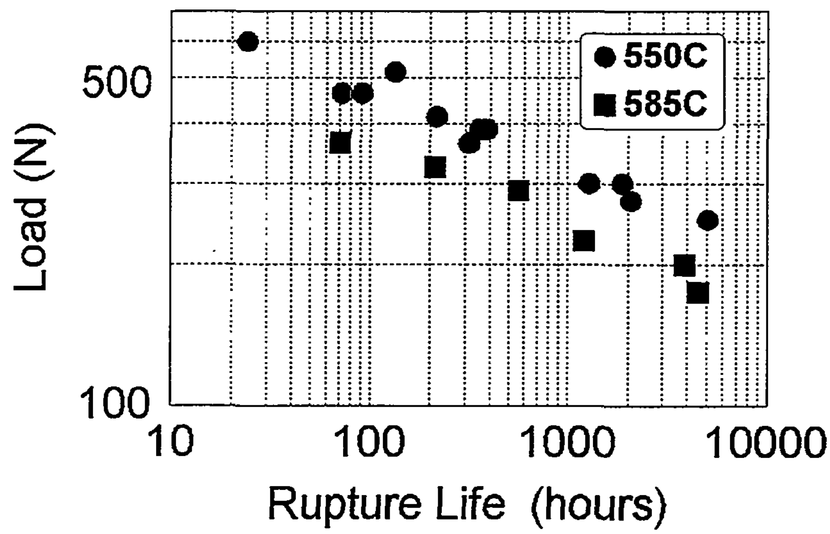

Fig. 7. Load dependence of the rupture life for disc tests at 550°C and 585°C.

3.3 Post-Exposure Testing

The specimens on the pre-exposed material were prepared for disc testing using the same procedures developed for new samples (8). The post exposure test programme was designed with a view to

i. conducting a disc test under conditions equivalent to those experienced in the uniaxial specimen. Thus, if true equivalent conditions were established, the life of the disc test plus the time of exposure before interruption should equal the total failure life of a standard test, and

ii. performing a series of disc tests at loading conditions equivalent to the original uniaxial exposure but with increased temperatures. This approach was therefore similar to the iso-stress, temperature acceleration method established for uniaxial loading. For the results to be valid, the lives obtained should form a linear relationship with temperature allowing extrapolation to the original conditions. Furthermore, the extrapolated life should be similar to that obtained in a test performed under those conditions.

The first disc test was conducted at 585°C, i.e. the same temperature used in the uniaxial test, and at an applied load of 190N. This load was selected based on a correlation established between disc and uniaxial tests. The creep curve obtained is shown in Figure 8. It is apparent that the life obtained in the post exposure tests of 1153 hours is significantly less than noted for new material under the same conditions.

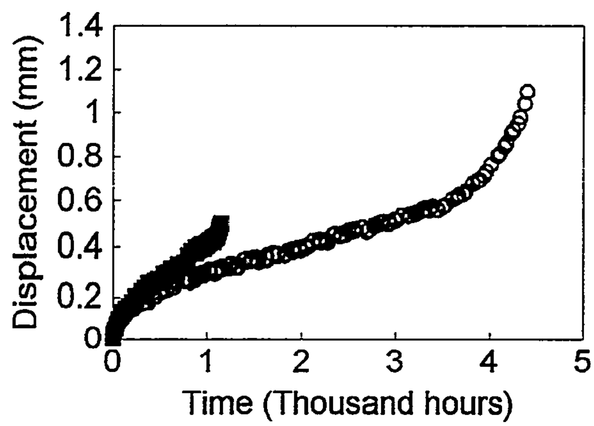

Fig. 8. Comparison of the disc creep curves for the material damaged to 69% life fraction (■) with data for a 'new' sample tested under the same conditions (o).

Moreover, since the full uniaxial life at 585°C and 154 MPa was 4425 hours and the test time to the interruption was 3077 hours, it would be expected that the material should have exhibited a post exposure life of 1348. Clearly, the failure life observed is within 20% of the estimate.

The series of post-exposure tests were performed at 190N and temperatures of 665°C, 645°C, 625°C and 605°C, giving failure lives of 14 to 325 hours. As shown in Figure 9, the results can be described by a reasonable straight line. Furthermore, the slope of this line is the same as results obtained for tests on new material indicating that the rate controlling processes were similar. Extrapolation of the data to 585°C indicates an estimate life under these conditions of about 900 hours. This is clearly in reasonable agreement with the test result obtained under these conditions.

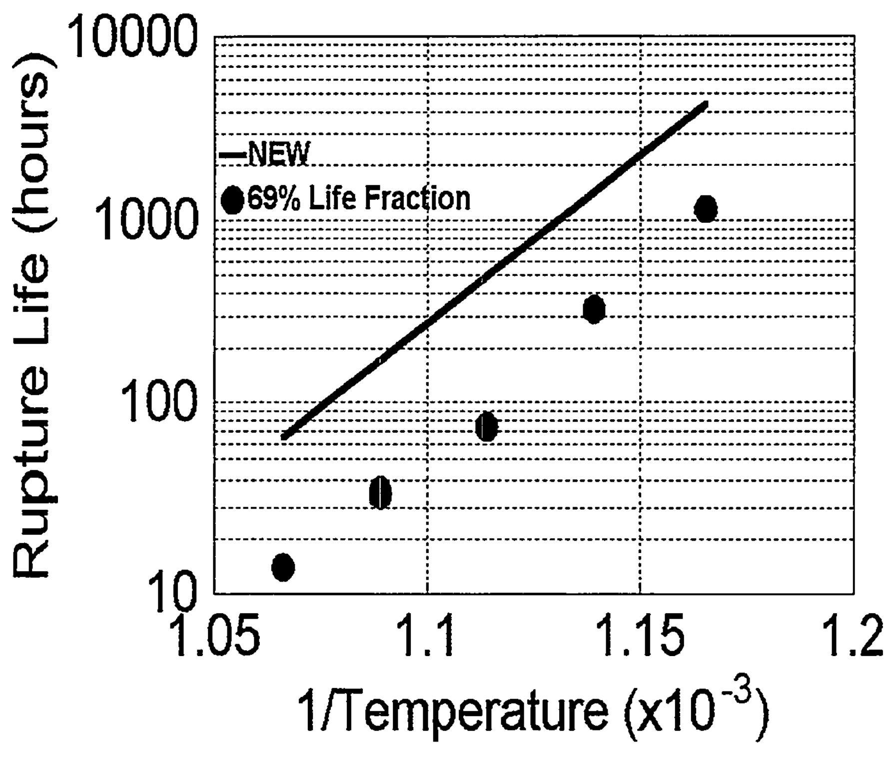

Fig. 9. The creep lives observed in post exposure disc tests (●) compared with lives for new material under the same conditions.

4. Discussion

High temperature rotors in power generating plant are major components which must be assessed periodically to minimise the risk of in-service failure. In general, this type of assessment requires:

i. evaluation of the existing damage level
ii. the ability to estimate future rates of damage accumulation for a set of defined parameters, and
iii. knowledge of an appropriate failure criterion.

The overall life of a rotor will involve damage development leading to the formation of a defect, a period of stable crack growth followed by very rapid propagation once a critical crack size is reached. In view of the uncertainties associated with quantifying the crack growth behaviour and specific critical defect size for a particular rotor, the most conservative end of life criterion is to retire a rotor at the stage of crack initiation. The ability to accurately establish the extent of damage development prior to cracking is therefore of critical importance. For equipment which is operated under broadly similar conditions throughout its service life, determination of current damage provides a reasonable guide to the period of operation expected before a macroscopic defect develops.

A range of non-destructive test methods have been applied to in-service rotors to provide an indication of damage levels (1). These approaches rely on measuring the change in a particular parameter, e.g. hardness and then relating that change to a level of creep damage. The present research programme suggests that miniature disc testing offers a new direct approach which will quantify the creep life fraction expired. The creep deformation and fracture behaviour observed in the disc tests exhibit very similar stress and temperature dependencies to standard uniaxial data produced on the same material. Moreover, post-exposure disc testing of material crept to a specific damage level demonstrates that the life observed under a disc load equivalent to the original test stress was very close to that expected if the uniaxial test had been restarted. Furthermore, tests under accelerated temperature conditions gave a sensible trend in rupture lives so that the life predicted by data extrapolation was in reasonable agreement with the measured value. Indeed, it should be noted that the estimated life was slightly below the experimental value so that the prediction was conservative.

Whilst additional research is required to further evaluate the potential for the miniature test method, the results achieved to date suggest that this approach can be used to support run/repair/replace decision making.

5. Conclusions

The present research programme has demonstrated that creep data generated using high sensitivity techniques on miniature disc samples exhibit similar stress and temperature characteristics to results produced by standard uniaxial methods. In addition, post exposure testing has established that these specialist small specimen approaches successfully measured a pre-determined level of creep damage. The achievements made suggest that these new techniques can be used to support condition assessment decision making for high temperature turbine rotors.

6. Acknowledgements

Approval for the publication of this paper has been received from National Power plc and Siemens Power Generation.

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THE SMALL PUNCH ASSESSMENT OF TOUGHNESS LOSSES IN LOW ALLOY STEELS

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ABSTRACT

The present paper deals at length with the relationship between the Small Punch ,SP, test transition temperature Tsp , behaviour and those displayed by the conventional Charpy Fracture Appearance Transition Temperature, FATT, obtained from large test specimens. Essentially it was demonstrated that the total test temperature range trends could reasonably be described by a non-linear expression such as FATT varied inversely with the square of the Tsp.

Finally when the Tsp against FATT trends were separated into different steel classes an encouraging picture emerged inasmuch that a reasonable amount of data exhibited good agreement with the predicted effects of grain size.

Fractographic details were also discussed and strong effects of strain or loading rates were identified.

INTRODUCTION

In an effort to overcome sample size problems, recent studies have been conducted in the development of small size specimen tests which yield mechanical property. Over a decade ago Baik et al (1) clearly showed that an estimation of the FATT through a knowledge of the Tsp value, defined as the temperature at the mid point between the ductile and brittle shelves, was possible. A few years later Misawa et al (2) demonstrated , by statistical analysis, that Tsp reliably reflected a steels FATT level.

It has been established that the trends between FATT and Tsp were linear in nature, viz.,

$$FATT = \alpha T_{SP} + \beta \qquad (1)$$

where α and β were constants. Later Bulloch and Hickey (3) and Bulloch and Fairman (4) suggested that the data could be better described by the expression;

$$FATT = C/(T_{SP})^2 \qquad (2)$$

where C was a scaling constant.

The present paper attempts to appraise, critically, all the various FATT- Tsp data available from the literature in some effort to establish a true FATT-Tsp trend. Also certain fractographic details of the small punch were highlighted and discussed

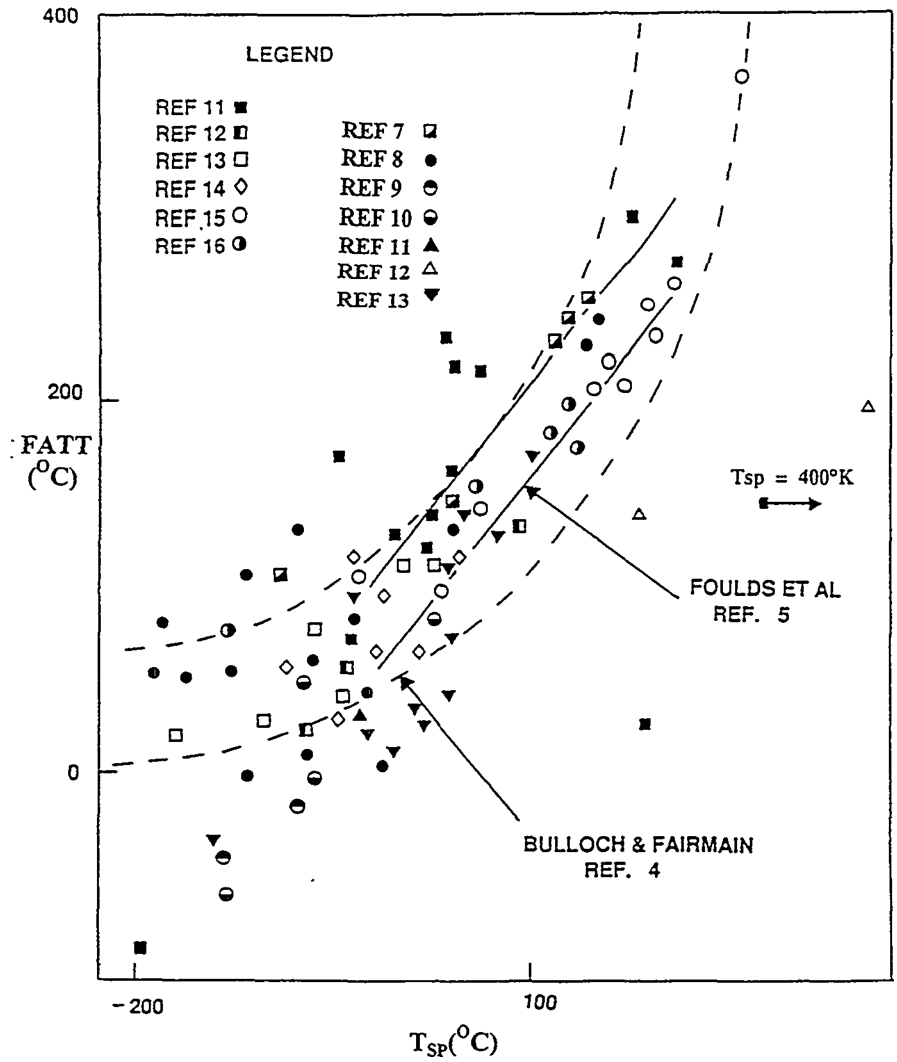

Figure 1. General FATT-T_{SP} Trends For Various Steels From A Literature Survey.

ASSESSMENT OF REPORTED SMALL PUNCH CHARPY DATA

As mentioned earlier, the relationship could be described by equations (1) and (2) and these trends are illustrated in fig. I together with the data from a detailed, but by no means exhaustive literature survey (1 - 13).From this it was evident that the linear trend shown by Foulds et al (5) i.e.,

$$\text{FATT } (^{o}\text{C}) = 3.15\ (\text{Tsp}) + 500 \qquad (3)$$

reasonably portrayed the data trend over the FATT range 100 to 300°C.

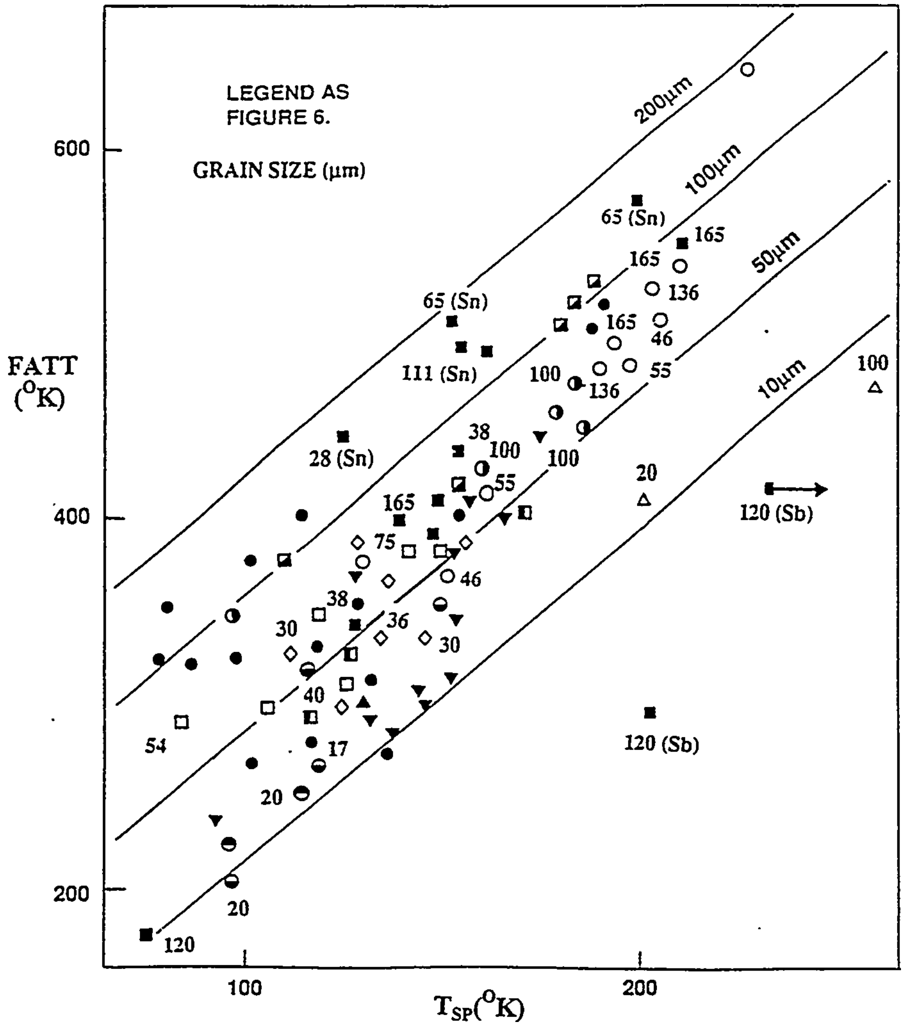

Figure 2.General FATT-T_{SP} Trends in Relation To Matsushita et als Predicted Grain Size Trends.

The other non-linear relationship, which was described by the equation

$$FATT\ ('C) = 1920000/(T_{SP})^2 \qquad (4)$$

however, gave an adequate description over the whole range of data. Certain facts were evident from fig. 1, viz., (a) the whole general data trend can be portrayed by eqn (4), (b) the Sn and Sb doped Ni-Cr steel results reported by Baik et al (1) and the CrMoV steel data of Joo et al (12) were located somewhat away from the general data trend and (c) approaching the lower limits of Tsp i.e., -150 to -200°C, the scatter in the FATT data was large and approached 200 C^{O}.

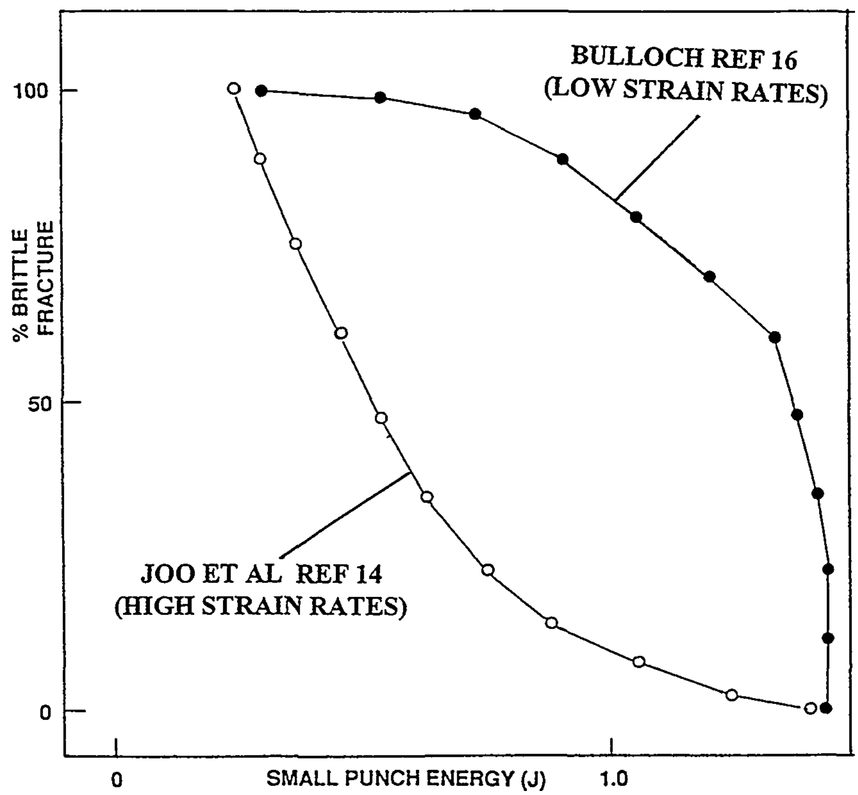

Figure 3.Fractographic Details of The Small Punch Test.

The trends from (b) above could be the result of (1) that Baik et al (1) have shown that other embrittling species than phosphorus produced differing FATT-Tsp trends and (2) the data reported by Joo et al (12) was for dynamic testing conditions where the strain rates were around one million times faster; such strain rate effects would have the effect of increasing FATT values.

Recently, Matsushita et al (10) conducted a significant study involving FATT-Tsp trends for a series of 1/2 Mo , CrMo and CrMoV steels. A multiple regression analysis was carried out to evaluate the influences of chemical composition, grain size , microstructure and hardness on FATT- Tsp trends. They established that the average grain size, d , was the only significant factor and that the Charpy FATT properties could be reasonably predicted by the following expression;

$$FATT\ (^{o}K) = 1.35(Tsp) - 26.6(d)^{-0.5} + 326 \qquad (5)$$

where d was measured in millimetres.
The predictions of this equation for various grain sizes are shown in figure 2 where it was clear that for a given Tsp level , the scatter in FATT values were predicted from grain size differences ranging from 10 to 200μm. Indeed such a grain size range was not uncommon in low alloy steels because (a) the steels are essentially not grain refined and (b) large components, such as bolts or turbine rotors, could well have variable grain sizes as a result of cooling rate differences across different section locations.

FRACTOGRAPHIC DETAILS

Baik et al (1) has recorded that at the lower shelf energy of the small punch test fracture occurred in a wholly intergranular, IG, fashion while at the upper shelf location failure occurred by a ductile fibrous or microvoid coalescence, MVC, fracture process. Lyu et al (7) have recently observed, in C-Mn steel welded joints , that failure in small punch tests occurred by (a) transgranular cleavage, TC, at low temperatures, (b) a mixture of TC and MVC at intermediate temperatures and (c) MVC at high temperatures. They further noted that the transition temperature in Crack Opening Displacement, COD, tests corresponded to a COD value of 0.25mm and at this point the first signs of MVC failure were observed. Matsushita et al (10) have conducted a significant study on a series of low alloy steels and have shown that (a) in the case of the 1/2Mo and CrMo steels a MVC process and a TC process were active in the ductile and brittle regions respectively and (b) the CrMoV steel exhibited IG failure in the low temperature region.
From the literature it was found that only two studies have reported quantitative fractographic details of the small punch test. Joo et al (14) have recently reported a detailed study on two CrMoV steel rotors, one fine grained, 20μm , and one coarse grained, 100μm. Essentially they recorded that in the brittle region the fine grained steel exhibited TC while the coarse grained steel showed IG type fracture. Furthermore, they recorded that the small punch energy-% brittle fracture trends exhibited a smooth curved relationship typical of that shown by conventional Charpy test specimens, see Fig. 3. Bulloch (16) has reported the following features for a CrMoV bolt steel (a) in the upper shelf region MVC failure occurred over the whole specimen thickness, (b) in the transition region an initial limited amount of MVC growth occurred before final brittle TC failure ensued and (c) at the lower shelf region wholly brittle TC fracture, which contained some isolated facets of rough IG failure. The initial MVC growth was semi-elliptical in nature and the extent decreased with decreasing temperature. Details of the small punch energy-fractographic trends are given in Fig. 3 and it was clear that the transition region occurred only in the advanced stages of brittle fracture i.e., at between 80 to 90% brittle fracture. Clearly these findings were different from the results reported by

Joo et al (14) , see Fig 3, which were for dynamically tested specimens where the strain rates were around two million times faster than the testing rates for the Bulloch study. At such high strain rates it was not surprising that that the fractographic characteristics exhibited good commonality with those of the Charpy test specimens which are also subject to dynamic loading conditions.

CONCLUDING COMMENTS

In terms of the FATT-Tsp characteristics of a number of low alloy steels , it has been verified that (a) the general data trend for the various low alloy steels could

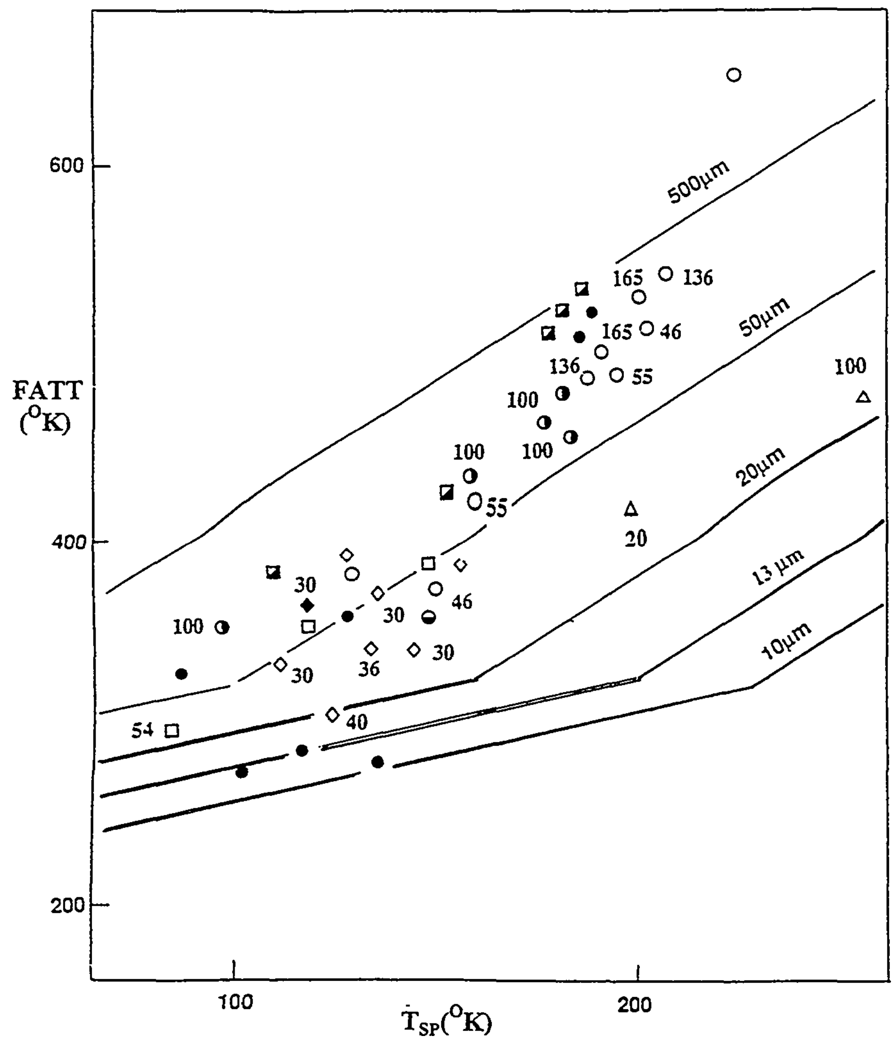

Figure 4.FATT-T_{SP} Data For CrMoV Steels.

be more fully described by the non-linear expressions of eqns (2) or (4) and (b) the data scatter could be explained by variations in microstructural grain size , through eqn (5) , over the average grain size range 10 to 200μm. However, in an effort to further reduce the data scatter (1) the steels were divided into four separate classes, viz., CrMoV, CrMo, NiCr, and NiCrMoV steels, (2) taking the average grain size effect, or vector, on FATT as 31 C^{O} per $d^{-0.5}$ for embrittled steels and only 12 C^{O} $per^{-0.5}$ for non-embrittled steels and (3) the transition point between the embrittled and non-embrittled condition for the CrMoV, CrMo, NiCr

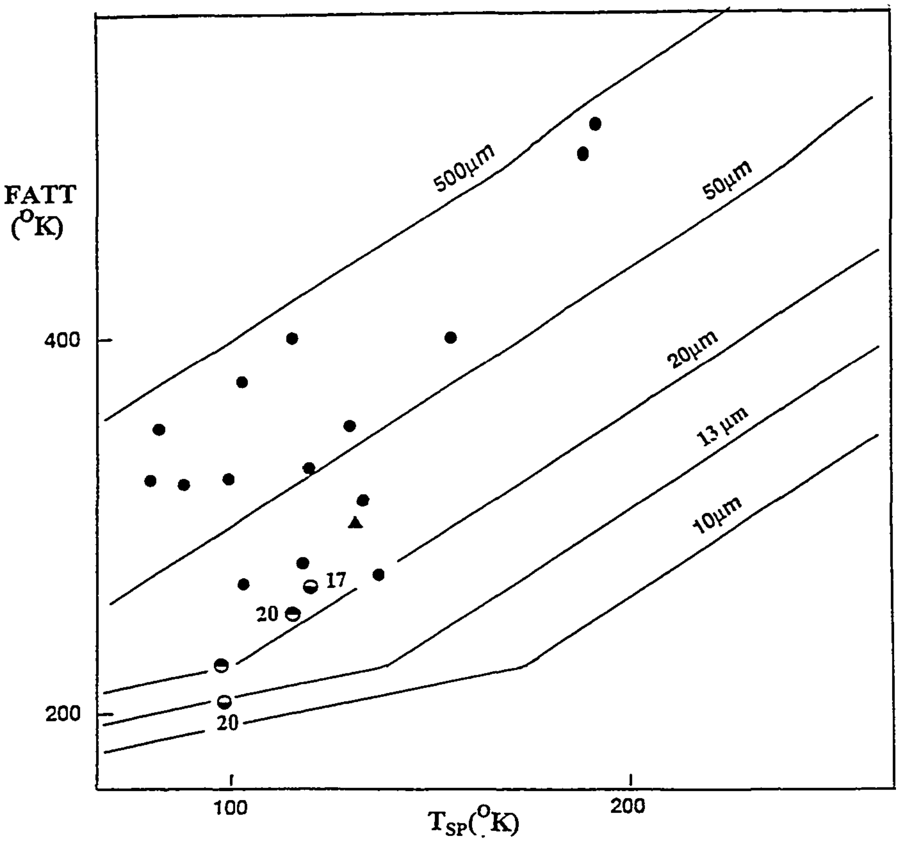

Figure 5.FATT-T_{SP} Data For CrMo Steels.

and NiCrMoV steels were assessed as 323, 223, 213 and 273°K respectively.(8, 15-18). In essence, the following expressions were used;

(NON-EMBRITTLED) $FATT(^{O}K) = 1.35\ Tsp - 12(d)^{-0.5} + 326$ (6)

(EMBRITTLED) $FATT\ (^{O}K) = 1.35Tsp - 31(d)^{-0.5} + 326$ (7)

The FATT-Tsp trends for the four steel classes are portrayed in Figs. 4 to 7 together with the predicted relationships from eqn (5), the conditions imposed by eqns (6) and (7) and reported individual grain size measurements in brackets.

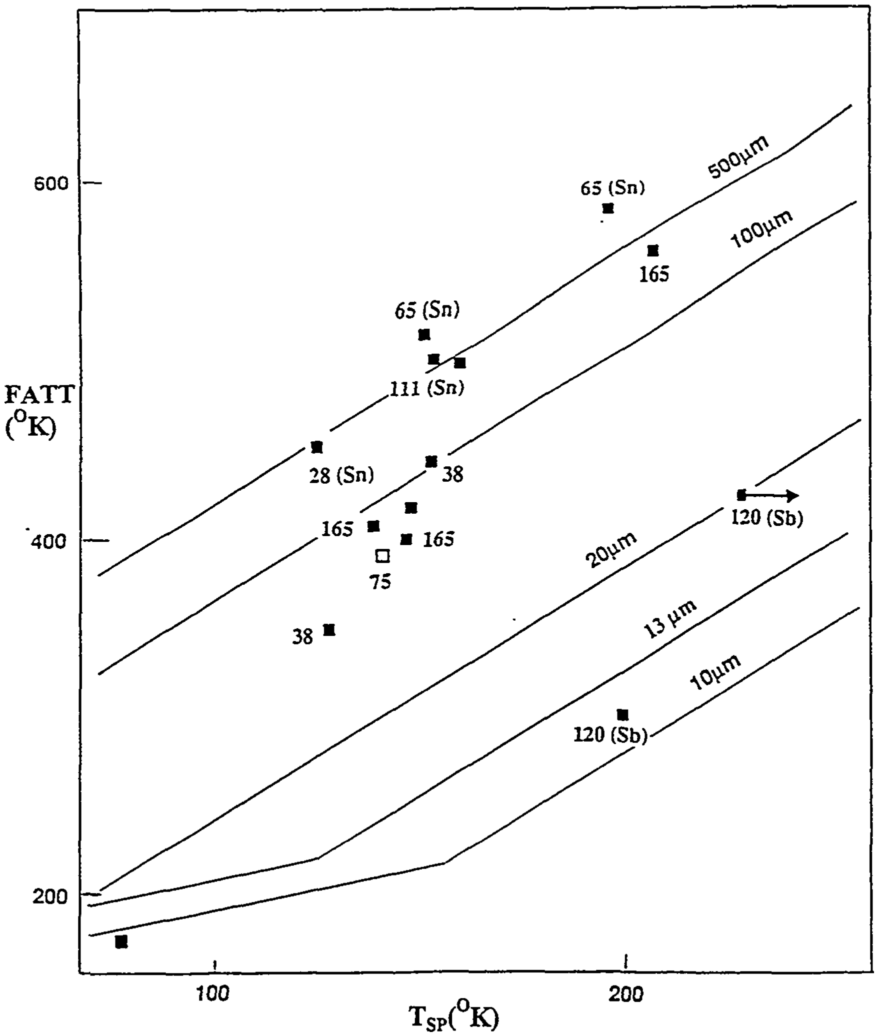

Figure 6.FATT-T_{SP} Data For NiCr Steels.

From Fig. 4 it can be seen that the CrMoV steel data spread, in both the embrittled and non-embrittled state, could be explained wholly by grain size variations over the range I0 to 500μm Indeed it was evident that many individual data points, where the grain size was known, exhibited good agreement with the predicted curves.

It was a general feature that the non- embrittled , or partially embrittled data points , had finer grain sizes than the embrittled data points and such a feature was indicative of the powerful influences that grain size , or more specifically grain boundary area per unit volume , exherts on reverse temper embrittlement behaviour. From Fig. 5 although a few individual grain sizes were known, the CrMo steel data were well described by the various constant grain size curves. In the case of the NiCr steel results , see Fig. 6 , it was clear that where was a significant influence of grain boundary segregant species in that the FATT values of the Sn-doped steels were higher than those recorded for the P-doped steels with the Sb-doped steels exhibiting the lowest FATT levels. The P-doped steel data, however, showed fair agreement with predicted trends. Indeed, even the non-embrittled data point agreed well with the 10μm grain size curve. The FATTTsp data for the NiCrMoV steels was illustrated in Fig.7 where it was evident that the small amount of data points resided within the grain size range 13 to 50μm.

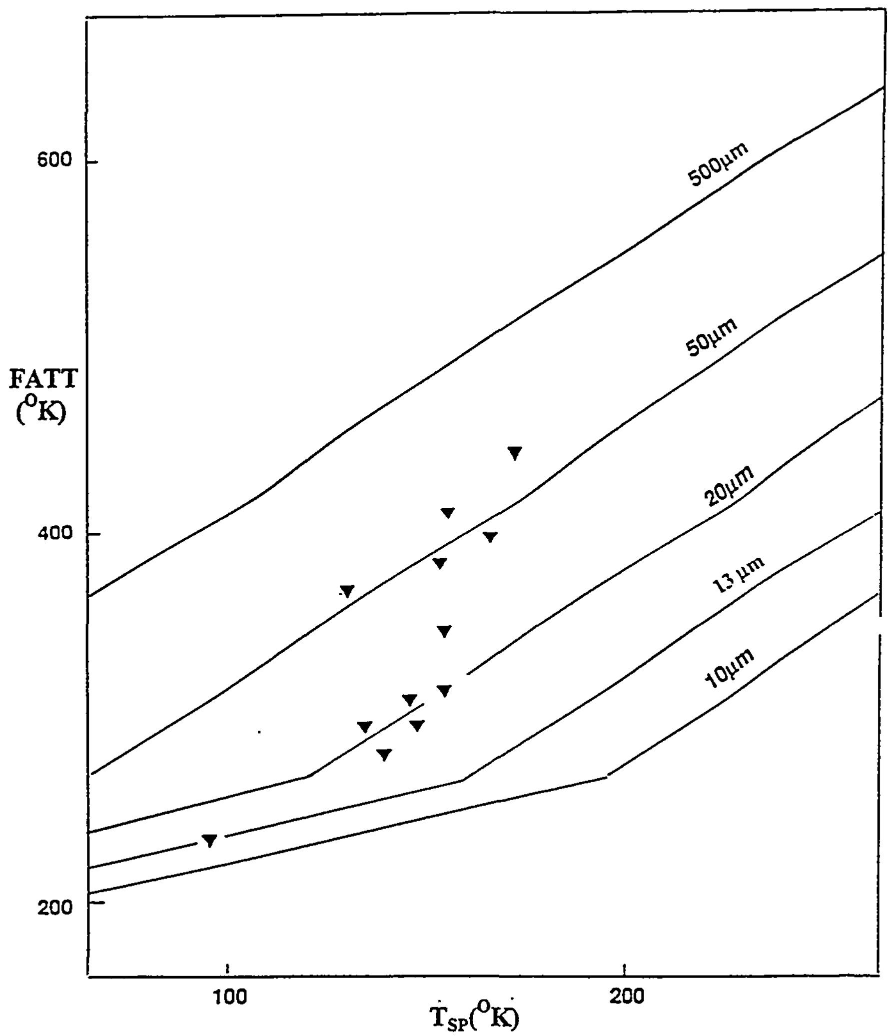

Figure 7. FATT-T_{SP} Data For NiCrMoV Steels.

Effectively, it was generally shown that the FATT-Tsp trends for all the low alloy steels could be reasonably explained by the grain size variations , implicit in Matsushita et al"s approach (10) , over the range I0 to 200µm. In terms of specific steel classes the CrMoV and NiCr steels exhibited a somewhat encouraging picture inasmuch that the predicted grain size trends showed reasonable agreement with a number of data points where the average grain sizes were recorded.

There is reasonable evidence to suggest that the influence of grain size on Tsp was not nearly as significant as its effect on FATT. Basically since Tsp was attained under material deforming conditions and Pickering (20) has reported that grain size had little effect on true strain levels because any change in grain size produced similar changes in both the yield stress and work hardening rate. Thus the data scatter, which was evident from the various figures, was most probably the result of grain size effects on FATT levels.
The fractographic details of the small punch test exhibited significant effects of strain or loading rate in that under dynamic loading the fracture trends were similar to those of the Charpy test while at low strain rates of testing the energy transition region occurred at much greater levels of brittle fracture.
Finally, the literature survey indicated significant variations in experimental factors such as punch size, loading rate, and test specimen dimensions and ,as such, some standardisation of the small punch test is required.

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SMALL PUNCH CREEP TEST: A PROMISING METHODOLOGY FOR HIGH TEMPERATURE PLANT COMPONENTS LIFE EVALUATION

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Abstract

CISE and ENEL are involved for years in a miniaturization creep methodology project to obtain similar non-destructive test with the same standard creep test reliability. The goal can be reach with "Small punch creep test" that collect all the requested characteristics; quasi non-destructive disk specimens extracted both on external or internal side of components, than accurately machined and tested on little and cheap apparatus. CISE has developed complete creep small punch procedure that involved peculiar test facility and correlation's law comparable with the more diffused isostress methodology for residual life evaluation on ex-serviced high temperature plant components. Aim of this work is to obtain a simple and immediately applicable relationship useful for plant maintenance managing. More added work is need to validate the Small Punch methodology and for relationship calibration on most diffusion high temperature structural materials. First obtained results on a comparative work on ASTM A355 P12 ex-serviced pipe material are presented joint with a description of the Small Punch apparatus realized in CISE.

1 Introduction

The Small Punch technique was applied for years at CISE to obtain the measure of tensile and thougness characteristics. It's a peculiar methodology for mechanical tests that uses strongly miniaturized specimens: diskettes of 10 mm diameter and 1 mm thickness.. A European activity was started in 1994 in the frame of a COPERNICUS program to validate the Small Punch test methodology for creep residual life under in temperature accelerated creep test of materials, [1]. The technique is understood alternative respect to the use of the traditional cylindrical specimens to obtain isostress creep curve: the general meaning is similar but the SP miniaturisation is higher than axial (1-D) specimen (also cheaper and non-destructive). CISE participates to the European consortium, that within 1995 and 1998, carry ahead the research.
Herein are shown results of a first Small Punch application for creep isostress characterisation of a steam pipe picked up from a ENEL power plant. On the same component (ASTM A335 P12 steel), was also made a creep isostress characterisation, in argon environment, on standard specimens. The obtained results, were compared and the life value was extrapolated to the service temperature, to assess the residual life of component, by means of statistic methods; the residual life and the uncertainty are obviously dependent by the number of tests and data scatter.

2 Application of small punch method to plant component

Purpose of this activity is to inspect the possibility of use Small Punch method for life assessment on plant components. The procedure we want to validate consists in doing Small Punch isostress tests and compares the achieved experimental results with those of analogous standard uniaxial (1-D) creep isostress programme. Six Small Punch tests were made for an aggregate test time of about 2500 hours. Obviously before doing tests it's necessary answer to the question: "which is the load value apply to SP specimen that get the same time to rupture than 1-D tests ? " The answer to this question is really the principal item for "SP iso-load" method.

2.1 Correlation laws

CISE proposed two different laws of correspondence "SP load vs. 1-D stress." In the first of them the value of SP load that give the same creep life as a standard cylindrical specimen under uniaxial stresses is achieved from the balance of forces:

$$\frac{F_0}{\sigma} = \left[2\pi t \left(R \div \frac{h_0}{2} \right) \sin\vartheta \right] \sin\vartheta \tag{1}$$

F_0= applied load from the punch on the SP specimen (doing the same duration as a cylindrical specimen),

h_0= thickness of the specimen (disk), (typically = 0.5 ± 0.005 mm),

R= radius of the ceramic sphere, applied at the top of the punch,

σ= uniaxial stress applied on a standard cylindrical specimens,

ϑ= angle between the upright axis and the last contact "specimen-sphere" point during the deflection process .

Sinϑ could be empirically obtained from the comparison among uniaxial and SP tests. From the tests on steel X20 in the Copernicus Project: F0/ σ= 1.876 and consequently $\vartheta = \pi/4.6$.

In the second formulation [2] the value of the load on to the SP specimen come from a different relationship describing the deflection process of the disk (applicable on large deflections).

$$\frac{F_0}{\sigma} = K\left[\pi * h_0 * d * \left(\frac{D}{d} - \chi \right) \right] \tag{2}$$

D= matrix hole diameter (typically 4 mm), d= 2R,

K= blocking coefficient : = 0.5 for not blocked condition for specimen (not pressed on the edge), and K > 0.5 if pressed (it could be 0.6÷0.8 for total block of the edge),

χ= friction coefficient, 0.6÷0.7, depending on temperature and the applied load.

With this second relationship is achieved a value of F0/σ= 1.95÷2.06, depending on tests characteristics, in not blocked conditions of specimen.
The peculiar characteristics of this model are as follow:

⇒ this relationship is based on considerations similar to those typically used for depict the plastic deflection processes on thin steel sheets (or other materials like aluminium, copper, superalloys etc.), both at room temperature than at high temperature (like pressing and deep drawing processes) and then we can use consolidate experiences on this technological field,

⇒ the material flows in some different ways depending on test temperature. In fact the "χ" parameter can be seen as a fluidity coefficient; high values (χ=0.7) are achieved at lower viscosity (low temperature and consequently high strenght at flow of the diskette into the matrix hole), while lower χ value (χ=0.6) means high fluidity depending on higher tests temperature.

To conclude, in this first experimental phase, the choice of load to apply on Small Punch tests was made following the (2) relationship, setting the value at F0/σ = 2.

2.2 Experimental aspects

For the execution of Small Punch tests is required a creep machine that allow to carrying out lower loaded tests (around 1 kN), with environmental chamber operating in vacuum or argon gas. Starting from a conventional creep machine frame, some devices like void pomp and argon equipment were added, an acquisition data system and "ad hoc device" (punch and matrix for diskette positioning) are built up on to the machine, Fig.(1). The principal characteristics of CISE Small Punch could be summarized: the machine has an environmental chamber and a one zone furnace. The load device has been deliberately realized to allow its application on a normal creep machine for miniaturized specimens. Through two brackets, like it could be seen from the constructive sketch, Fig.(2) was realized the load inversion transforming the traction procured from the weights set on the inferior plate in a compression action on the Small Punch diskette.

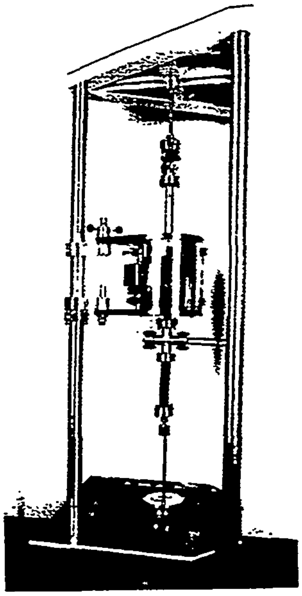


Fig.1. Small Punch Creep machine.

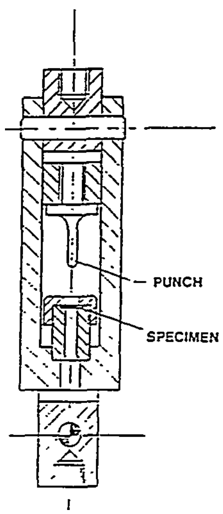


Fig.2. Small Punch device.

The adopted measure system is formed from a couple of LVDT's disposed next the load axis. This solution shows good reproducibility, fast initial setting, after load realignment, (if necessary), and finally low sensibility against accidental movement during the loading phase. It was realized an acquisition data software that allows fast acquisitions, during the load phase, in the first test minutes and toward the end, following the final penetration phase of specimens. The temperature control was made using two different K thermocouples, first of them for furnace adjustment and the second one near the specimen; we preferred don't fix the thermocouples directly onto the specimen because the weld spot could changes the local microstructure in the specimen.

2.2.1 Materials

The specimens were extracted from a piece of ASTM A355 P12 steel of the following dimensions: (ϕ= 368 mm, thickness = 20 mm). We speak about ex-serviced material (227000 hours at 540 °C under a pressure value of 40.4 Ate, correspondent to a tangential stress of 3.7 Kg/ mm^2. Drawing was made orthogonal to the tube axis, (side A, entrance flow) in the middle diameter to do comparable stresses with those of cylindrical specimens; (stresses on Small Punch diskette are plane biaxial.).

2.2.2 Small Punch specimens

Specimens are manufactured according to Copernicus Project indication paying attention to tolerance dimension and surface finish level that the diskette must

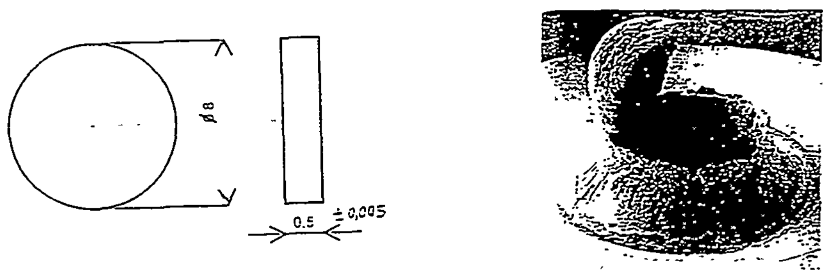


Fig.3. Small Punch specimen: new and after test.

have onto the side opposite at load application. This peculiar point is necessary to reduce the surface irregularity on the primer of cracks.

2.3 Test results

All the creep Small Punch tests are at the same load value (74 N) but accelerated on temperature (the temperature level is higher than the service temperature) to obtain creep life from few hours to 1000 hours for a total test matrix of about 2500 hours.

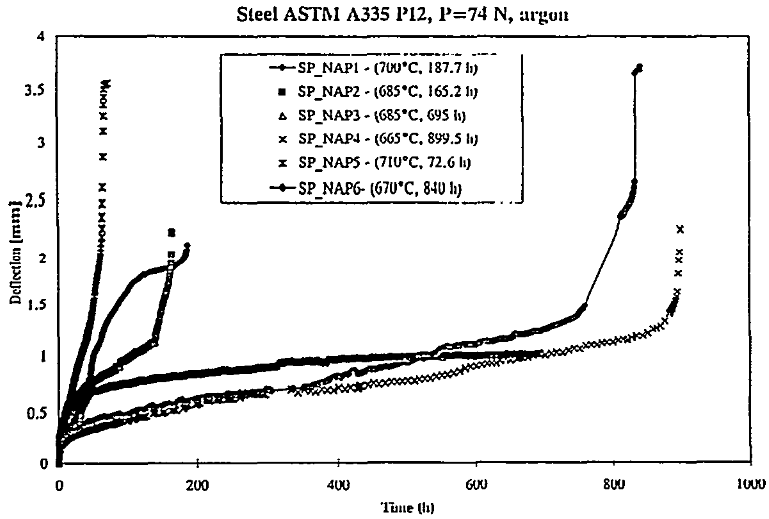


Fig.4. Small Punch tests: "Deflection vs. Time to rupture" curves.

As it could be noticed from the "Deflection- Time to rupture " curves, the SP shape is quite similar to the uniaxial creep curve. It shows three phases; primary creep with a decreasing deflection rate followed by a stationary period and finally an accelerated deflection period with macro cracks and rupture of the material.

3 Residual life method

3.1 Isostress method

The method,[3], consists in doing few creep tests (4 or 5) with a stress level equal to the service stress but at higher temperatures than service. Creep life at service conditions (stresses and temperatures) is so obtained extrapolating, at service temperature, the duration of tests made at higher temperatures.

The extrapolation follows a Manson-Haferd type law (linear dependence between T and log (tr), where T= temperature in °C and tr = time to rupture, [4]. Tests are made at a proper temperature to obtain time to rupture between few hours and some thousand of hours. The choice of test temperatures depends on a compromise among different and contrasted demands:

1. reduce the total time of test matrix,
2. the statistic meaningful of extrapolation, (that requires tests in wide temperature range),

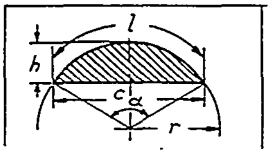
3. the existence for each material of limits for the maximum temperature for tests, beyond them change the physical mechanisms of damage,

The last point, is connected to the loss of meaning of the isostress correlation and consequently of the Manson-Haferd method changing the micro mechanisms of creep, [5].

3.2 "Small Punch vs. 1-D" compared results

The isostress method was applied to Small Punch tests. The most important creep indicators were calculated from creep isostress tests [6], but to obtain them was necessary arrange the fundamental data of the creep curve; minimum creep rate, creep ductility, - time to rupture, load and temperature.

The record of SP tests consists in mapping the punch penetration of specimen during the time. In reality the punch push the diskette and the deformation start with a deflection and only in a second phase, near the rupture, begin the real penetration phase. However, from these data we are able to obtain only the penetration rate that is not directly comparable with creep rate. For do this is necessary, as in practice happens, that during the deflection the diskette see an extension of the fibres on the traction side so, in first approximation the diskette bends with spherical radius that decrease, increasing the penetration, with fold angles ranging from 0 to 180°. According to these considerations was calculated the extension of the arc that insists on the same chord, (equal to the hole matrix, 4 mm), using the simple geometric diagram brought in Fig.5, and forward the deflection to the process rate, assuming that



$$A = 0.5[rl - c(r-h)] \; ; \quad c = 2\sqrt{h(2r-h)}$$

$$r = \frac{c^2+4h^2}{8h} \; ; \quad \alpha = \frac{57.296\,l}{r} \; ; \quad l = 0.01745\, r\alpha$$

$$h = r - 0.5\sqrt{4r^2-c^2} \; ; \quad h = r[1-\cos(\alpha:2)]$$

Fig.5. Geometric scheme for creep strain of the diskette.

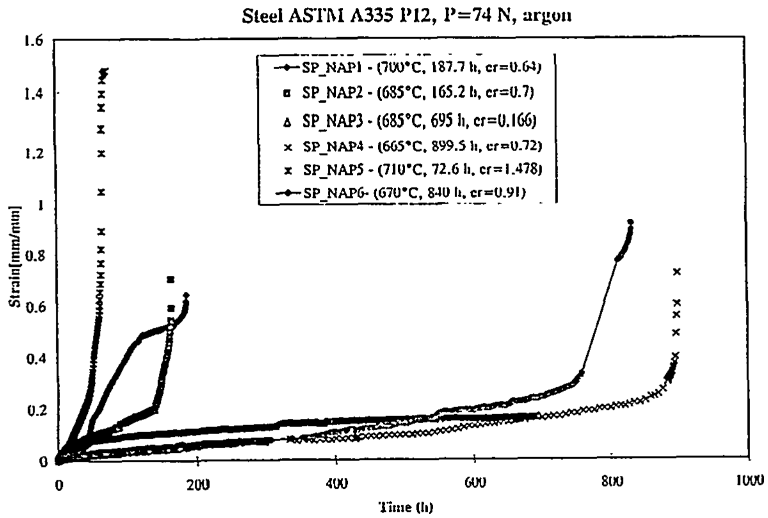


Fig.6. Small Punch tests: "Strain vs. Time to rupture" curves.

creep rate is equal at uniaxial creep rate. Fig.6 shows the "Strain vs. Time to rupture "curves and the calculated values are reported in Tab.1.

T (°C)	665	670	675	685	700	710
Small Punch Tests	SP-4	SP-6		SP-2 SP-3	SP-1	SP-5
1-D tests	1-D.6	1-D.5	1-D.4	1-D.3	1-D.2	1-D.1
Time to rupture (h)	899	840		165.2 695	187.7	72.6
	1580	968	629	399	149.5	77
εp_min (/h)	2.5E-4	2.2E-04		1.2E-03 4.5E-4	2.5E-3	3.5E-03
	4.0E-05	5.0E-05	8.0E-05	1.0E-04	4.0E-04	8.0E-04
Δl (%)	72	91		70 16.6	64	147.8
	44	47	57	52	57	64

Table 1. Creep 1-D isostress and Small Punch iso load test results. Steel: ASTM A335 P12.

Tab2 collect the values of the principal correlation's from a series of isostress tests .

		Small Punch	**Creep 1-D**
Larson-Miller	C	20.25	18.18
	PLM (avg.)	21696	25795
Activation Energy (1)	Q (kJ/mole)	503	500
Milika-Dobes (2)	constant A	7.03	7.35
	slope B	0.74	0.926
Monkman-Grant (3)	CMG ε_{min}=(/h), t_r=(h)	2.28	13.92
	slope (1/β)	-1.079	-1.034

Table 2. Principal parameters obtained from a 1-D creep isostress serie.

1) $\ln(1/\varepsilon_{min})=Q/R*(1/T)-\ln(K1)$ R=gas constant = 8.3143 J/mole
2) $\ln(\varepsilon_r/\varepsilon_{min})=A+B*\ln(t_r)$ ε_r= strain to rupture
3) $(\varepsilon_{min})*t_r$=CMG

The SP experimental date are directly poses on the chart of the preceding isostress curve of standard cylindrical specimens., Fig.7.

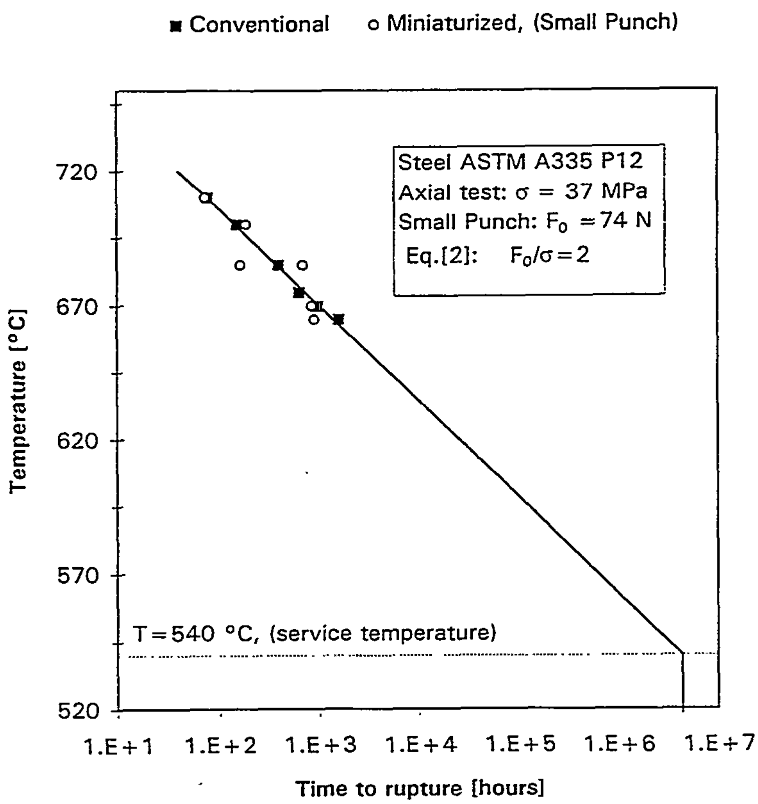


Fig.7. 1-D vs Small Punch Residual Life Assessment.

Conclusions

Here are reported results of a first Small Punch creep isostress activity made on pipelines material of ENEL power plant, (serviced for 227000 hours at 540°C and 40.4 Ate pressure value, hoop stress 3.7 Kg/ mm^2, ASTM A335, P12 steel). On the picked up peace was done a creep characterisation by means of a Small Punch isostress test series in argon atmosphere . The forecasts esteem the residual life up to rupture at 540 °C in 934000 hours. Purpose of this activity was to validate the Small Punch methodology giving a comparison with analogous experimentation made on to the same material but with creep tests on 1-D standard specimens. The obtained results are acceptable also if the values of SP life are fairly different from those 1-D; it's confirmed the wide residual life of this material. The SP method results conservative respect of 1-D tests. The value of activation energy, Monkman-Grant indicator and Milika-Dobes law confirms that is possible make reliable assessment using SP tests. The correlation law "$\sigma_{1\text{-}D}$ vs. N_{SP}" adopted permits of plan SP tests with load values to give comparable with 1-D test duration., but with a lightness higher

scatter data. However is possible reduce the scatter doing some other tests then the 5-6 commonly used for 1-D isostress characterisation.
Also if it's premature give a completely positive judgement on the SP creep method, the here obtained results are encouraging and they push toward trying other test conditions (load and temperature) and turning our attention also toward other materials.

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Computer-Aided Ultrasonic Inspection of Steam Turbine Rotors

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Abstract

As the output and economic value of power plants increase, the detection and sizing of the typ of flaws liable to occur in the rotors of turbines using ultrasonic methods assumes increasing importance. An ultrasonic inspection carried out at considerable expense is expected to bring to light all safety-relevant flaws and to enable their size to be determined so as to permit a fracture-mechanics analysis to assess the reliability of the rotor under all possible stresses arising in operation with a high degree of accuaracy. The advanced computer-aided ultrasonic inspection of steam turbine rotors have improved reliabiltiy, accurarcy and reproducibility of ultrasonic inspection. Further, there has been an improvement in the resolution of resolvable group indications by appling reconstruction and imagine methods. In general, it is also true for the advanced computer-aided ultrasonic inspection methods that, in the case of flaw-affected forgings, automated data acquisition provides a substsantial rationalization and a significant documentation of the results for the fracture mechanics assessment compared to manual inspection.

Introduction

As the output and economic value of power plants increase, the detection and sizing of the typs of flaws liable to occur in the rotors of steam turbines, as illustrated in Fig. 1, using ultrasonic methods assumes increasing importance. An ultrasonic inspection carried out at considerable expense is expected to bring to light all safety-relevant flaws and to enable their size to be determined so as to permit a fracture mechanics analysis to assess the reliability of the rotor under all possible stresses arising in operation with a high degree of accuarcy. It is crucial, on the one hand, to avoid too conserative an evaluation in view of the high cost of manufacture and the long lead time involved and, on the other hand, to rule out any disastrous losses and long outages in consequence of a brittle fracture.The rejection rate of rotors is currently still of the orders of about 5%.

An overview of published brittle fractures in rotors of torbogenerators for thermal power stations since 1910 is provided by Fig. 2. Of the total of 23 low-pressure turbine and generator rotors which failed due to to brittle fracture, natural flaws were identified to be the primary cause of the failures in 16 rotors, this means 70%.

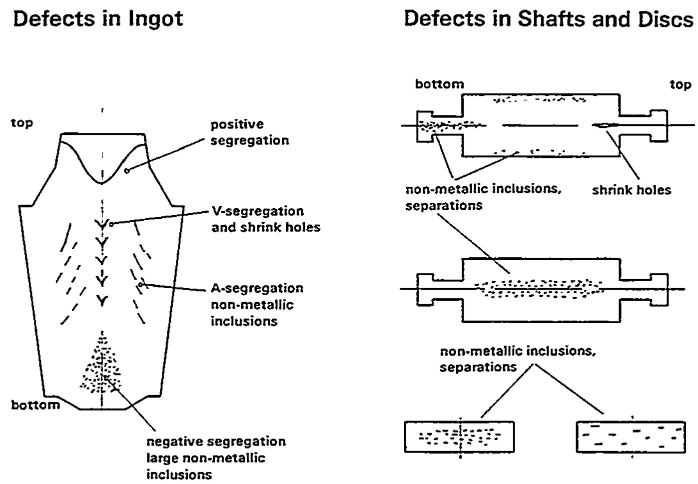

Fig. 1. Typical Defects due to Manufacturing of Steam Turbine Rotors and Discs.

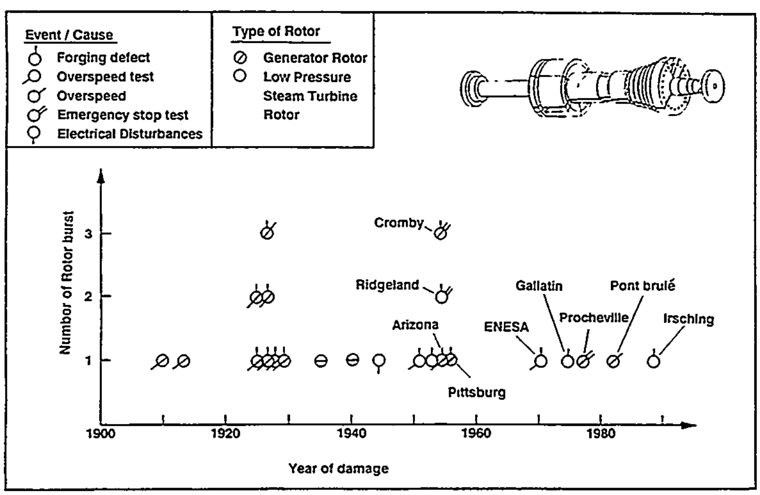

Fig. 2. Summary of Rotor Burst as a Function of Operational History and reported Causes of Damage.

The main tool for evaluating the acceptance of flaws and their effects on life expectancy is the method of fracture mechanics which was first introduced some 30 years ago and has been continually developed. An essential question relates to the accurarcy with which the size and location of the flaws can be determined by ultrasonic inspection and which improvement can be gained by replacing the manual inspection due to computer-aided inspection.

Ultrasonic Inspection of Rotors

Fig. 3 provides information on the scanning procedure used for modern ultrasonic inspection with the highest accuarcy which is possible.The minimum amount of information required to be available on flaw size for a fracture-mechanics analysis is needed on the width and length of the flaws and, in the case of flaw clusters, the spacing of the flaws is also significant. Flaw configurations with a spacing larger than the largest involved flaw are to be considered to be individual flaws. In the case of smaller spacing the individual flaws are grouped with an envelope.

Tests under the COST 505 and COST 501-2 projects were aimed at establishing the relativ degree of accuarcy afforded by the manual and the mechanized computer-aided ultrasonic inspection (1).

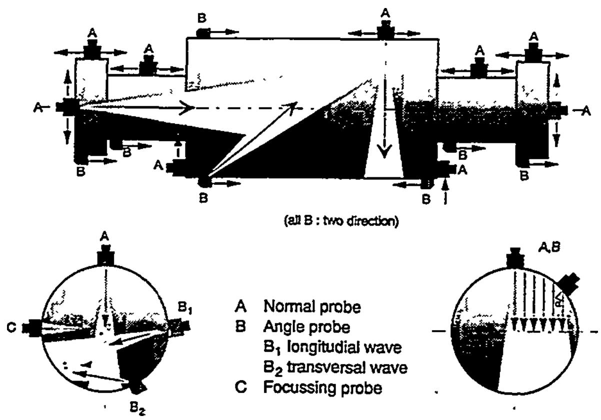

Fig. 3. Scanning of a modern Ultrasonic Inspection of a Steam Turbine Rotor.

Flaw Size Determination by Ultrasonic Inspection

Fig. 4 shows the most important inspection parameters which are currently employed to determine the flaw size and flaw space during the inspection of turbine rotors:

1. The echo height of the refector

   The reference basis is the echo height of a flat-bottom hole(FBH), whose size is known, hit perpendicularly by the sound beam. The flaw size determined by means of an empiric area comparison of the flaw with the flat-bottom hole(2). This method primarily serves to determine the sizes of small individual flaws and group indications.

2. The echodynamics of the reflector

The flaw size is determined by means of half-value width of the echodynamics curve of the reflector. In the case of reflectors which are smaller than the sound beam diameter the actual flaw extension is calculated on the basis of the diffraction theory. This method can be employed for individual flaws with a minimum extension of roughly 3 mm. Where reflectors are larger than the sound beam diameter the flaw extension is determined straight from the 6 dB drop in the echodynamic curve (3).

Physical Effect	Analysis	Type of Reflector	Remarks
Reflexion	AVG (FBH)		Reflector like Modelreflector (FBH, Stripe, Spherical)
Diffraction	Echodynamics (H, x)	Reflector Planar	Reflector smaller beam diameter, greater or equel 2 λ
Reflexion Diffraction	Echo-Drop (H, -6 dB, x)	Reflector planar volumetric	Reflector greater than beam diameter
Backscattering	Attenuation and Reflector	Reflector planar volumetric	Clusters non-resolveable, determination of flaw distance
Reflexion	Counting Echo-peaks (d)	Reflector planar volumetric	Clusters resolveable, determination of flaw distance

Fig. 4. Methods for analysing Ulrasonic Indications.

3. The sound attenuation due to non-resolvable group indications

This method is used to determine the mean interspacing of the flaws, based on an empiric correlation of the measured variables (4).

4. The echo peak spacing in the A-scan

This method serves to determine the mean flaw spacing of resolvable group indications. The method is also based on an empiric correlation of the measured variables (1).

Mechanized Computer-Aided Ultrasonic Inspection Methods

The available computer-aided ultrasonic methods werde checked and assessed by the European turbine manufacturers, forgemasters and relevant research institutes under the joint European research programme COST 501-2. Workpackage 8.2 (1).

Tests werde made on five different rejected forgings with representative ultrosonic indications or flaws. A total of ten different computer-aided methods were investigated. The project involved four turbine manufacturers, four forgemasters, one power utility and eight research institutes.

Table 1 provides a rating of the 10 computer-aided methods in comparison with the manual inspection method. As anticipated, flaws are located with more precision.

Table 1. Evaluation of Ultrasonic Test Methods for Sizing of Flaws in Rotors.

Computer aided test methods	Data Aquisition			Reconstruction Method	Imaging System
	Coordinates	Echo Height	Time of Flight		
P-SCAN	x	total A-Scan	x	B-, C-, D-Scans	Colour coding of amplitudes
DRUID	x	total A-Scan	x	B-, C-, D-Scans	Colour coding of amplitudes
VISUS	x	x	x	circles with sum - mation of possible reflector points	Colour coding of probality distribution of reflection points
ALOK	x	max. values	x	B- and C-Scans, summation of max. amplitudes	Colour coding of amplitudes and time of fligth
TUSIS	x	total A-Scan plus back wall attenuation	x	Time-Displacement - Scans (TD-Scans)	Colour coded tomogramme
L-SAFT	x	total A-Scan	x	Summation of all RF amplitudes	Colour coding of amplitudes
AMDATA	x	total A-Scan	x	Summation of all RF amplitudes	Colour coding of amplitudes
ARGO	x	total A-Scan	x	Circles with sum - mation of all RF amplitudes	Colour coding of amplitudes
ECHO TOMOGRAPHY	x	total A-Scan plus back wall attenuation	x	Intersection of RF Signals	Colour coded tomogramme
SYNTOM	x	total A-Scan	x	Rephased and summation of all RF Signals	Colour coding of amplitudes

In 6 of the 10 computer-aided methods the echo height of the flaws, as required by the the turbine manufacturers, is determined to the equivalent flat-bottom hole. The P-Scan, Druid and Tomoscan methods determine the echodynamics of the reflectors in addition to the echo height. This enables the flaw size extension to be calculated from the half-value width. In all other methods the flaws size is determined by the „isobar colour coding" or, in the case the VISUS method, by a „colour coding of the probability distribution of coincidence".

In most cases these colour images have been calibrated with the true flaw size only in isolated cases. A distinction between the reflectors according to planar or volumetric shape is possible in all methods.

The resolution ability of group indication is not enhanced in any of the computer-aided methods. They merely determine the location and size of the zones with group indications. It is, however, advantageous if the A-scans and the sound attenuation of all flaws-affected zones are stored so that the methods described above to determine the flaw spacing of resolvable and non-resolvable goup indications can be applied for the evaluation of the measuring results and the software of the inspection methods can be extended accordingly.

Compared with manual inspection the mechanized computer-aided inspection methods overall offer an improvement in the documentation and reproducibility of all relevant inspection data, such as reflector position, echo height, echodynamics, back wall echo, sound attentuation and probe coupling.
The inspection period is reduced if the inspection is carried out in several beam direction simulaneously.

The requirements for the industrial application of the investigated computer-aided inspection methods with regard to the data processing hardware, the data processing and the practical testing are met above all by the „Echotomography" and the „Tomosan" methods (5 to 7). Recently reported one forgemaster also about positiv results by using the „Scanmaster" method for the inspection of turbine discs and rotors (8).

„TUROMAN" Inspection System

The „TUROMAN" manipulation system of GEC ALSTHOM Energie consists of an inspection carriage mounted on rails located alongside the rotor shaft, - Fig. 5.

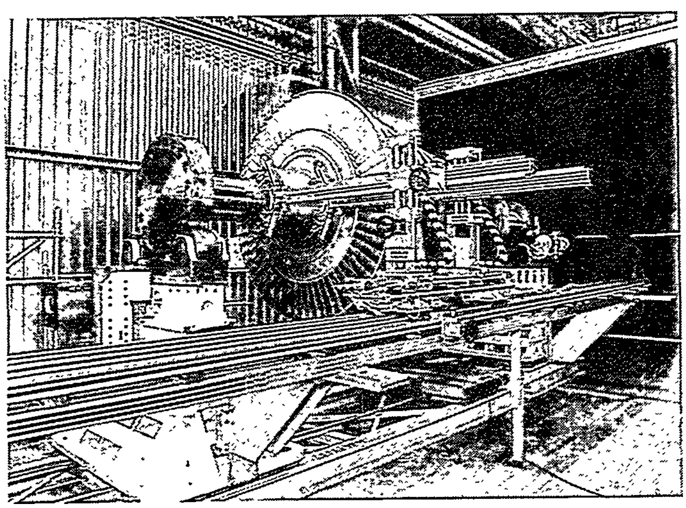

Fig. 5. Inspection Arms of „TUROMAN" each with 4 different Probes on the Surface of a IP-Rotor during an In-service Inspection.

The carriage has two arms which can be adjusted for height and distance. The probe mduls are attached to the arms. Each probe module can incorporate a maximum of four probes. In order to detect all flaws in their various orientation the turbine rotor is scanned by 8 probes with the following beam angle: 0, 7, 14, 21, 28° with longitudinal waves and 35, 45 and 60° with transversal waves, - see right part of Fig. 6. Based on the crystal sizes used and the scanning frequency of 2 MHz these beam angles result from the need for the sound fields to overlapp sufficiently in the radial-axial plane. In addition, a tandem probe system can be employed for an in-service inspection of a rotor to detect any flaws underneath the wheel discs. This system consists of four probes for different beam angles arranged on each side of the disc.

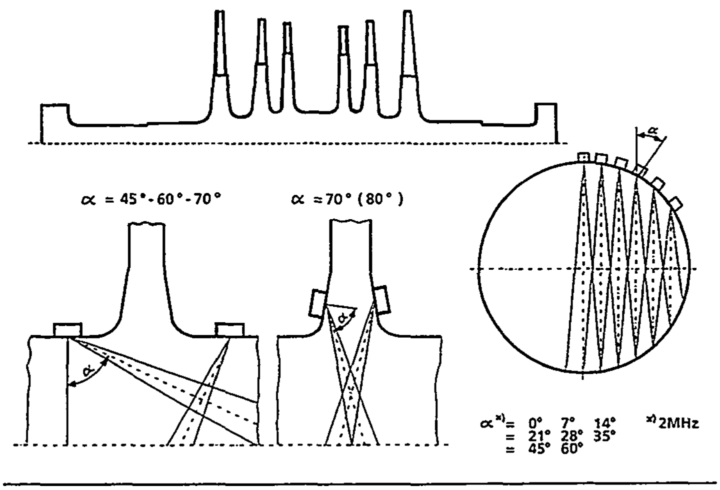

Fig. 6. Example Probe Positions and Angles of Incidence for the Ultrasonic Inspection of a Service-Stressed Steam Turbine Rotor.

The probe are coupled to the surface of the rotor by meanings of running water containing anti-corrosion additives. Detailed examination revealed that the coupling fluctuations are less than a max. of 1 dB.
Depending on ist diameter the rotor is turned on roller benches at a speed of roughly 0,5-to 2 revolutions per minutes and the inspection carriage is moved simultaneously in a axial direction, thus producing helical-shaped lines. An inspection speed of approximately 30 to 50 mm/s results in a minimum inspection density of about 1 mm, i.e. each probe emits one impulse per mm travel path.

In the case of indications the probe coordinates in relation to the rotor (axial and rotational position) together with the echo height, sound path and corresponding A-Scan are taken from the computer and processed.

The „Tomoscan" ultrasonis electronic unit enables the echo height of flat-bottom holes to be plotted irrespective of the time of flight using a correction which operates in 256 steps. This results in a rapid evaluation of echo indications by the AVG method. The back-wall echo of the component can be monitored by means of a separate gate. This provides on-line informations on change in the sound attenuation of different microstructure formations or on the degree to which the back-wall echo is influenced by flaws or flaw zones. In the case of indications all relevant data are stored, thus allowing the following evaluation options:

1. The preperation of B-Scans to define the location of reflectore in the rotor cross section

2. The determination of the equivalent flaw size of reflectors by evaluating the Echo height of the A-Scan (AVG method)

3. The preparation of C-Scans, were reflectors are plotted on a perpendicular pattern in the form of an isobar display

4. The curve of the echodynamic of reflectors detected in circumferential and in axial direction enabling the flow configuration to be calculated in radial and axial direction

5. The calculation of the indication density in the case of clouds by means of counting of the echo peaks in the A-Scan

6. The statistical calculation of indication densities versus sound attenuation

„TOMOSCAN" Inspection Results

Fig. 7 shows the method of evaluation ultrasonic indications pursuant to the inspection of a turbine rotor. All the necessary data for determining the effective flaw dimensions are shown simultaneously on the computer screen.
The top half shows the equalizing curve which enables the echo height of flat-bottom hole reflectors to be irrespective of the travel time. The curve pattern is dot-shaped according to the AVG law and permits the eco height to be corrected. The length of the grey bar (gate width) shown in the figure indicates in what range of the time of flight the echo height must be corrected. The height of this bar (gate height) shows the threshold in percent of the screen height(in this example 20%) from which the computer will take all data important for further evaluation of the indications. On the right-hand side there is another gate by means of which the back-wall echo can be monitored.

The middle section of the figure shows the A-Scan of one indication. It is the indication of a single flaw with an echo height corresponding to that of an equivalent flaw of 5mm diameter.

The C-Scan of this indication is illustrated in the lower part of the figure. By

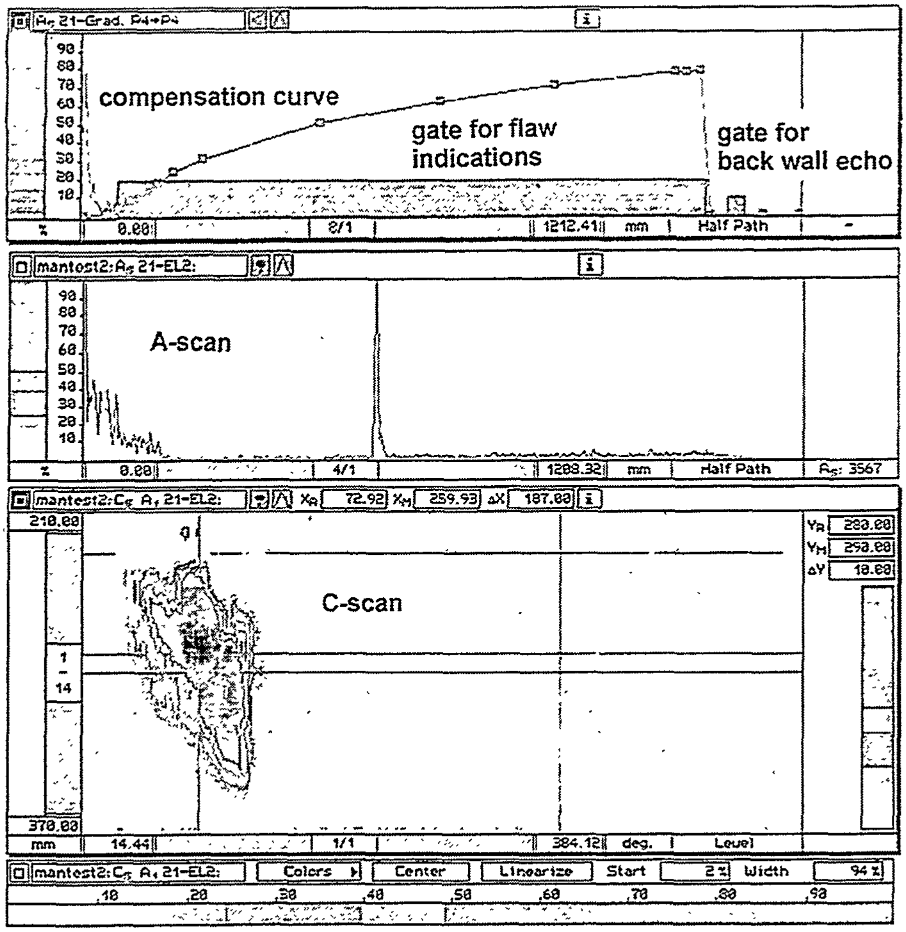

Fig. 7. Possibilities of the Presentation of the Ultrasonic Test Results with the Tomoscan System.

moving the cursor the corresponding A-Scans can be interrogated in axial and in circumferential direction. The exact position of the maximum echo height can thus be determined.

Fig. 8 illustrates another test result. In addition to the A-Scan and the C-Scan the TD-Scan and the echo-dynamics curves are shown. The TD-Scan provides a „Dynamic B-Scan“ for the characterisation of the typ of flaw. The echo-dynamics curves at the bottom of the display exhibite the circumferential and axial pattern of the single flaw.

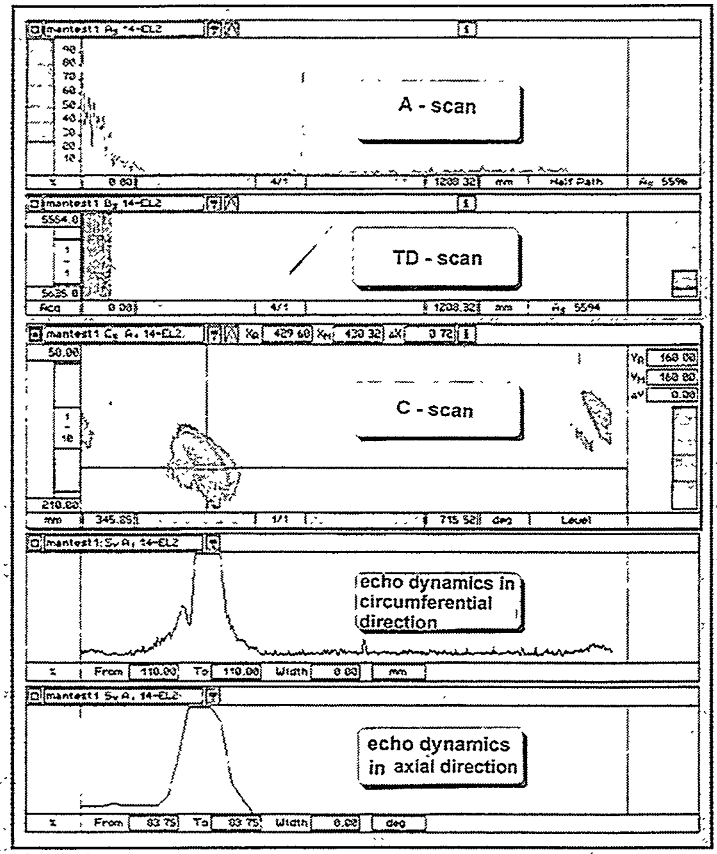

Fig. 8. Possibilities of the Presentation of Ultrasonic Test Results with the Tomoscan System.

Summary and Conclusion

In an extensive COST joint research programme the European turbine manufacturer, assisted by the research institutes and forgemasters, have investigated the available computer-aided ultrasonic inspection methods in comparison to the manual inspection of steam turbine rotors. The established results are:

- there is no improvements concerning defect sizing and resolution of non-resolvsable cluster indications

- there is an improvement in the resolution of resolvable cluster indications
- there is an significant improvement in reliability, accuracy and reproducibility
- in the case of flaw-affected rotors, the computer-aided methods afford a substantial rationalization effect compared to manual inspection
- in the light of experience gained, it is primarily the „Tomoscan" and the „Echotomography" methods that are suitable for the inspection of rotors on an industrial scale
- GEC ALSTHOM Energie found excellent results by using the „Tomoscan" system in connection with the „TUROMAN" manipultion equipment during the in-service inspection of service-stressed turbine rotors

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Ultrasonic Test of Highly Stressed Gear Shafts

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1 Introduction

In the power plant industry, gears are used for increasingly higher turbine capacities. Efficiency enhancements, particularly for the combined gas and steam turbine process, lead to an increase in stresses, even for high-performance gears. Consequently, the requirements for non-destructive material testing are on the increase as well.

At Siemens KWU, high-performance gears are used so far only for gas turbines with lower rating (65 MW) to adapt the gas turbine speed (5413 rpm) to the generator speed (3000 rpm/ 50 Hz or 3600 rpm/60 Hz).

The gear train consists of a forged and case-hardened wheel shaft and pinion shaft made of material 17 CrNiMo 6, where the weel shaft can be either a solid or a hollow shaft. Dimensions are typically 2.3 m length and 1 m diameter. As a rule, pinion shafts are solid. The gear design, calling for an additional torsion shaft turning inside the hollow wheel shaft, can absorb more torsional load surges and is more tolerant of deviations during gear train alignment. This design requires two additional forgings (torsion shaft and hub) and an additional bearing.

2 Objective

Fig. 1 shows a gas turbine station with a gas turbine of Type V64.3, gear train and generator.

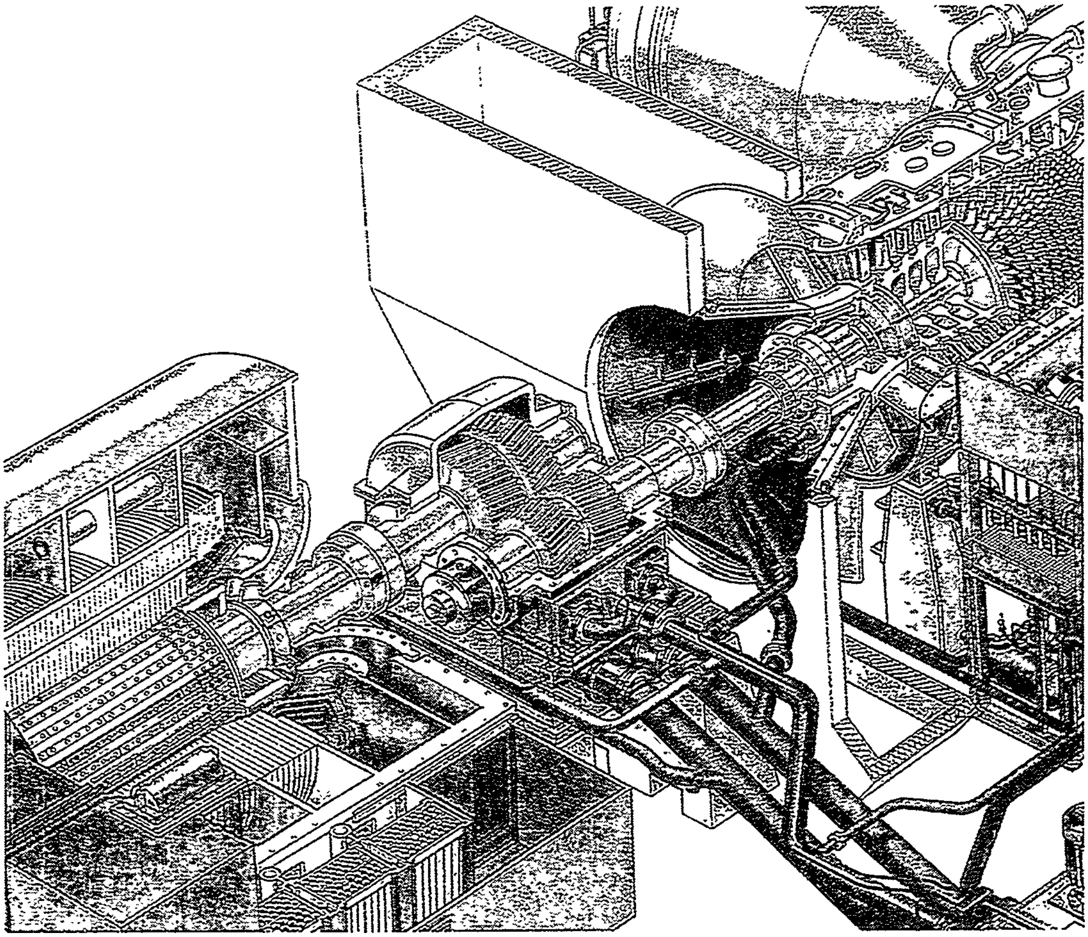

Fig. 1: gas turbine, gear train and generator.

Gears in this rating class are offered by several experienced gear manufacturers, who are qualified accordding to DIN ISO 90001. Following a demage at Leipzig /11/, Siemens KWU became more committed to place greater emphasis on the quality assurance effort during gear manufacture. A quality assurance concept, binding for all sub-contractors, was then developed and agreed upon with insurance companies and independent consultants. This concept contains, among others, the following points:

Suppliers' qualification (gear and forging manufacturers)
- process qualification
- prototype manufacture
- system and product audits

Order specifications
- delivery specifications for quality assurance, function and material
- general specification for non-destructive testing

List of documents for manufacture

- preliminary test documents with manufacturing and test sequence plan, component-specific test instructions, plans for forging, specimen location and heat treatment
- acceptance test

A general specification was prepared for the non-destructive test, with emphasis on ultrasound, which was subsequently converted to component-specific test instructions by the gear manufacturers and forges. In this general specification, which often refers to SEP 1923, such as in the case of beam entry angles and definition of echo forms, the following special design requirements are needed from the non-destructive test:

- examination of 50 % of the internal shaft volume for tangentially stressed flaws
- examination of the shafts's core region, also below the gear teeth
- highly sensitive examination of the bore surface and bore region close to the surface
- high probability of flaw detection in the critical regions

Consequently, the non-destructive test procedures and methods, the test times and the reporting and acceptance limits for indications are established in the general, non-destructive testing specification as well.

For the finish-machined wheel shafts, the traceability limit for the ultrasonic examination is about 2.0 mm equivalent flat bottom hole (EFH) in the center volume below the toothing. Since the distance from the reporting limit (3.0 mm EFH) is therefore rather small, the ultrasonic examination of such forgings requires highly qualified and experienced test specialist, who have received additional, special training on this test procedure.

3 Testing Concept

Specifications for the gear manufacturers focus on testing the shaft volume and bore surfaces of hollow shafts. Specifications for testing the gear teeth area are largely left to the gear manufacturers. In order to attain a high rate of flaw detection probability, a mechanized test with data recording is specified for the final test. The individual test procedures and methods for wheel shafts and pinion shafts and their test times are compiled in the following table. Whether there is a need for additional testing is left to the gear manufacturer's discretion.

Table: Test procedure and test times for wheel- and pinion shaft.

Machining condition	**Heat treatment condition**	**Volumetric test**	**Surface crack test**
premachined forging	pre-heat-treated	manual UT of entire volume	–
with machining Allowance, without Relief	case-Hardened	manual UT of entire volume	–
finished contour	case-Hardened	mechanized UT of volume below toothing; mechanized UT of bore	* mechanized ET of bore

UT: ultrasonic test ET: eddy-current test
*according to information from gear manufacturer

The preferred test frequency is 2 MHz, due to better flaw detection probability 4 MHz transducers may be used if the test sensitivity is not sufficient with 2 MHz or to analyse findings. In this case approval from Siemens KWU is needed prior to the inspection.

In scanning for tangentially stressed flaws (flaws with axial-radial main extension), which may also be located off-center, longitudinal wave transducers with Plexiglas wedges are used *(Fig. 2)*.

frequency : 2 MHz, longitudinal wave

scanning : radial
radial-tangential

crystal : Ø 10 mm / Ø 24 mm

scanning area : ~ 50% of the outer diameter

Example:

UT-probe	B2S-E	MB2S-E
6dB-beam angle	$\gamma_6 = 3{,}7°$	$\gamma_6 = 9{,}0°$
angle of incidence	$\alpha = 0°, 7°, 14°, 21°, 28°$	$\alpha = 0°, 12°, 24°, 32°$

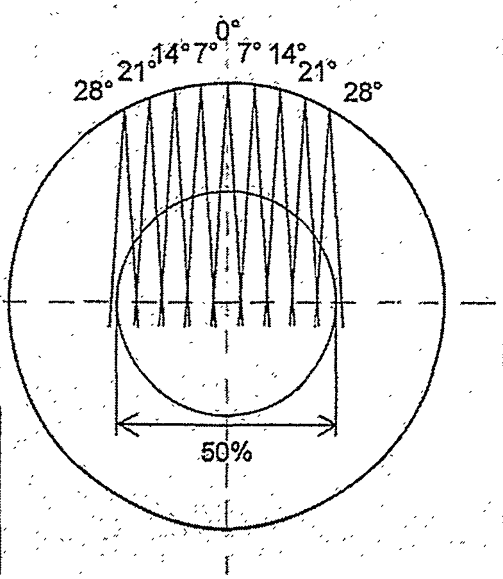

***Fig. 2:** parameters for ultrasonic test.*

Calibration takes place, according to the DGS method (distance-gain-size-diagram) with a 0°-wedge at the shaft. Beam entry angle is based on the sound field geometry (6 dB sensitivity range) of the transducer used. For the detection of flaws in the vicinity of the bore end contour, specifically for the evaluation of indications, a special beam entry angle (depending on shaft diameter and bore diameter) is used to scan the bore surface by gracing incidence.

The body range below the gear teeth is examined by coupling the transducer to the tooth tip and to the tooth flank (in case of mechanized scanning). Using transducer MB2S (10 mm crystal) for manual scanning at tooth widths of about 8 mm, the coupling face reduction on the tooth tip is taken into consideration by adding 3 dB.

4 Volumetric Test

To increase the flaw detection probability and reproducibility and in addition to the manual test *(Fig. 3)*, an UT-system was developed to carry out a partially mechanized volumetric test in the regions of the toothing *(Fig. 4)*. By comparing the results of reinspection with prior inspections a major change of findings due to the loading can be determined.

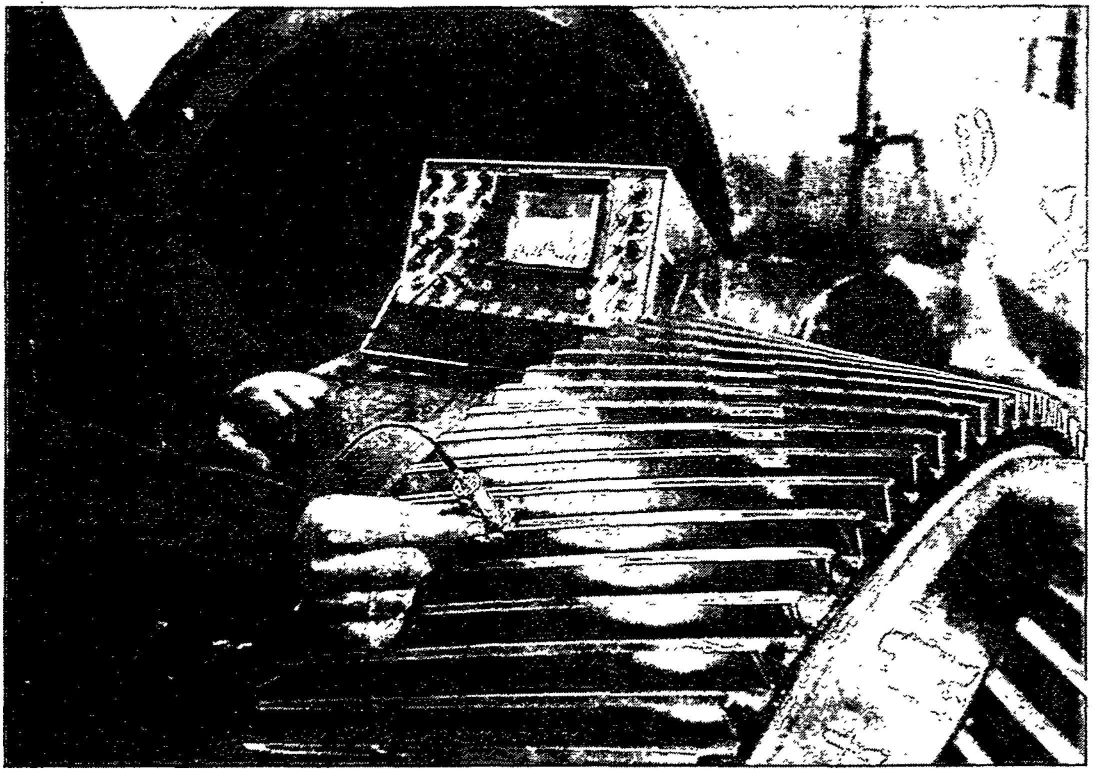

Fig. 3: manual scanning.

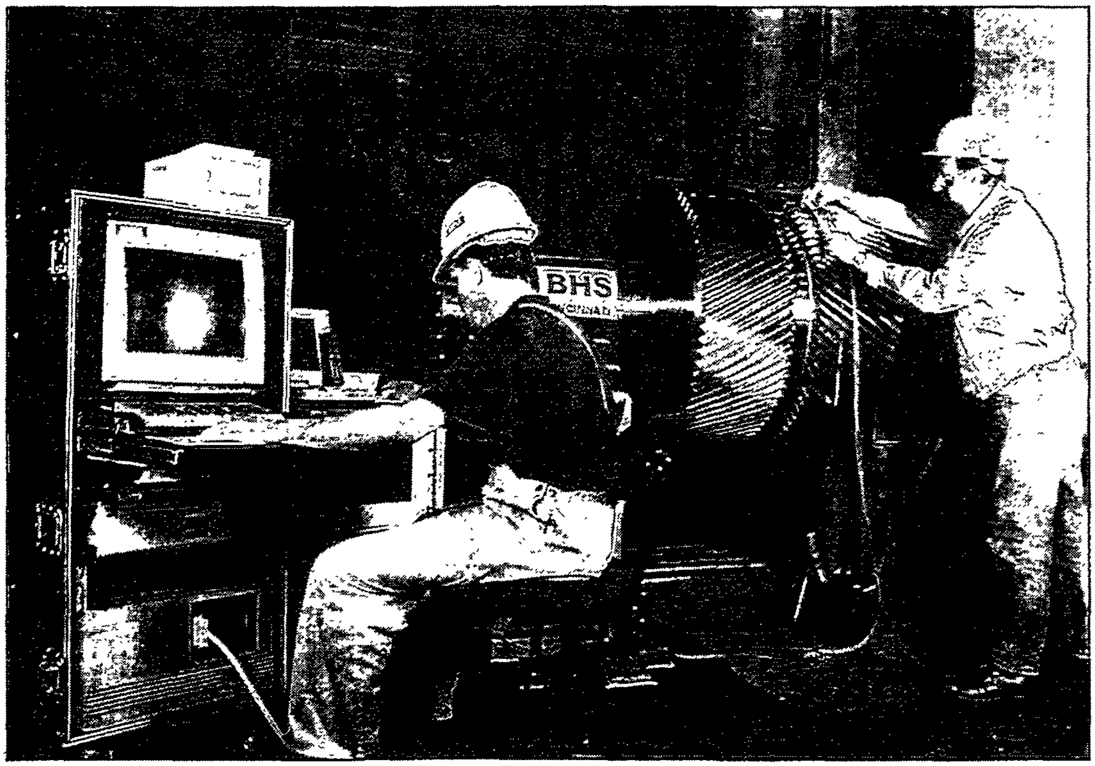

Fig. 4: UT equipment for partially mechanized scanning.

4.1 Testing Procedure

To carry out a partially mechanized volumetric test, a fixture which fits to the toothing of wheel shaft or pinion shaft was designed. Into this fixture four transducers (2 MHz) are installed, which allow access to more than 50 % of the core volume for tangentially stressed flaws. The beam entry angles are 0°, 12° and 24° for the tooth tip scanning and 32° for the tooth flank scanning.

For measuring the sound beam, for calibration and for evaluating the reflectivity of flaws, test specimen made of orginal material and original contour were used.

4.2 Carrying out the Test

The fixture with the 4 transducers is shifted two times over the entire length of the gear teeth *(Fig. 5)* to scan clockwise and counterclockwise. The position data are provided by a magnet wheel position indicator mounted on the fixture. Digitized transducer position and the complete A-scans are stored to an optical disc.

4.3 Data Acquisition

After the entire tooth length has been tested the TD-image (time displacement image) of each transducer is displayed on the monitor *(Fig. 6)*. The approach for an assessment of the data acquisition is as follows:

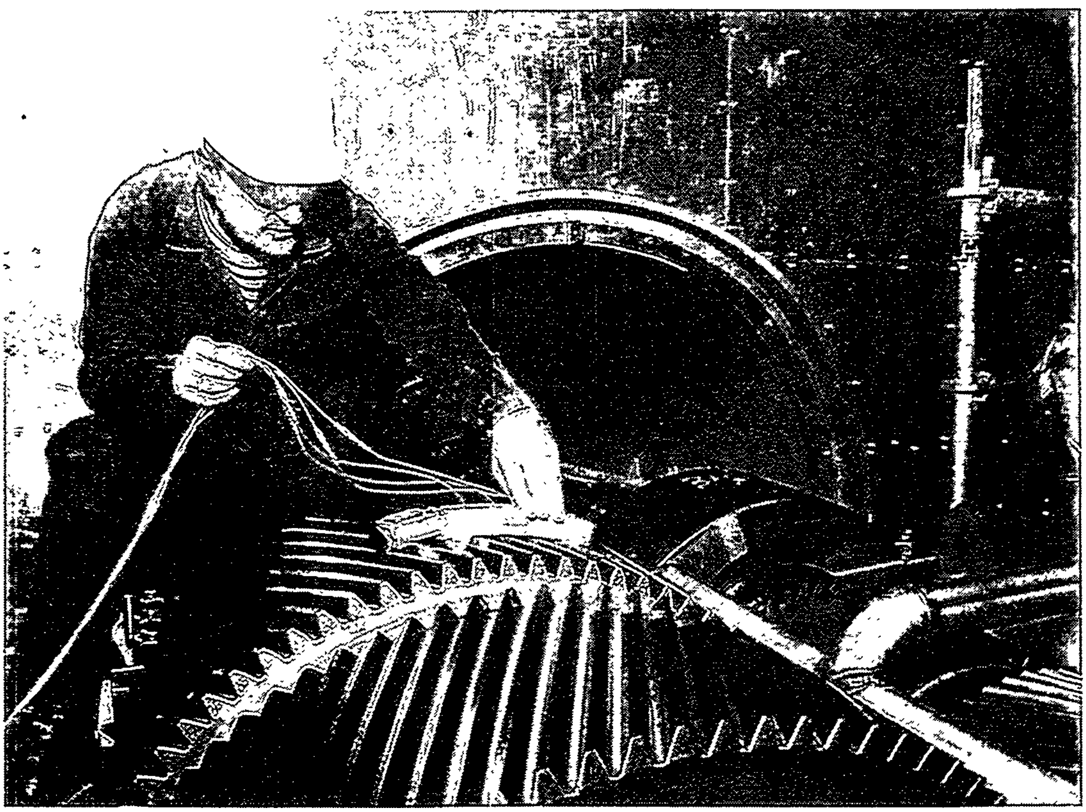

Fig. 5: partially mechanized test during outage.

- check the coupling; if inadequate, repeate the scan
- identify geometrical indications, indications from balancing bores or threaded bores, as well as surface waves
- evaluate indications
- store the scan

This approach provides a rather good reproducibility, referenced to previous tests. A 4-channel digital UT-device connected with a PC is used for data acquisition, assessment and documentation. Special software was develeoped for this application. It allows a mostly automatic assessment.

4.4 Data Assessment

There are numerous indications from the geometry, balancing bores and threaded bores which have to be separated from indication from natural flaws. ***Fig. 6*** shows relevant indications in the center volume of the body and non relevant indications from the geometry. The evaluation of relevant indications is performed based on A-scan (reflector size) and TD-image (type of indication and echo dynamics). The reflector size (EFH) is determined on basis of amplitude and sound path. The entire test range is evaluated by way of a qualified analysis procedure, where all parameters are calculated and processed.

Up to now about 45 gears have been inspected with this system during the past two years. Two test specialists need about four shifts to examine one gear (wheel shaft and pinion shaft) by manual and partially mechanized test.

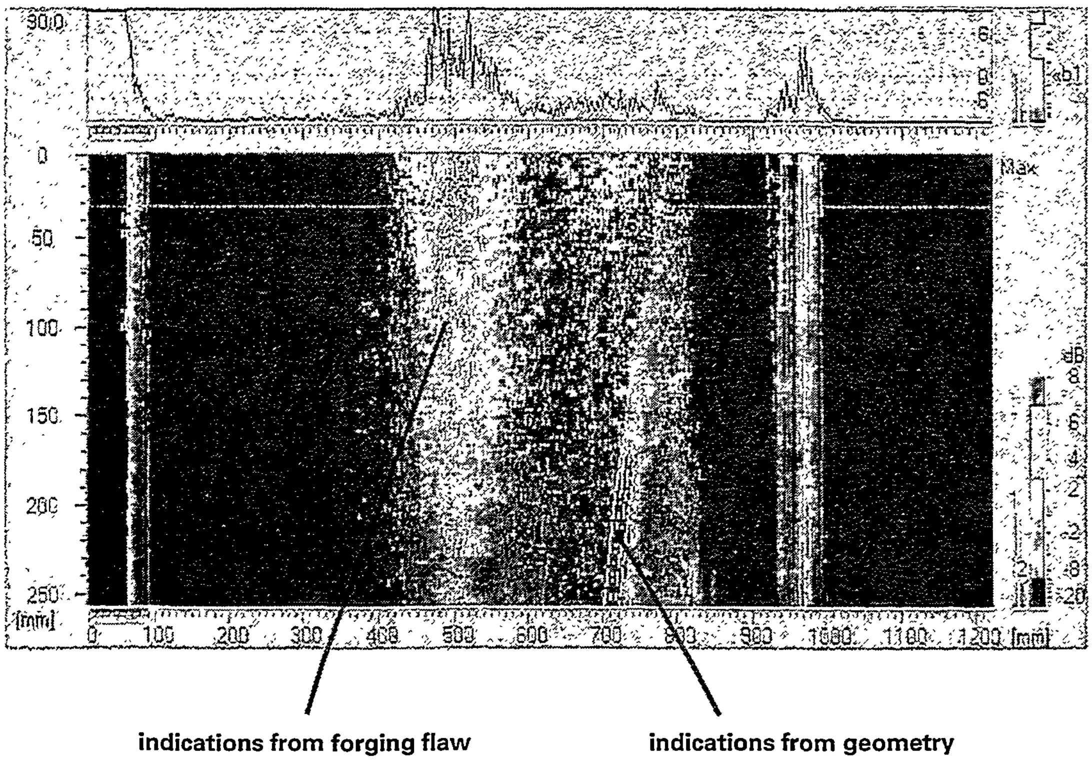

Fig. 6: TD-image from 0°-transducer with findings in the center volume.

5 Bore Inspection

Gear shafts with bores are also subjected to a non-destructive test from the bore surface. Due to nearly double the tangential stress cause by the bore, the allowable flaws in the volume close to the bore are considerably smaller than in the remaining volume.

This near bore volume is not always accessible from the outside for the ultasonic test. Furthermore, the sensitivity of the test from the outside is frequently insufficient for an accurate detection of relevant flaws at the bore surface. Therefore bore inspection is performed with BORIS (bore inspection system) using eddy current technique (ET) for surface crack detection and ultrasonic technique (UT) for testing the near bore volume.

5.1 Test System

The most important functional groups of BORIS are:

- 2-axis manipulator with PC control
- 4-channel, digital ultrasonic device
- special designed UT transducers (3 MHz, focussed)
- ET rotating probes (absolute and differential probes)
- 2-channel, digital eddy-current device
- PC for evaluation and documentation

The test system is a portable equipment, which can be used without difficulties on jobsites or in factories *(Fig. 7)*. It is possible, with this device, to test bores of a diameter range from 40 mm to 300 mm and a length of approximately 10 m. An expansion to accommodate other bore dimensions is easily accomplished.

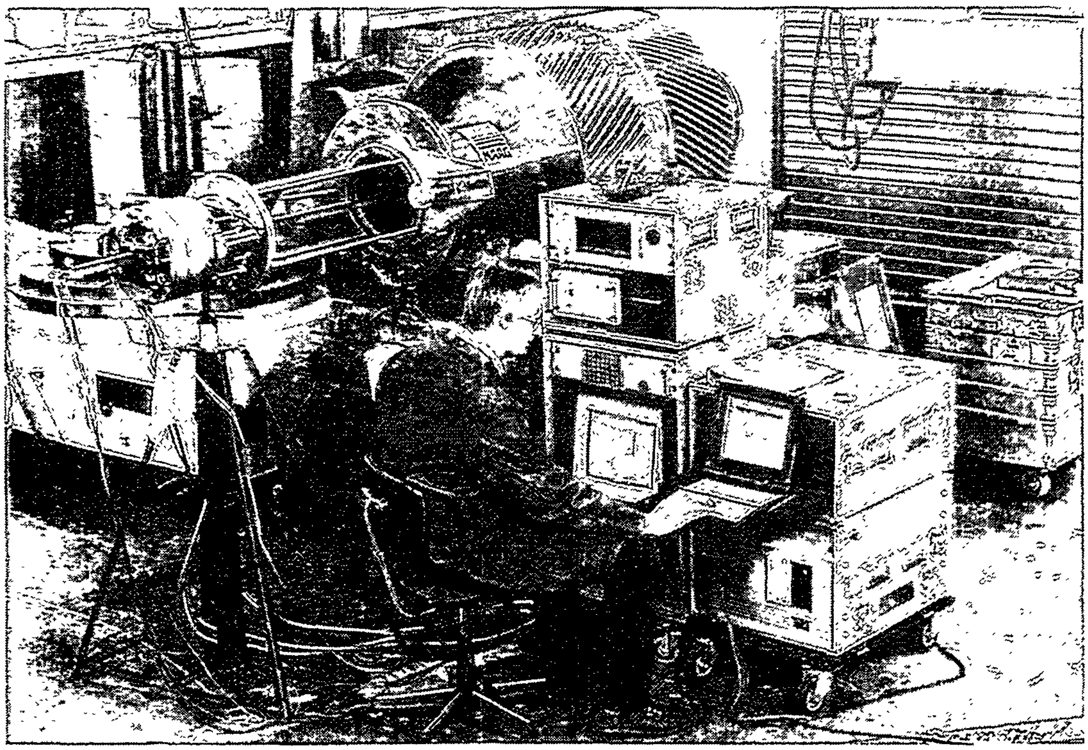

Fig. 7: equipment for bore inspection by UT and ET.

5.2 Carrying out the Test

Preparing the bore surface is of utmost importance to the test sensitivity, for the eddy current test as well as for the ultrasonic test. Prerequisite is a smooth, even surface without coating (corrosion products, lubricants, etc). In case the bore is honed, which - as a rule - leads to a surface roughness of approximately R_z = 15 µm, minute flaws can be detected (0.5 mm with ET and 0.5 mm EFH with UT). Lower surface quality grades adversely affect the detection sensitivity, primarily for ET inspection.

After the bore surface has been prepared, a manipulator is flanged onto the shaft and aligned with respect to the bore axis. A rotor *(Fig. 8)* with two ET probes (absolute and differential) is fixed to the manipulator. Dependent on the flaw length to be found, the axial track offset for the manipulator is specified. The eddy current signals are digitized and are stored to the PC together with the corresponding position data (axial and cicumferential position) of the probes.

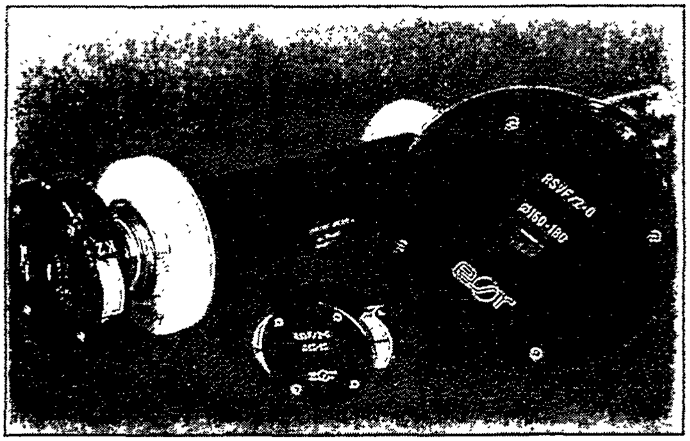

Fig. 8:
ET probes for bore inspection.

The test result is shown in the form of a C-scan. This C-scan, which respresents the development of the examined bore suface, provides the position, the orientation and the dimensions of the indication *(Fig. 9)*.

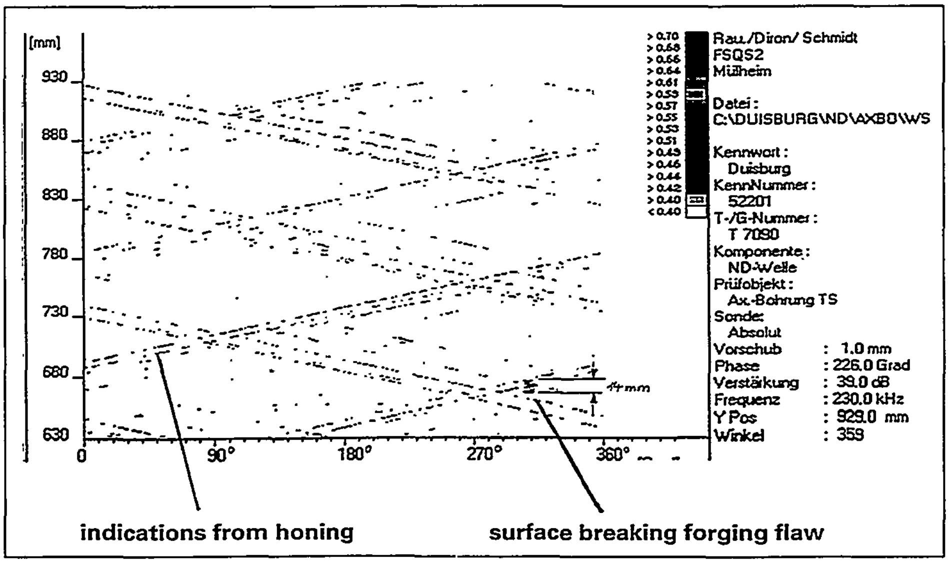

Fig. 9:
C-scan with ET findings.

Following the eddy current test, the near bore volume is tested via ultrasound. The eddy current rotor is replaced by a fixture containing 4 ultrasonic transducers. Focused angle transducers were developed for coupling to the concave bore surface ***(Fig. 10)***. Because of focused sound field, a high detection sensitivity (~ 0.5 mm EFH) is achieved on the one hand. On the other hand, the small sound field dimensions in the focus area allow a flaw size determination by way of flaw rim scanning. This analysis technology is highly significant. Customary methods, such as flaw size determination via reflectivity cannot be used, because the stress-relevant area flaws are not oriented vertically to the impact point of the sound wave.

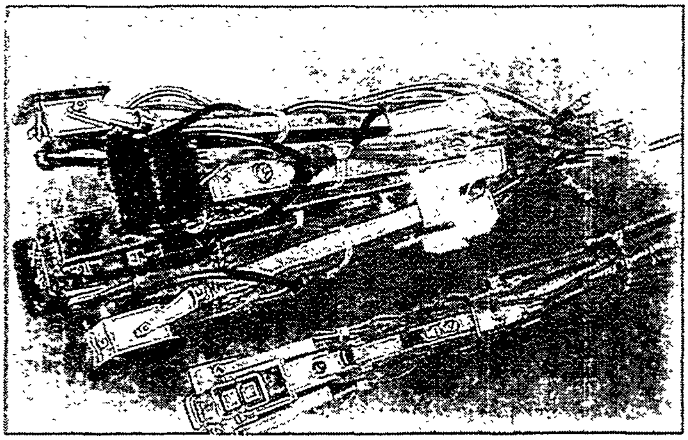

Fig. 10:
UT transducer for bore inspection with Ø 40 mm - Ø 300 mm.

The cylindrical area of the bore is scanned completely. The 4-channel ultrasonic device records all test parameters as well as the entire ultrasound information (complete A scan) for each transducer in real time. The data are stored to an optical disc. Consequently, such an efficient test procedure can be submitted for fracture-mechanical calculation in a very short amount of time.

All registered reflectors are compiled in a list containing information on position, orientatin and size. To improve the way the flaw distribution in the volume is represented, the infiltered data are reconstructed into a cross-sectional representation (tomogram, ***Fig. 11***).

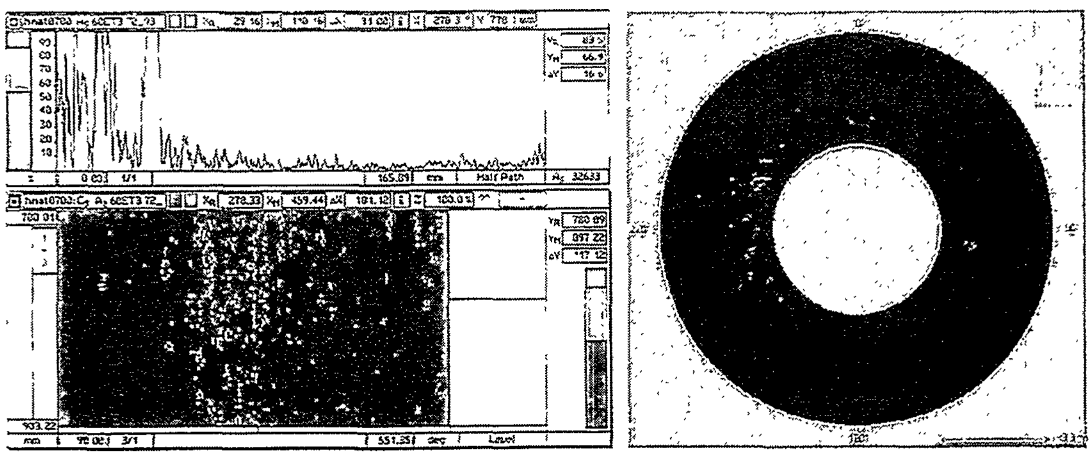

Fig. 11: A-scan, C-scan and cross-sectional representation with UT findings.

5.3 Calibrating the Test System and Proof of Guaranteed Performance

For the calibration of the ET system, test blocks are used which contain artificial flaws (grooves, holes, etc.). The test block for determining and setting the detection sensitivity of eddy current probes contains 0.5 mm – 2.0 mm deep artificial notches which were machined in longitudinal, transverse, and angled position with respect to the bore axis. For each work area (depending on diameter) of the rotating probes, a separate test block was manufactured with the appropriate bore diameter.
The differential probe as well as the absolute probe can verify the 0.5 mm deep notch with a signal to noise ratio of > 18 dB.
This rather good detection capability of the eddy current probes was confirmed using natural flaws. The eddy current test on a bore with a sectioned forging flaw agreed very well with the flaw presentation in the C scan and with the video recording of the flaw from a visual inspection per borescope.

The test blocks for calibrating the UT system contain cylinder bores (3.0 mm diameter) in the near bore volume at different distances from the surface and 0.5 mm – 2.0 mm deep artificial notches in the bore surface. The test flaws (bores and notches) are oriented longitudinally as well as transversely with respect to the bore axis.

Examinations revealed that the focused angle transducers can accurately detect surface flaws and flaws in the volume. Due to the highly sensitive transducers, the 0.5 mm deep groove is detected with a signal to noise ratio of > 18 dB.

The proof of guaranteed performance was carried out on a natural flaw (forging flaw) which had been found during an ultrasonic test of a turbine rotor axial bore. An analytical test in the area of the finding revealed that it was a longitudinal planar flaw, approcimately 25 mm from the surface. The lenght expansion of the reflector was sized by 62 mm, and the radial depth expansion was sized by 7 mm.

The decision was made to eliminate the flawed area via bottle boring. This procedure progressed in 2-mm increments, where the surface was examined after each step by way of magnetic-particle testing and video borescope. Agreement of the incrementally exposed flaw with the ultrasonic result was very good. Confirmation was obtained that the flaw size determination (radial depth expansion and length) per ultrasonic corresponds well to the real flaw dimensions (length: 58 mm; radial depth expansion: 6 mm; distance to surface: 26 mm) within parameters of physically caused inaccuracies.

So far, approximately 500 bores have been examined, specifically on steam turbine / generator rotors. Two test specialists need about three shifts to examine one gear shaft bore.

6 Summary

The non-destructive examination is part of the quality assurance concept for procurement of highly-stressed gear shafts. The quality assurance concept contains a standard non-destructive test specification, which has been established in cooperation with insurance companies and independent consulants. Therefore, it can be considered state-of-the-art technology.

The test systems presented here can be used not only in detecting but also sizing operation-relevant flaws. Because digital instrumentation technology is used in conjunction with optimized ET probes and UT transducers, a high level of detection reliability and reproducibility can be attained. Support provided by computers for data evaluation can make the test result, containing position and dimensions of flawed area, available in a very short time.

7 Literature

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The application of RBI-concept to ultrasonic measurement of fatigue cracks

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Abstract

In many power plants there are problem areas, which are not included in the official inspection programs. Flaws can be induced during service due to the service conditions in components and welded joints. These can lead to failures, which cause unforeseen shutdowns during operation and unscheduled repairs have to be carried out. The basic idea of Risk Based Inspection (RBI) methodology is to include this kind of objects in the inspection program. In this presentation two possible objects for RBI are described - thermal fatigue cracking in process piping and fatigue cracking in spinning fly wheel.

1 Introduction

It was assumed in the past, that flaws will occur both topologically and chronologically more or less randomly in the components. Later on it was noticed that flaws occur mainly in the locations where there are high stresses and high fatigue loading. Typically this kind of locations are in structural transition joints.

Recent experience has shown that degradation due the stress corrosion and flow accelerated corrosion are of great importance in different failure cases detected in piping (Ammirato, 1997).

Formation of thermal cracks is based on alternative loads, which are caused by the changes in the temperature of the surface of the material. These temperature gradients have to be large enough to cause stresses which go beyond the yield strength of the material. The stress variations cause local yielding on the surface and when this stress variation is strong enough a continuous crack growth starts. The higher the frequency of stress variation the smaller the surface layer affected. This means that lower frequencies affect deeper in the material.

Thermal cracks usually form a crack field (mosaic structure) where several cracks having random orientation are located close to each other. For ultrasonic testing this type of crack field offers remarkable challenges. In manual testing the random orientations of cracks are difficult to cover and the separation of individual cracks locating close to each other is difficult. The ultrasonic signal seen on the screen of UT-equipment may contain simultaneously information from several cracks. Therefore a lot of expertise is needed in the evaluation of results.

In this paper the thermal cracking of an austenitic piping material AISI321 with wallthickness 28 mm is discussed. This austenitic piping contains one inlet nozzle of gas which has considerably lower temperature than the fluid circulating in the piping. A thermal crack field has been formed near the inlet nozzle in the direction of the fluid flow. The cracks itself are circumferential. The largest crack has caused a leak in the pipe. The pressure in the pipe is about 150 bar.

There are 2 possible reasons for high stress concentrations in certain locations in the spinning fly wheel: high stress intensity because of the high spinning rate per minute (centrifugal force) and high axial force caused by the water pressure on the rotor wheel surface. Electromagnets are used to compensate this axial force. The location of highest stress intensity in this kind of wheels is calculated to be at the upper corner, see Fig 6.

2 Equipment and sensors

For the thermal fatigue crack field measurements a digital portable ultrasonic equipment and a PC-based SAFT-system were used. The PC used in the measurements contains an ultrasonic card for data-acquisition and a SAFT- reconstruction software for the visualisation of data, Fig.1.

Figure 1. One-channel ultrasonic equipment for mechanised inspections.

The ultrasonic probes used in the measurements were a single crystal mode conversion probe for manual measurements and 55°T and 65°T composite probes for measurements with the hand-scanner.

The hand-scanner is shown in Fig. 2. In to the handscanner incremental encoders were attached for the localisation of scanning movement in 2-axis. With the hand-scanner either axial or circumferential scanning can be performed. The scanning direction can be changed. One of the major advantages of the scanner is that it can be easily mounted on pipes or on flat surfaces. During scanning the "touch" of ultrasonic inspection is kept all the time. The hand-scanner is originally designed for more accurate and reliable evaluation of indications than can be achieved in manual evaluation.

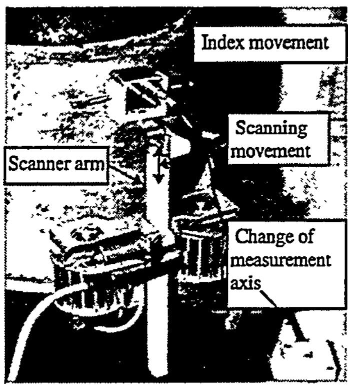

Figure 2. The hand-scanner for 2-axis scanning.

For spinning fly wheel inspection EMAT-equipment and SH-transducer (Shear horizontal transversal wave) were used. The frequency of the transducer was about 700 kHz. Shear horizontal wave was generated just below of the surface.

3 The measurements

In the manual inspection of austenitic piping a thermal crack field was detected. This field was formed by a lot of cracks having different sizes. The cracks were detected with a mode conversion probe. In the manual measurement all the cracks could not be clearly distinguished. The component was afterwards measured also with the hand-scanner and from this measurement the SAFT-reconstructions are shown in the C-scan and B-scan images in Fig. 3. In these measurements the different cracks could be distinguished and their sizes can be estimated either from the crack tip indications or from the summation of crack face indications. This crack field contained also smaller cracks detected manually but they were not in the volume measured here.

From each scanning line a SAFT-reconstruction was made. The line SAFT-reconstructions were combined in the C- and B-scans images shown in Fig. 3.

B-scan evaluation can be performed separately if indication is detected. The back-wall of the pipe is clearly seen. The crack face formation of the first crack and even the crack tip can be detected. If required, the reconstruction area can be restricted to contain only one reflector and all possible ultrasonic effects occurring can be evaluated, Fig. 4.

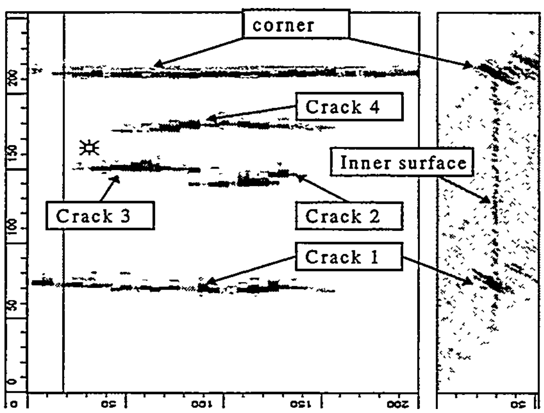

Figure 3. A measured thermal fatigue crackfield visualised with SAFT-reconstruction.

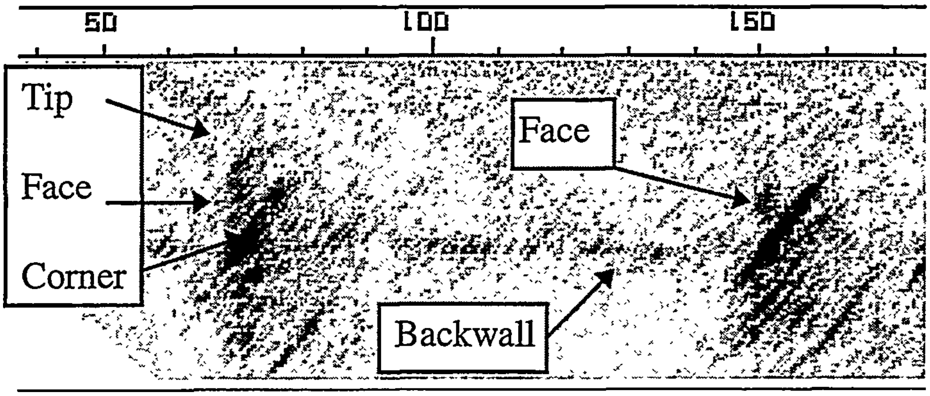

Figure 4. B-Scan SAFT (line SAFT) reconstruction.

The effects of ultrasonic signals interacting with a crack can be seen in B-scans of Fig. 5. The reflection from the crack face can be calculated to the correct position where these indications are created. It is important to notice that actually no tip signals can be seen in Fig. 5A. In this case the face reflections are more important. The heights of these indications vary from 6 to 10 dB above the noise level. With the help of the SAFT-reconstruction the S/N-ratio can be improved considerably. In Fig. 5 the raw data from some cross-sections of the pipe is shown. In Fig. 5B only tip reflections are seen and there are no reflections from the face of the crack. The both indications can also be seen at the same time as shown in Fig. 5C. All these measurements have been performed with a real thermal crack field and show that crack indications do not always have the same type of pattern.

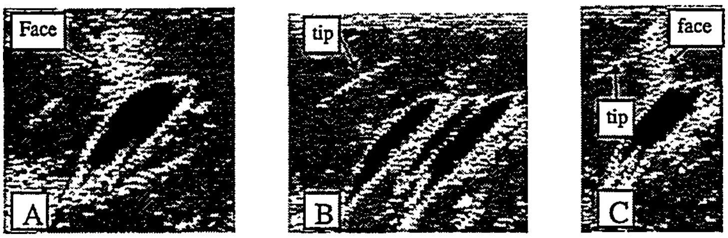

Figure 5. The interactions of the ultrasonic fields with real cracks are revealing different effects.

Corner reflection indications are always present, but for the accurate sizing of a the crack more information is needed. The heights of the corner reflections vary from 15 to 30 dB above the noise level with the probes used (55T,65T).

The calibration defect was electro-discharge machined into the spinning fly wheel, Fig. 6. The measured signal from the calibration defect is seen on the screen in shown in the Fig. 6. The advantage of the electromagnetic acoustic (EMAT) -technique is that SH-waves propagate long distances without attenuating strongly. The waves concentrate in the near surface zone, where the possibility of crack formation is highest. The SH-waves hit the calibration defect perpendicularly.

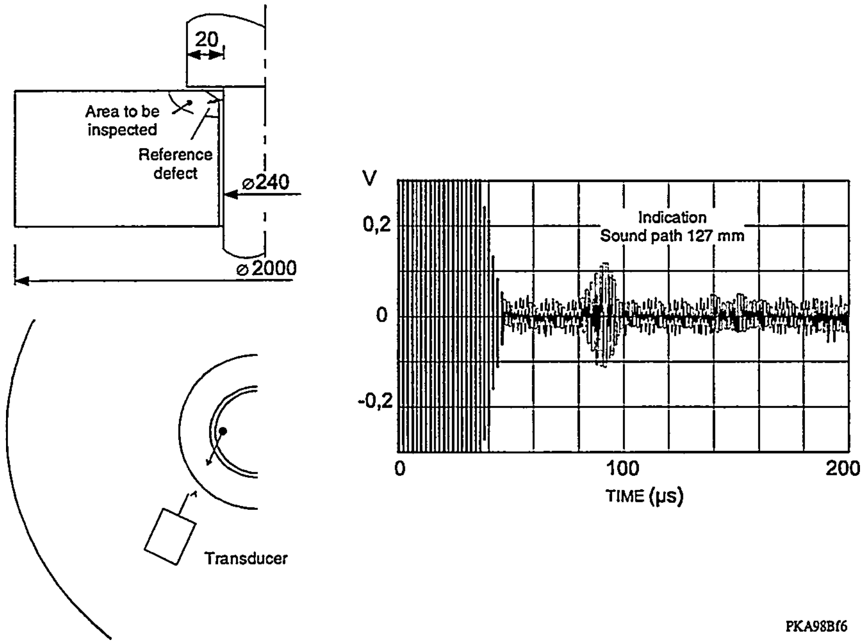

Figure 6. EMAT inspection of the fly wheel

4 Discussion

The application of RBI-approach to selection of additional items in the inspection program is an important tool to improve the safe operation of industrial installations. In the case of thermal fatigue cracking RBI-approach could prevent serious damages during service. In the inspections of spinning fly wheels no flaws have been detected so far.

The manual measurement of a thermal crack field by ultrasonics is a difficult task. On the other hand, a totally mechanised inspection is difficult to realise. With the help of a hand-scanner that is easily mounted on the item to be inspected the inspection time can be de-creased and an accurate inspection comparable to a mechanised inspection can be performed.

All the ultrasonic interactions occurring in the material can be visualised with the help of a suitable software. SAFT-reconstruction offers one possibility to combine the data measured for evaluation of indications.

In this paper the effect of a crack to the ultrasonic signal measured was discussed. In some cases only the crack tip is seen on the screen, in some other cases the crack face or even both crack tip and face can be recognised on the screen. These different possibilities have to be carefully considered when deciding the details of the inspection technique and the ultra-sonic probes that will be used in the inspection.

EMAT-technique with SH-waves is used for crack detection because the long distance to the supposed crack location prevents the efficient use of Rayleigh-waves. The sound path is also long because the orientation of the crack is radial and sound field must be as shown in Fig. 6. The use of SH-waves is a very practical solution to the inspection of spinning fly wheel.

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New Unified Fracture Toughness Estimation Scheme for Structural Integrity Assessment

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Abstract

At present, treatment of fracture toughness data varies depending on the type of data (K_{IC}, J, CTOD) that are available for fracture mechanics analysis. This complicates structural integrity assessment and makes it difficult to apply any single, unified procedure. Within the Brite-Euram project 'SINTAP' a fracture toughness estimation scheme has been developed for the unified treatment of data for use in structural integrity assessment. As a procedure, it can be applied to Charpy data, as well as to fracture toughness data, and is suitable for the treatment of data at both single and different temperatures. The data sets may contain results from both homogeneous and inhomogeneous material, making the procedure applicable also to welded joints. The procedure allows fracture toughness assessment with quantified probability and confidence levels. Irrespective of the type of the original data, one material-specific K_{mat} value representing a conservative estimate of the mean fracture toughness is obtained (with its probability distribution). This information can then be applied to structural integrity assessment.

1 Introduction

At present, treatment of fracture toughness data that are to be used in fracture mechanics analysis varies depending on the type of data (K_{IC}, J or CTOD) that are available. This complicates structural integrity assessment and makes it difficult to apply any single, unified procedure. Particularly regarding welds, significance of material's inhomogeneity (LBZs) in terms of quantified probability and confidence levels is not encountered in structural integrity assessments in a unified manner. In the cases where fracture toughness data do not exist and cannot be easily obtained, it is necessary to base the estimate on Charpy data via the use of appropriate correlation between Charpy energy and fracture toughness. Many of the existing correlations, however, may only be applicable to a certain part of the transition curve or a small range of materials or just parent plate.

Within 'SINTAP', the aim was to develop a fracture toughness estimation scheme [1,2] for the unified treatment of various forms of toughness data for use in structural integrity assessments. Formulated to a procedure, one material-specific toughness parameter, K_{mat}, together with its probability density distribution $P\{K_{mat}\}$ is defined, irrespective of the type of the original data. For assessment against brittle fracture, the procedure is based upon the maximum likelihood concept (MML) [3] that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. As a result, a conservative estimate of the mean (50 %) fracture toughness (and the distribution) is obtained.

The present methodology can be applied to indirect (Charpy) data [2] or to actual fracture toughness data [1] and is suitable for treatment of data at both single and different temperatures. This way, a reliable estimate can be obtained for various forms of data sets containing results from both homogeneous and inhomogeneous material. Thus, the Procedure is expected to work well not only for base materials but, in the case of welded joints, for weld metals (WM) and heat-affected zones (HAZ). For the cases where the design of a structure against brittle fracture is not necessary, reference [4] is made to a separate approach.

The procedure represents a user-friendly step-by-step methodology which allows a reliable fracture toughness assessment with quantified probability and confidence levels. The work within 'SINTAP' is currently progressing towards the aim of establishing a unified European procedure for structural integrity assessment tailored towards the practical user.

2 Indirect Determination of Fracture Toughness

In reality, direct fracture toughness data are often not available and cannot be easily obtained, making it necessary to base the estimate of fracture toughness on the Charpy impact energy (Cv). Since no single correlation can be applied to all parts of the toughness transition curve, the SINTAP Procedure provides the following options [2]:

(i) A lower bound correlation for brittle (lower shelf) behaviour
(ii) A statistical method for the transition regime (The 'Master Curve')
(iii) A lower bound correlation for the ductile (upper shelf) behaviour.

Within this framework, guidance is also provided for:

(i) Determination of the Charpy 27/28 J temperature (T_{28J}) from data at other temperatures
(ii) Conversion of J and CTOD values into equivalent K_{mat} values
(iii) Quantification of the influence of strain rate
(iv) Treatment of Charpy data determined on sub-size specimens.

The principles of the treatment of Charpy data are described in [2] and shown as a flow-chart in Fig. 1. The selection of the appropriate correlation is based on knowledge of the expected operating regime of the material (brittle/ductile), and on the quality of the Charpy data that are available.

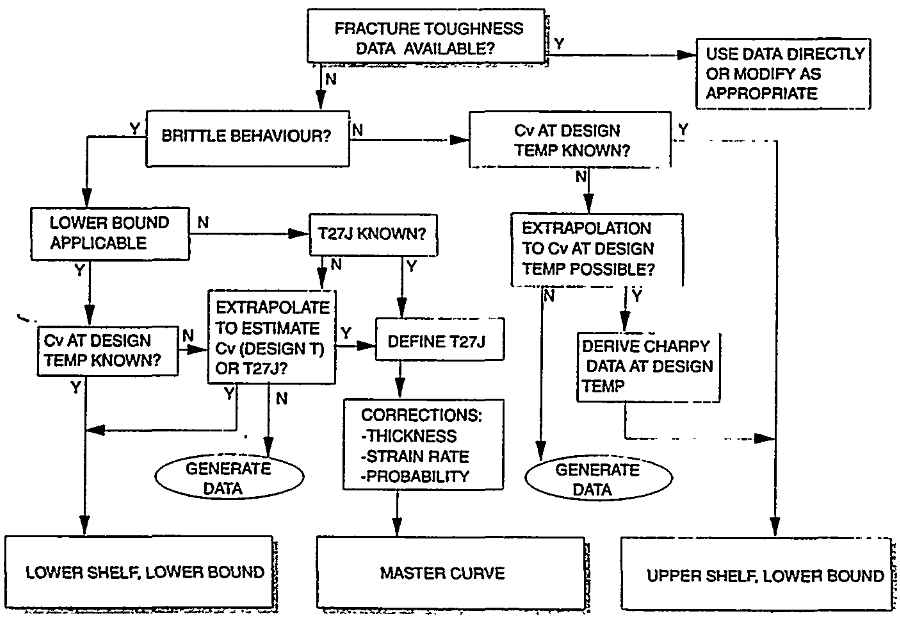

Fig. 1. Flowchart for selection of appropriate Charpy - fracture toughness -correlation [2].

2.1 Determination of fracture toughness in the brittle regime: Master Curve Concept

For materials operating in the brittle regime the determination of fracture toughness follows the 'Master Curve' concept, which is based on the correlation between the Charpy 28 J (27 J) temperature and the temperature for K_{mat} = 100 MPa√m. The relationship is modified to account for the required failure probability (Eq. 7), thickness effect (Eq. 8) and the shape of the fracture toughness transition curve (Eq. 9). Consequently, fracture toughness (K_{mat}) in the transition regime can be defined as [2]:

$$K_{mat} = 20 + \{11+77 \exp(0.019\,[T-T_{28J}+18\ °C])\} \cdot (25/B)^{1/4} \cdot \{\ln (1/[1-P_f])\}^{1/4} \quad (1)$$

T	= design temperature (°C)
T_{28J}	= 28/27 J Charpy transition temperature (°C)
B	= specimen thickness or flaw width (2 · c) (mm)
P_f	= probability of failure
Std. dev.	= 13 °C
Cv	= Charpy impact energy (J)

At a Cv of 28 J the use of Eq. (1) with the lower 5th percentile of fracture toughness and a 90 % confidence level leads to a simple equation which represents a conservative lower bound estimate of fracture toughness:

$$K_{mat25} = 12 \sqrt{Cv} \quad (2)$$

where K_{mat25} is the estimated K-based fracture toughness of the material in MPa√m for a thickness or flaw width (2 · c) of 25 mm.

The fracture toughness evaluated in accordance with Eq. (2) applies to 25 mm thick specimens. The resultant calculated K_{mat} must therefore be corrected for the appropriate thickness (or flaw width) by:

$$K_{mat} = [(K_{mat25} - 20) \cdot (25 / B)^{1/4}] + 20 \quad (3)$$

A comparison of the fracture toughness values predicted using Eq. (2) with a number of other published correlations is given in [2].

2.1.1 Validation within SINTAP

The 'Master Curve' approach has been applied [2] to a number of steels including line-pipe, ship plate, high-strength quenched & tempered steels, welds and structural steel beams and columns. The relationship between

T_{27J} and $T_{100MPa\sqrt{m}}$ for this wide range of steels demonstrates the generally good description of the data by the expression.

Where discrepancies were observed, these could be attributed to dissimilar microstructures sampled in the Charpy and fracture toughness tests or to the occurrence of splits on the fracture surfaces of specimens in TMCP steels.

2.1.2 Additional Factors Applicable to the Master Curve Concept

For the cases where Charpy data corresponding to an energy level different to 28/27 J are available the use of limited extrapolation is permitted. This is based on a lower bound fit to Charpy data on a wide range of structural steels. Extrapolation from 40 °C above and 30 °C below T_{27J} can be made to estimate T_{27J} for structural steels [2].

Where a material is operating in a high loading rate regime, corrections can be made by applying a strain-rate dependent temperature shift to the transition temperature $T_{100MPa\sqrt{m}}$ since the shape of the fracture toughness transition curve is unaffected by the strain rate [2].

The adjustment of transition temperature (by introducing a shift) becomes necessary when sub-sized Charpy specimens are used instead of standard 10 x 10mm specimens (where the 28 J value corresponds to 35 J/cm^2). The shift in this transition temperature associated with sub-size specimens (ΔT_{SS}) can be described as [2]:

$$\Delta T_{SS} = 51.4 \ln (2 [B/10]^{0.25} - 1) \quad (4)$$

Consequently, the Master Curve concept can be applied to a wide range of steels, the reliability of the resultant estimate of fracture toughness quantified and factors such as high loading rate or sub-size Charpy data accounted for. The method is also fully coherent with that used for the fracture avoidance clauses of Eurocode 3.

2.2 Determination of fracture toughness in the ductile regime: Deterministic Approach

There is, at present, no equivalent of the 'Master Curve' for upper shelf behaviour, consequently a deterministic approach is used. For the ductile regime the Procedure [2] provides two correlations, both of which have been validated for a wide range of steels:

$$K_{mat} = 0.54\, Cv + 55 \quad (5)$$

$$(K_{mat} / \sigma_y)^2 = 0.52 ([Cv / \sigma_y] - 0.02) \quad (6)$$

The upper shelf fracture toughness is evaluated in accordance with both expressions and the lower value taken. Eq. (5) is only recommended when the Charpy energy is greater than 60 J. Validation exercises demonstrated that, while no statistical quantification was made, the predictions were reliably conservative [2].

3 Treatment of Fracture Toughness Data

In general, treatment of fracture toughness data (i.e. K_{IC}, K_{JC}, J_{IC}, J_i, J-R, $K_{ICductile}$) can be classified as either (i) design against brittle fracture or (ii) design against ductile fracture, with either (iii) brittle or (iv) ductile fracture data available. The procedure is described in detail in [1] and shown as a flow-chart in Fig. 2. In the case of CTOD data in the form of δ or J, the treatment is conducted using relevant K-CTOD-J conversions [2].

3.1 Assessment against brittle fracture

The 'SINTAP' Procedure [1] is based upon the MML concept [3] that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. The method makes the following assumptions: (i) specimen size adjustment, (ii) distribution of scatter and (iii) minimum toughness and temperature dependence. Being equally applicable to welded joints, (iv) a data homogeneity check is included. As a result, a conservative estimate of the mean fracture toughness (and its distribution) is obtained. The method is in compliance with the recent standard ASTM E 1921-98.

3.1.1 Scatter and size effect of fracture toughness

The procedure [1] assumes the scatter to follow the statistical brittle fracture model which uses a Weibull type distribution function to describe scatter as:

$$P[K_{IC} \le K_I] = 1 - \exp\left(-\left[\frac{K_I - K_{min}}{K_0 - K_{min}} \right]^4 \right) \quad (7)$$

where $P[K_{IC} \le K_I]$ - i.e. P_f - is the cumulative failure probability at a K_I level, K_I is the stress intensity factor level, K_{min} is the lower bound to the fracture toughness and K_0 is a temperature (T_0) and specimen thickness (B) dependent normalisation fracture toughness which corresponds to a 63.2 % cumulative failure probability (and is approximately $1.1 \cdot \overline{K}_{IC}$, where $\overline{K}_{IC}$ is mean fracture toughness).

The methodology [1] predicts a statistical size effect of fracture toughness test specimens of the form:

$$K_{B2} = (K_{B1} - K_{min})(B_1 / B_2)^{1/4} + K_{min} \quad (8)$$

where B_1 and B_2 correspond to respective specimen thickness (length of crack front). Although "K_{min}" itself can be regarded as "theoretical" in nature, it has been found that for structural steels, a fixed, experimental value of $K_{min} = 20$ MPa√m can be used.

The model here is based upon the assumption that brittle fracture is primarily initiation controlled, even though it contains a conditional crack propagation criterion, which among other factors results in the lower bound fracture toughness K_{min}. Close to the lower shelf of fracture toughness ($K_{IC} < 50$ MPa√m), the equations are expected to be inaccurate because the initiation criterion is no longer dominant, and the macroscopic fracture is propagation controlled. In this case there is no statistical size effect [1].

In the ductile-to-brittle transition region the equations presented here should be valid as long as loss of constraint and/or ductile tearing do not play a significant role [1].

3.1.2 Temperature dependence of fracture toughness

The 'Master Curve' is used in the new ASTM standard (E 1921-98) for fracture toughness testing in the ductile-to-brittle transition region. It gives an approximate temperature dependence of the fracture toughness, K_0, for ferritic structural steels as [1]:

$$K_0 = 31 + 77 \cdot \exp(0.019 \cdot [T - T_0]) \quad (9)$$

where T_0 (°C) is the transition temperature where the mean fracture toughness, corresponding to a 25 mm thick specimen, is 100 MPa√m and $K_0(T_0)$ which is a normalisation fracture toughness at 63.2 % cumulative failure probability, is 108 MPa√m.

3.1.3 Homogeneity check

In the case of 'homogeneous' material the estimate can be based on the mean value of the data. In the cases where the 'brittle microstructure' is substantially more brittle than the 'matrix microstructure', the fracture behaviour will be dominated by the former, consequently the estimate must be based on the minimum value of the data [1].

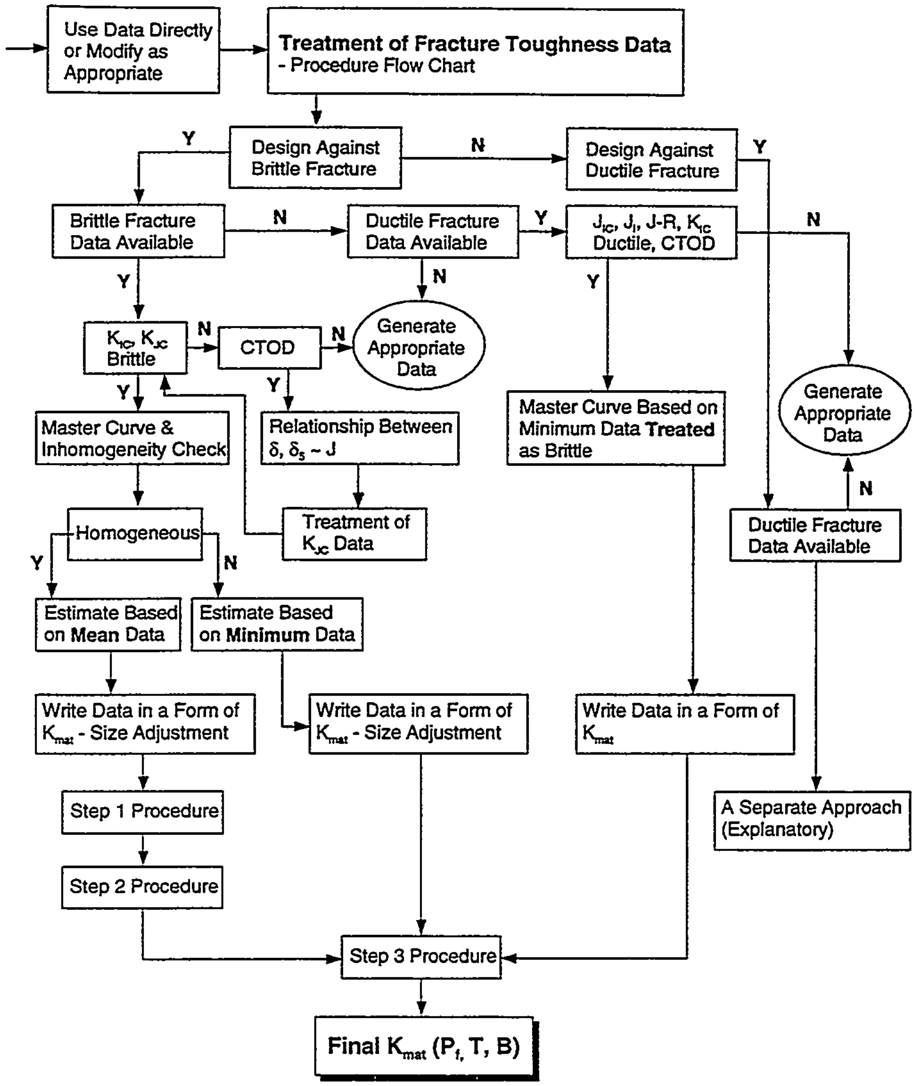

Fig. 2. Flowchart for treatment of fracture toughness data [1].

3.1.4 Procedure description

Firstly, the original fracture toughness data is written in the form of K_{mat}, with size-adjustment made for specimens of thickness other than 25 mm. The procedure progresses according to three steps, each of them setting a different validity level for that part of the data that is to be censored. It should be emphasised that censoring the data does not mean neglecting the data. The whole data set is involved in the analysis, however, a certain pre-assumption is made concerning the nature of the data being censored.

Depending on the characteristics of the original data available, the procedure guides the user towards the Step that gives the most appropriate toughness estimate K_{mat} for the fracture toughness analysis to the particular case being assessed. In the last stage, the final $\overline{K}_{MAT}$ fracture toughness estimate (and its probability distribution) are calculated either according to Step 1, 2 or 3.

Step 1: Normal MML Estimation. All the available data is used for the estimation, with the exception of ductile results ending in non-failure, and those results which are affected by large-scale yielding (thereby exceeding the specimen's measuring capacity limit). Censoring can be made e.g. according to: $K_{JC(limit)} = (E \cdot b_0 \cdot \sigma_{ys} / 30)^{0.5}$, defined by the new ASTM standard (E 1921-98).

Step 2: Lower-Tail MML Estimation. The 50 % upper tail of the data set is censored and the remaining data (corresponding to a cumulative probability of 50 % or lower) is used for MML estimation of K_{mat} or $T_0(K_{mat})$. This ensures that the estimate is descriptive of the material (i.e. microscopic properties), without being affected by macroscopic inhomogeneity, ductile tearing, or large-scale yielding (i.e. unrealistically high 'apparent' toughness values).

The Step 2 then proceeds as a continuous iteration process, until the 'constant' level for either K_0 or T_0 has been reached.

Step 3: Minimum Value Estimation. Only the minimum toughness value (i.e. one value corresponding to one single temperature) in the data set is used for the estimation. The intention is to assess the significance of a single minimum test result, with the aim at avoiding unconservative fracture toughness estimates which may arise if median (50 %) fracture toughness is used for a material expressing significant microscopic inhomogeneity.

Consequently, Step 3 sets a criteria to the allowable difference between the median (50 %) and the lower-bound (5 %) fracture toughness levels. Provided that the obtained K_{mat} or $T_0(K_{mat})$ estimate according to Step 3 is more than 10 % lower or 8 °C higher, respectively, than the corresponding estimate according to Step 1 or Step 2 - whichever of them is lower: K_{mat} (or higher: $T_0(K_{mat})$), this single minimum value is regarded as significant and the estimate according to Step 3 is taken as a final estimate of material's fracture toughness. Otherwise, the lowest (highest) one of the estimates given by Step 1 and Step 2 is taken as a final estimate.

By taking into account the possibility that a single minimum value in a data set can become significant (i.e. capable of triggering brittle failure) due to material's microscopic inhomogeneity, the procedure can be applied in the cases where the HAZ of an otherwise tough steel exhibits LBZs [1].

3.2 Treatment of ductile fracture data

The treatment of data in the case that only ductile fracture data is available depends on whether the possibility of brittle fracture in a particular structure can be excluded or not.

3.2.1 Design against brittle fracture

For the cases where only ductile fracture data are available, but the possibility of brittle fracture in a structure cannot be excluded, Step 3 which treats the minimum initiation value as a brittle cleavage fracture event, can be reliably used for fracture toughness estimation [1]. This is often the case in structures with their operating temperature in the material's transition regime or close to the lower shelf.

3.2.2 Design against ductile fracture

For materials with their operating temperature in the upper shelf regime, or materials which do not exhibit brittle cleavage fracture, a separate approach [4] is advised to be used. Due to insufficient knowledge of the extent to which e.g. constraint, mismatch, scatter, definition of 'initiation', testing etc. influencing the fracture behaviour should be considered, this approach is not meant as a procedure, but is suggested as guidance [1].

4 Advantages and Limitations

Validation exercises have demonstrated the advantages of the 'SINTAP' Procedure in obtaining fracture toughness estimates for various forms of data sets from base materials and welds [1,2]:

(i) The various treatments including specimen size adjustment, inclusion of strain rate effects etc. can be applied directly to K_{mat} data.
(ii) Even the estimate derived from 'lowest quality data' is always 'safe' because the less sufficient/accurate the original data, the more it will be penalised in the probabilistic fracture mechanics assessment.
(iii) By relating the penalty to the quality of the original data any additional data improving the accuracy of a previously existing data set can be readily utilised in terms of reduced conservatism.

(iv) The procedure enables the quantification of probability and confidence levels of the K_{mat} estimate.
(v) Multiple safety margins that could lead to unnecessary conservatism, are avoided.
(vi) The whole data set can be fully utilised in the analysis, regardless of whether the results are ductile or brittle.

To ensure the reliable use of the procedure, the following premises must be fulfilled [1]:

(i) The data set must be representative to the application of the structure/ component being assessed.
(ii) In the case of welds, data should be available for all the 'critical' zones (e.g. HAZ, WM).
(iii) For the final structural integrity assessment, suitable confidence and probability levels should be chosen in relation to the criticality of the particular component/structural member.
(iv) Should the structure's operating temperature lie close to the material's upper shelf and only brittle fracture data being available, appropriate ductile fracture data should be generated.

5 Conclusions

A fracture toughness estimation methodology for the unified treatment of various forms of toughness data for use in structural integrity assessments of ferritic structural steels has been described. The most important findings can be drawn:

(1) Reliable correlations between Charpy and fracture toughness have been established: (i) a lower-bound correlation for lower shelf behaviour, (ii) Master Curve based correlation for transition regime incorporating thickness adjustment and statistical scatter and (iii) a correlation for upper shelf behaviour.

(2) The influence of loading rate and treatment of sub-sized Charpy data can be numerically incorporated to the indirect evaluation of fracture toughness.

(3) Relationships describing K-CTOD-J conversions, as well as guidance for approximating T_{27J} from Charpy data at other temperatures have been determined.

(4) A 'SINTAP' Procedure for the treatment of fracture toughness data in three Steps has been developed, in which one material-specific K_{mat}

value (and its probability distribution) is defined. For assessment against brittle fracture, the procedure is based on the MML concept using the Master Curve method, producing a conservative estimate of the mean fracture toughness. The procedure has been verified to work well for various forms of data sets containing results for both homogeneous and inhomogeneous materials. For cases where only ductile fracture data are available, but the possibility of brittle fracture cannot be excluded, Step 3, treating the minimum value as brittle, can be reliably used.

(5) The procedure allows fracture toughness assessment with quantified probability and confidence levels. With a confidence of 75 %, a conservative and hence 'safe' estimate is obtained., irrespective of the type of the original data. The procedure thereby produces a realistic description of the lower tail probabilities. The verification calculations show that with as few as 6 tests (i.e. 6 parallels), the probability of having a conservative estimate of the mean is ≈ 75 %. This would be considered quite adequate for the majority of structural integrity assessment purposes.

(6) The work within SINTAP is currently progressing towards the aim of establishing a unified European procedure for structural integrity assessment tailored towards the practical user.

6 References

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Towards a more consolidated approach to material data management in life assessment of power plant components

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Abstract

The paper discusses the necessity of having a more consolidated (unified, possibly "European") framework for <u>all</u> (not only pure experimental) material data needed for optimized life management and assessment of high-temperature and other components in power and process plants. After setting the main requirements for such a system, a description of efforts done in this direction at MPA Stuttgart in the area of high-temperature components in power plants is given. Furthermore, a reference to other relevant efforts elsewhere is made and an example of practical application of the proposed solution described (optimized material selection and life assessment of high-temperature piping).

1 Introduction

For a long time collecting and storing material data has been one of the most undisputed activities for engineers that have decided to devote their time to computers. Virtually no one would dared asking for the sense and purpose of their activity - it was self-explaining that it must "be good" to collect material data. Starting point for most of the project was usually a statement like *"oh, you/we have so much (so important!) material data - why not put them in a computer"*. Inquiring too much about who and how is (ever) going to use the data, or how the system must be organized and what hardware and/or software should be used (so that the system can be used in 10 years, too) was usually considered as a secondary problem, *"we will solve it later, let's collect and store the data first"*.

Of course, nobody offering a database today will agree that in <u>his</u> project the things went that way. Therefore, no references will be made on this place, but it is not difficult to uncover the traces of this approach in many material database projects. For some of the problematic solutions in the existing systems the explanation is still - "historical reasons" and this will tell that at least some of the story depicted above did happen.

Nowadays, the situation has changed, the "pioneer" times of development of material database are mostly over and most of the new projects do not suffer the above trouble. But, many of the databases started say 10-12 years ago must live with the inheritance from the past. So their today's developers have to find a solution for problems like:

a) how to upgrade to new operating systems (e.g. Internet)

b) how to make major changes in "rigid" database structures fixed a long time ago

c) how to "get rid" of the database tools/shells used for development of the databases initially: the database lives and should be developed further, but the shell/tool is not maintained and/or developed any further

d) how to implement new functionality into the system that was not initially design to support it

e) how to support data formats not foreseen in the initial specification

f) how to put databases (e. g. similar databases developed in projects in different countries, or different EU[1]-projects) together, etc.

The list can be very long and the requirements like *"cannot we use our old database in the network?"* or *"can't we put it on Internet, too?"* can often lead to many headaches.

In such cases saving data from the old databases is usually not a problem at all, but much of the functionality of the database (queries, reports, different programmed routines, e.g. for statistical evaluation, plotting, etc.) usually must re-programmed. Therefore, the question can be raised: is there a general "recipe" for solving the problems above?

This paper does not pretend to deliver such a "recipe". It will only show how some of the above issues have been dealt with in the material database system developed at MPA Stuttgart. Some of these solutions can probably provide contribution to development of a more generic, more consolidated (unified?) approach to material data management in life assessment of

[1] EU - European Union

power plant components. Although the issues mentioned above are not necessarily limited to materials for high-temperature components in power plants, all of the discussion and considerations made in the paper, as well as the examples described, will be limited to these materials and these material databases.

2 The concept

2.1 What kind of material data: Experimental and standard data

We talk here about metallic materials (steel plates, castings, forging) for high-temperature components in power plants. When compared to the overall range of materials, even when compared only to the overall range of metallic materials only, this is relatively narrow band (small group) of materials.

Furthermore, the assumption will be made that the material data, to be stored in the databases, can be classified in the way as shown in Figure 1. The reference to "Level" comes from the EU project CFAT (Holdsworth 1997).

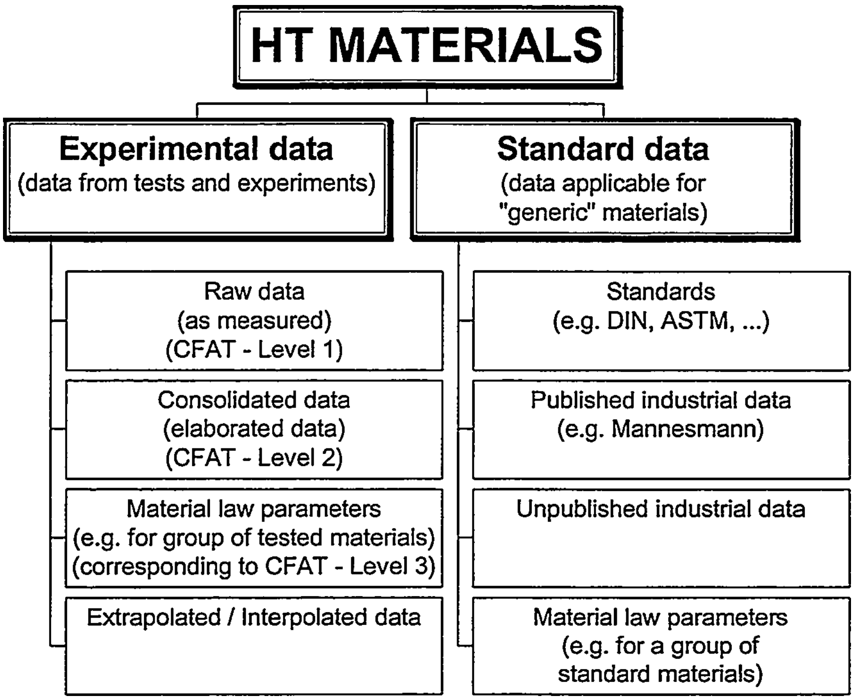


Figure 1: Two main categories of HT material data.

Most of the databases developed so far were covering just one type of data: like for instance experimental data stored in Alloys DB of JRC Petten (Over 1997), or basic standard data given "Stahlschlüssel" database.

The concept proposed here (a possible "unified framework") suggests that there should be no separation of data and no development of separate databases for experimental and standard data. In other words that an overall framework supporting both categories of material data should exist.

Main reason for this is that the distinctions i.e. limits of two categories are all but crisp and the way from raw experimental data to the values printed in the standards may need many intermediate steps: e. g. simple data elaboration, data consolidation, data verification, data interpolation, data extrapolation, etc. In practice it can mean that a typical user of standard data (e. g. a designer) might still want to see the scatter bands in experimental data behind the standard ones, or that typical user of experimental data (e. g. a laboratory researcher) might like to plot his experimental results against the standard data (Figure 2 - as from SP249 system, Jovanovic, Friemann 1995).

2.2 Use and users of data and databases

Poor definition user profiles of yet-to-be-developed material databases has been another source of problems. Essentially, there are three main categories of material database users:

a) The material data "producers":
They need a database primarily for storing and management of data they produce in testing. Sometimes, this would be extended to the tasks data evaluation and like (usually quite sophisticated and user-specific) further life assessment analysis based on these data. Scatter band, possible influences of single production related parameters (e. g. heat treatment, welding procedure and similar) or chemical composition parameters are often the most interesting features required by this group of users.

   This group is relatively small, their interest middle- and long-term oriented, usually very heterogeneous, the ways how they use the database very different across the group and in time - standardization of tasks difficult.

   Obviously, the databases produced for (or even by) these users are the experimental data ones (e. g. Over 1997).

b) The material data "consumers":
They need data primarily for something else - e. g. FE analysis,

design calculation or remaining life analysis. Their primary target are the standard data and the reliability of data (certainty that one is working with "right" e. g. DIN or ASME data) is one of the most important required feature by this group of users.

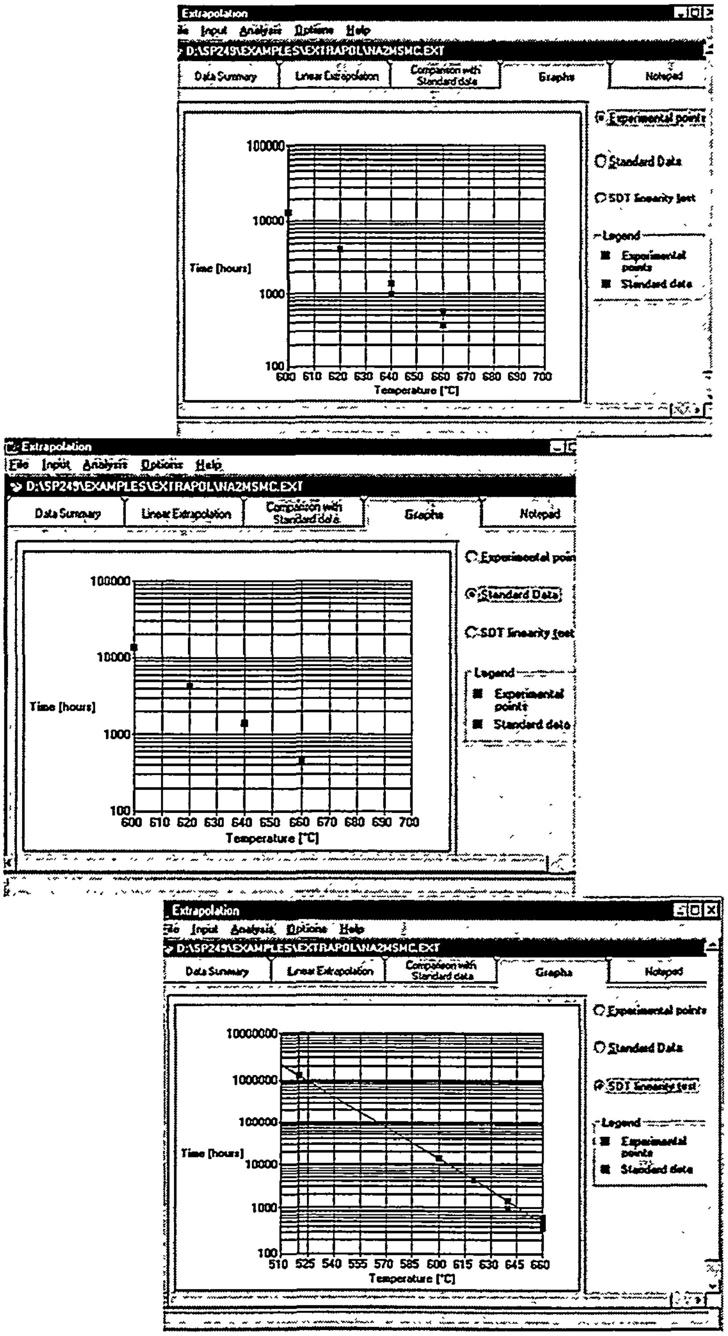


Figure 2: Comparison between experimental and standard data in SP249.

This group is very large (equipment manufacturers, designers, consultants, etc.) and their interest straight-forward and short-term (immediate productivity of the database required) - they are real "market customers" for material databases. The ways how they use a database are often typical or even "standardized".

c) The standard material data "managers":
This group of users is somewhere between the two previous ones. These are usually national or international groups (e. g. ASTM, DIN, VDEh, ...) responsible for "setting the rules". On the basis of experimental data they establish the "generic" data to be used for/in standards.

A handful of users, however of a big "strategic" importance. They are setting standards and what they use is often considered as recommendation for all.

2.3 "Fixed" vs. "flexible" data format

One of the above questions (see chapter 0), *namely "how to put databases (e. g. similar databases developed in projects in different countries, or different EU -projects) together"*, leads in the next iteration to the questions

a) should one ("fixed") format be used as a standard and all data "reduced" to this format - a sort of the common core, or

b) the variety of existing databases may continue to exist but they should be extended by a series of standardized interfaces and exchange protocols (exploiting new database and data warehouse technologies - Jovanovic 1997).

2.4 Link to analyses and calculations

Most of the databases developed so far can be divided into one of the two following groups:

a) databases used as stand-alone software package, use of data from the database in a calculation possible only indirectly, say via "copy-and-paste",

b) databases integrated into the analysis/calculation packages, data used by calculation directly, but usually not editable or even directly visible to the user.

The answer proposed here is: a possible "unified framework" should be a offer both options, tight integration with calculation <u>and</u> easy access to and transparency of the database.

2.5 What kind of database: stand-alone, client-server (network, LAN), Internet-Intranet

Although this question can still be heard in some engineering conversations it is completely out of place. The real question is how and how quickly one can port the "unified framework" database to the Internet level. Of course that subsets of this framework database may still be used as Intranet, LAN and even stand-alone solutions, but, yes, there must be "data-freeway" oriented framework in the background, similar to the solution described in the paper of Fujita (1997). Clearly, a precondition for success of such a project is reliable management of distributed user-rights and protection of distributed data.

The concept presented here proposes, hence, scalable and distributed solutions, flexible enough to be adjusted to the needs of different users mentioned above (see chapter 0).

2.6 What kind of data gathering: Distributed, centralized, "censored" ...

Even for the issue of data gathering the concept here proposes a "middle way" between the extremes of fully distributed and fully centralized ("censored", etc.) solutions. The concepts promotes right "labeling" of data as the solution: the data should not be pre-selected and/or "allowed", they must be properly labeled/marked and accompanied by an extensive subset of "meta-data" (i. e. data about data - e. g. current set has been obtained, by whom, when, under which testing conditions, etc.). In such a way the user can decide which combination of data sets will he use for his particular purposes: e. g. only data from "trusted" laboratories or similar.

3 Results - Development of a system based on the concept

3.1 General

Having the concept described above as its final goal, an innovative material database (ALIAS-Materials) has been developed at MPA Stuttgart. Of the particular interest are the applications related to

(a) management of remaining life of critical high-temperature components in power and process plants, and

(b) gathering of data in the national and international networks of material testers (Internet and Intranet base collaborative work).

Its contents already at this stage of development corresponds fully to the one presented in Figure 1, i. e. it contains both

(a) standard and

(b) experimental material data.

The database is built into the overall shell ALIAS (Jovanovic, Kussmaul 1997) and it assures full compatibility and integration (Figure 3) with

(a) documentation bases

(b) other material databases and

(c) calculation/analysis modules.

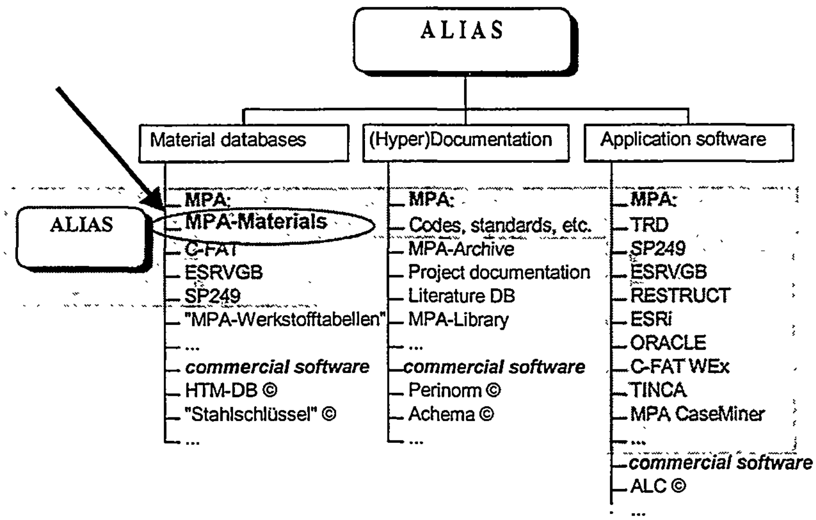


Figure 3: ALIAS Materials as a part of the overall ALIAS shell.

In comparison with the older models based on gathering data from single users via e.g. diskette, ALIAS-Materials is a fully networked database. The data can be entered from any site, provided that the user has the corresponding rights. The standard data can be entered/modified only by administrators, the user's data by himself and by the administrator.

3.2 Architecture and Functionality

The architecture of the database is the modern client-server one. The data are fully separated from the programs. Advantages for the users are in the simple installation and maintenance. Any of the sources definable as an ODBC servers (e. g. MS SQL Server, Oracle, Access, Paradox, etc.) can be defined as the data source. This data source can be in LAN, Intranet or Internet. The advantage for the user is that he can have different servers at different sites (e. g. in headquarters and/or at the plant site - Figure 4).

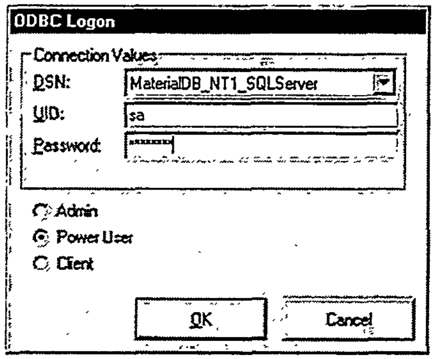


Figure 4.

In the current version the client part of ALIAS-Materials has two versions: the MS Visual Basic (for LAN applications) one and the ActiveX one (for Internet/Intranet applications). Any 32-bit PC machine can run the client software, the software is lean and simple, self-explaining and intuitive. Access to both the server and the client part of the software is controlled (see Figure 4).

3.3 Materials covered

Currently over 700 materials are available in the database (Figure 5), divided into two main groups:

- "standard" data and "user's" data in the same format the standard data
- experimental data (heat, sample and specimen properties, test features and test results)

Most of the materials are steels for high-temperature applications, defined according to different European standards and manufacturers' norms. The user can add his own data any time and keep the separated from those delivered by MPA. Advantage for the user is that he can compile a collection of data that fits his needs exactly.

Materials features covered are:

- brief description of the material
- chemical composition
- tensile data
- rupture strength and rupture parameters
- creep strength
- physical properties and constitutive equations (constitutive laws)
- experimental data, stress-rupture dependencies, rupture strength, etc. (Figure 7)

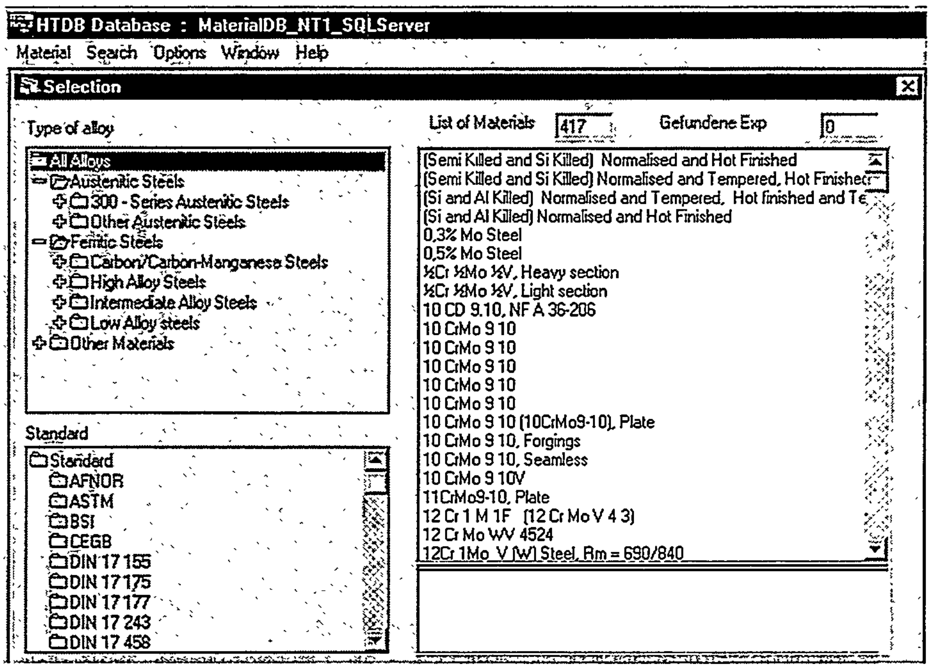


Figure 5: Materials in the ALIAS-Materials.

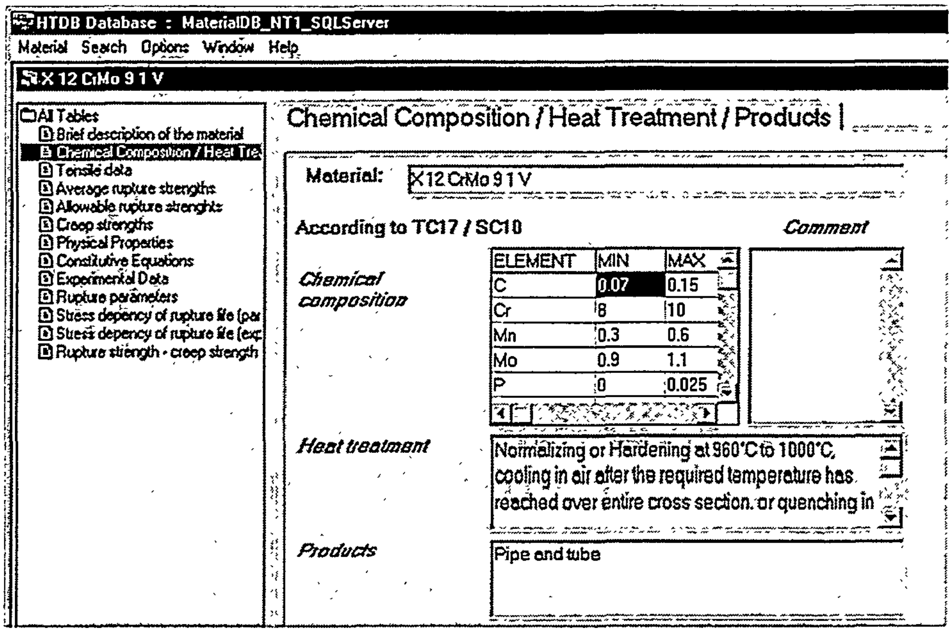


Figure 6: Materials features for standard data in ALIAS-materials.

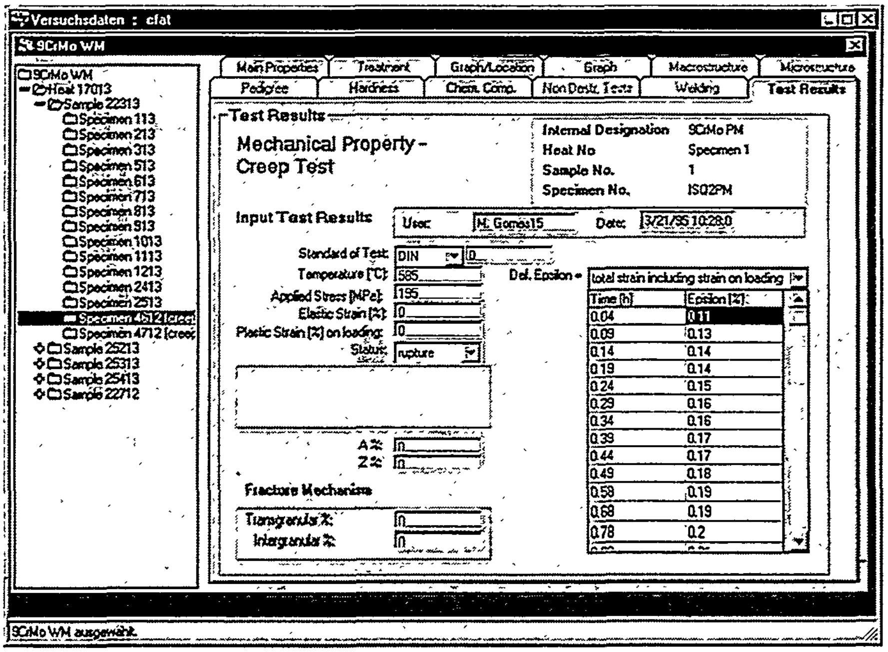


Figure 7: Experimental data in ALIAS-materials.

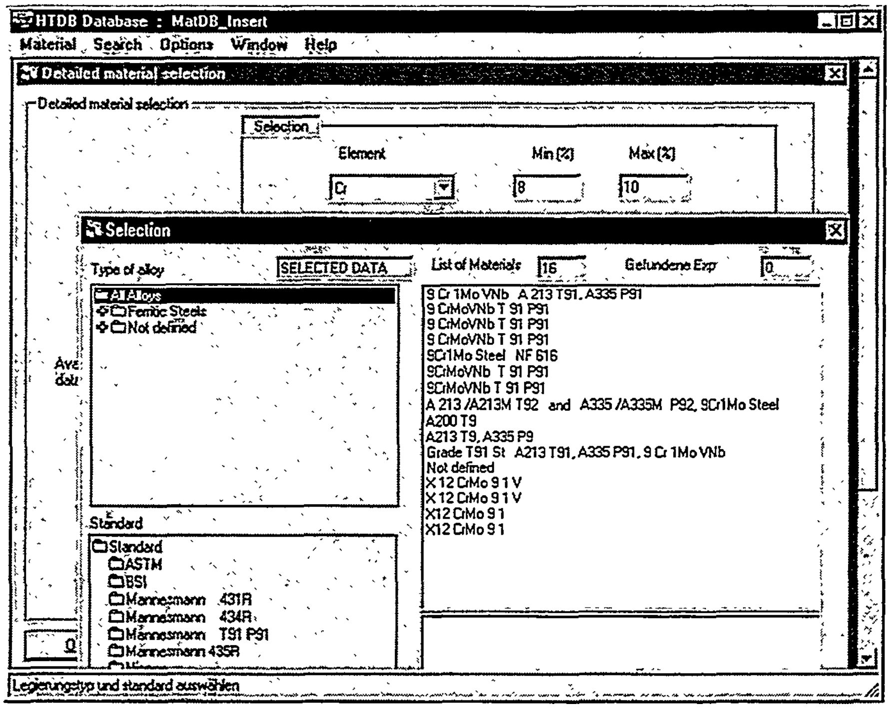


Figure 8: Search in the database (example).

3.4 Direct use of the database – standard and experimental data

Data are entered by the administrator and/or by the user, locally and/or remotely (e.g. via FTP, directly, through import from other applications like Excel, etc.). Data can be searched according to standards, names and properties (Figure 8). Data for retrieved/selected materials can be viewed, graphically represented and exported to other applications (e.g. remaining life assessment, Excel, Word, etc.).

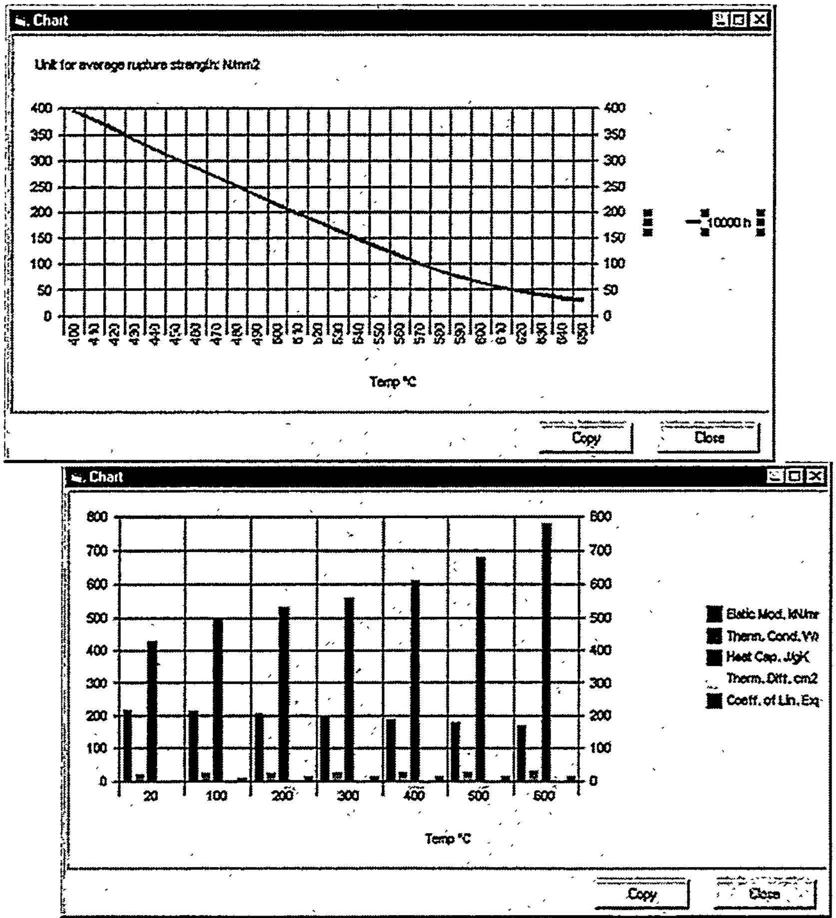


Figure 9: Graphical representation of results (two examples).

4 Applying the system in practice

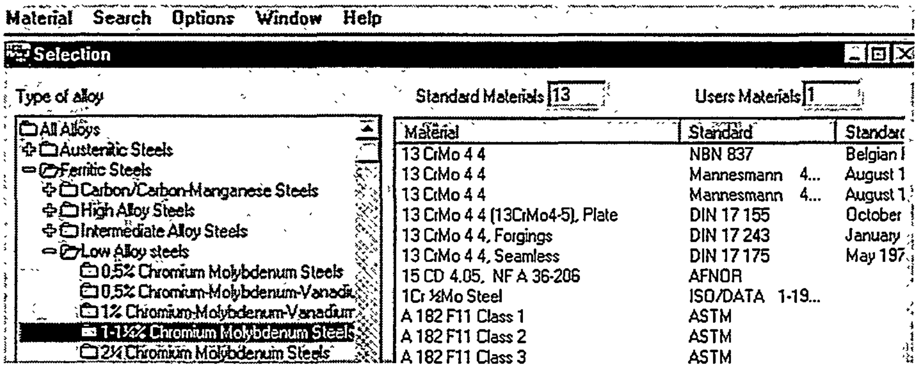
It is only in the practice that possible advantages of the proposed concept can be really assessed. Number of different application in a complex system like ALIAS is virtually unlimited. The following example will, thus, show just two aspects in which the advantages of the proposed concept can be clearly identified with respect to

(a) optimized material selection
(b) practical applications for the remaining life management.

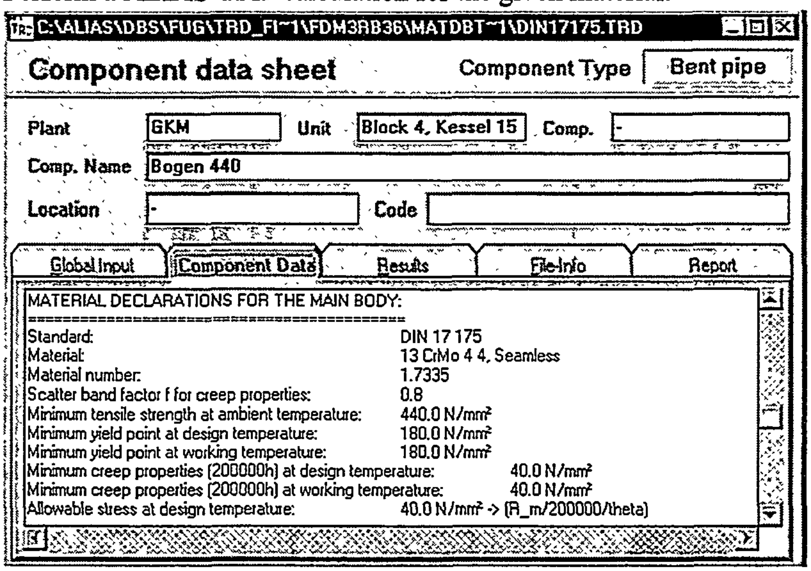
The ALIAS-Materials database can be directly linked with over 30 applications in the area of remaining life assessment built-in ALIAS, e.g. to the TRD calculations, A-parameter analysis, monitoring systems, crack growth analysis, extrapolation routines, etc.

Taking a simplistic example of an elbow made out of 13 Cr Mo 4 4, within ALIAS and ALIAS materials the following fast analysis can be made in a matter of minutes:

Step.1. See the related materials from the same group in ALIAS-Materials:



Step.2. Perform a ALIAS-TRD calculation for the given material:



Step.3. Calculate remaining life according to TRD
Total usage factor due to creep = 94.0 %

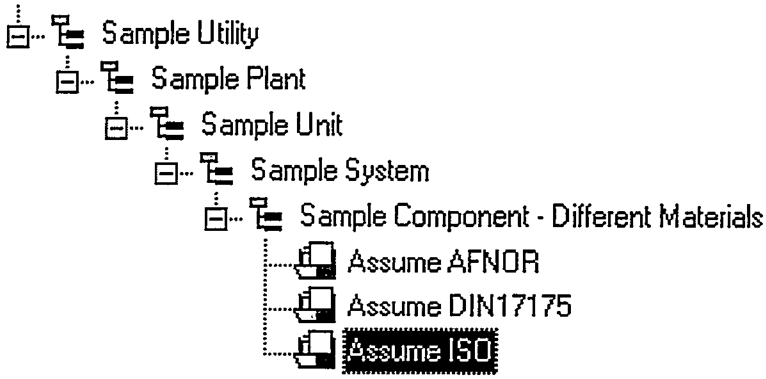
Step.4. See TRD, DIN and other relevant documents in the ALIAS Internet Documentation Base (optional)

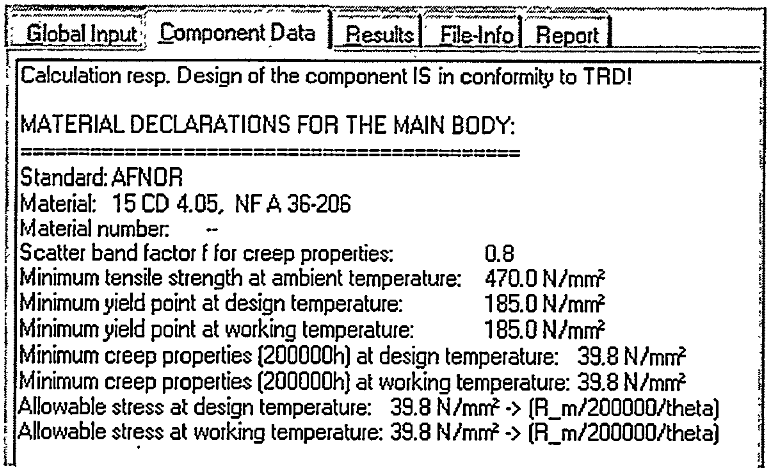
Step.5. Examine the influence of alternative materials from the same group.

e. g. AFNOR Total usage factor due to creep = 91.7 %
e. g. ISO Total usage factor due to creep = 80.1 %

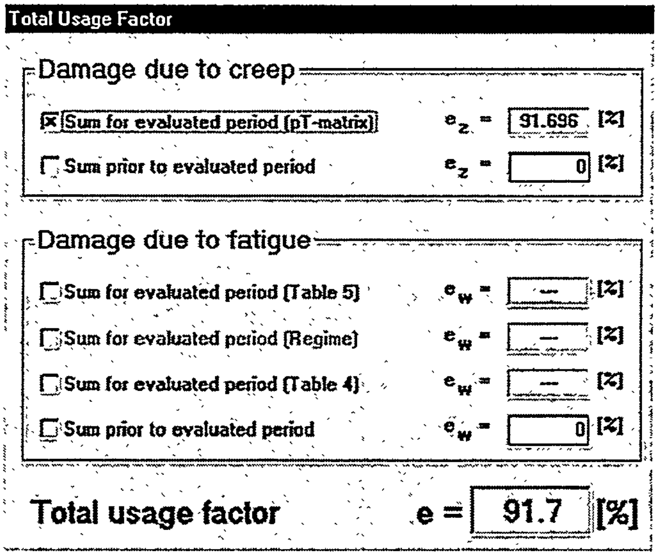
Step.6. Reexamine the data in the database to identify the reasons for the differences.

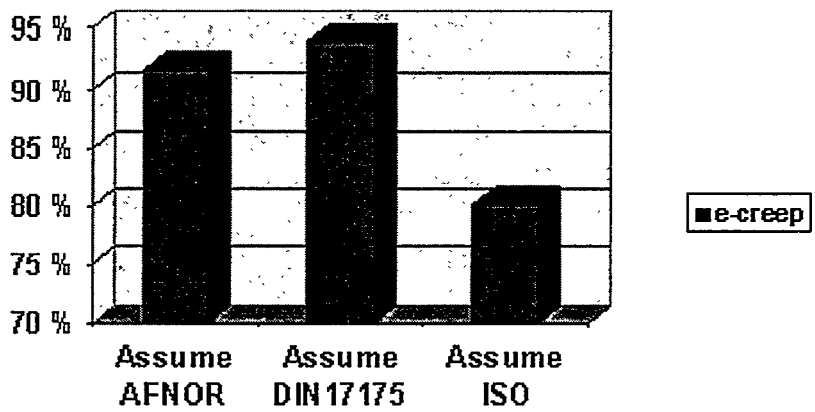
Step.7. Store and manage the calculations in ALIAS Object Management





Step.8. Compare results graphically





Step.9. Use comparison for an ALIAS Report

Further tools for advanced statistical analysis and data mining are available within ALIAS.

5 Conclusions

The concept presented in the paper allows for a comprehensive integration of HT data and HT databases among themselves and with external applications. Many of them are already integrated within ALIAS shell of MPA (Figure 10). This integration on its own allows for

a) Very different types of remaining life analysis including the code-based ones and the inspection-based ones (e. g. Jovanovic, Balos, Auerkari, Kautz 1997)

b) Coverage of the full life cycle of a component under different assumptions (i. e. influence of different assumptions can be followed from the design phase to the end-of-life)

c) Analysis of single aspect incl. risks (e. g. Jovanovic, Hagn 1997)

d) Embedding of above into the final decision on what to do with a component (Jovanovic 1997a)

e) Extension of the use in the direction of telediagnosis and Internet (e. g. Divona, Poloni, Jovanovic 1997)

Current efforts of MPA are devoted to the further implementation of the concept in the framework of ALIAS and its permanent verification in practice (recent applications in Finnish and German power plants).

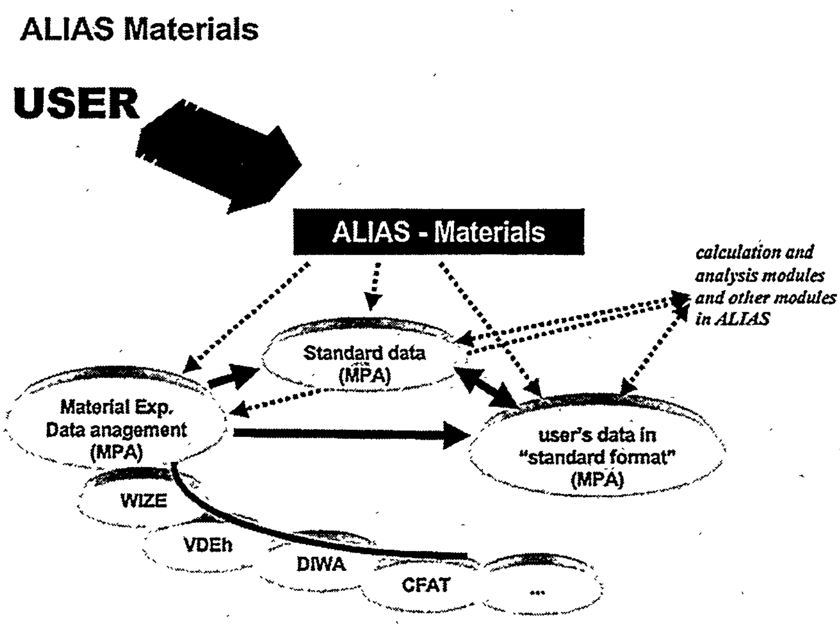


Figure 10: Material databases integrated within ALIAS-Materials and linked to ALIAS Calculations (code-based, inspection-based, etc.).

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Examination of Observed and Predicted Measures of Creep Cavitation Damage Accumulation

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Abstract

Brittle intergranular cavitation represents a primary degradation mechanism for high temperature plant operating within the creep range. Fundamental to formulating estimates of remanent life, or consumed life fraction for such components are: the observation and quantification of the level of actual creep cavitation, typically using an A-parameter type approach, and the correlation of observed creep damage accumulation with some phenomenological model which characterises the rate of damage evolution and, thereby, rupture lifetime.

The work described here treats inhomogeneous damage accumulation - in otherwise uniform material and loading situations. Extensions to the A-parameter are considered as a practical measure of damage localisation and an extension of the Kachanov-Rabotnov continuum damage mechanics model is proposed to allow theoretical treatment.

1 Introduction

Two schools of thought and practice exist regarding the relationship between observed creep cavitation and component life. In continental Europe, it is common to classify the damage level, according to well defined standards, and use heuristic rules to decide on future inspection and repair or replacement strategy. In the United Kingdom, more emphasis has been placed on the development of quantitative measures of damage and of mechanistically informed models to enable direct life prediction (e.g. ref. 1). Both approaches have their merits and can usefully complement each other.

One area of concern with regard to the model based approach is a common tendency for component cracking or failure to occur with observed damage levels considerably lower than theory would suggest. There are several possible reasons for this. It is accepted that, in some situations, damage may initiate sub-surface and that in others cavitation is not the only, or even the dominant, failure process. These situations are now well enough understood at least to prevent serious misunderstanding of the observations.

Another potential cause for apparently premature failure is the presence of an inhomogeneous damage distribution. There are several sources of such inhomogeneity. Stress or temperature gradients will obviously cause corresponding damage gradients. Large scale variation can be treated using Kachanov's damage front propagation concepts; local effects rapidly enter the province of creep fracture mechanics. Material inhomogeneity will also be reflected in damage variation. Concepts of 'quasihomogeneous' materials, 'cohesion fibres' and self-consistent microstructural models have been used to address this. Another possibility is that the damage formation process may be inherently unstable, allowing a stochastic damage concentration to propagate in a manner similar to that by which a tensile neck develops. It is this phenomenon that is addressed here.

To treat this problem, some attention needs to be given to the difference between continuum and discrete structural representations of a mechanical material. Figure 1 shows the scale and orientation relationships between some of the common conceptual tools. It is proposed here to work predominantly at the level of the individual grain and the Chokshi field (refs. 1,2) and to consider, for simplicity, a uniaxial loading. The concepts of a cohesion section, normal to the maximum principal stress axis, and of cohesion fibres and prisms parallel to it are useful.

Figures 2,3 show schematically what might be expected to occur around a locally damaged zone. Adjacent to it, within the cohesion section, stress concentrations will occur, leading to enhanced damage accumulation. Above and below it, in the cohesion fibre, areas will be shielded from the stress field and reduced damage accumulation rates will result. Together, these effects will lead to zones of damage concentration in planes normal to the stress and to periodicity of damage level along the stress axis.

2 Modelling damage localisation

The damage parameter, ω, can be treated in a purely phenomenological fashion, with no explicit link to any particular physical process. However, considerable success has been obtained in creep life prediction by assuming that it is directly analogous to the A-parameter measure of creep cavitation. This is physically reasonable, since both can be related to the concept of effective load bearing area. Despite this, one should not lose sight of the fact that, where ω is a continuum variable, A describes a mechanism that is discrete in both space and time. Whilst it is common to use continuum approximations to model discrete processes, care should be taken that any implicit assumptions or constraints are recognised and understood.

In the present case, the simple linear relationship assumed between ω and A implies that the stress redistribution resulting from the presence of a damaged grain boundary is uniform across the section. As suggested earlier, it is more likely that stress concentrations will be generated, leading to the possibility of enhanced damage rates local to, and in the plane of, existing cavitated or cracked grain boundaries. If each cohesion section is considered to be divided up into regions with size equivalent to the Chokshi field and the usual damage mechanics equations (refs.1,4) are taken to hold in each, then:

$$\dot{\varepsilon}_i = C.\sigma_i^n.\varepsilon^\mu / (1-\omega)^n$$
$$\dot{\omega}_i = D.\sigma_i^\nu.\varepsilon^\mu / (1-\omega)^\eta \qquad (1)$$

Strain rate compatibility and force balance then require:

$$\dot{\varepsilon}_i = \bar{\dot{\varepsilon}}$$
$$\sum_1^N \sigma_i = N.\bar{\sigma} \qquad (2)$$

whence:

$$\sigma_i / \bar{\sigma} = (1-\omega_i)/(1-\bar{\omega}) \qquad (3)$$

and so the local damage rate equation becomes:

$$\dot{\omega}_i = \left[D\sigma_i^\nu.\varepsilon^\mu / (1-\bar{\omega})^\eta\right].\left[(1-\bar{\omega})/(1-\omega_i)\right]^{\eta-\nu}$$
$$\dot{\omega}_i = \dot{\bar{\omega}}.\left[(1-\bar{\omega})/(1-\omega_i)\right]^{\eta-\nu} \qquad (4)$$

Thus if $\eta < \nu$, then damage will tend to homogenise, whilst if $\eta > \nu$, then damage will tend to concentrate. If the strain and damage exponents are similar, i.e. $n \sim \nu$, then these regimes correspond to the usual 'ductile' and 'brittle' classes of material corresponding to $\eta < n$, $\eta > n$, respectively (ref. 4)

The Kachanov-Rabotnov continuum damage mechanics model can thus be extended consistently to describe inhomogeneous damage accumulation within a cohesion section. Work is in hand to address the situation normal to this plane.

3 Measuring damage localisation

It was shown above that the two likely manifestations of damage inhomogeneity would be concentration within a cohesion section and periodicity perpendicular to it. The question then arises, can these effects be consistently measured in a way that is sufficiently simple for routine purposes? If damage occurred randomly, and the basic premise of the A-parameter method can be accepted, that grain boundaries need only be classed as damaged or undamaged, then binomial statistics would suffice to describe the damage distribution (refs. 4,5). Deviations from this hypothesis would form a basis for identifying and quantifying any inhomogeneity.

Classical A-parameter measurements count the numbers of damaged and undamaged grain boundaries intersecting a line-scan parallel to the maximum principal stress axis. Along this line, 'chains' of successive boundaries of like character will be encountered. Identifying these and recording their lengths is only a slight complication of the standard technique. According to the binomial theorem, the frequency of occurrence of a chain of exactly *c* successive damaged boundaries is:

$$P_{c,d} = A_l^c.(1-A_l)^2 \tag{5}$$

and for *c* successive undamaged boundaries:

$$P_{c,u} = A_l^2.(1-A_l)^c \tag{6}$$

where A_l is the classical linear A-parameter value. The total number of chains (neglecting end effects, there must be equal numbers of chains of damaged and undamaged boundaries) is given by:

$$NC = 2.A_l.(1-A_l) \tag{7}$$

Taking data from a 0.5CrMoV casing material, crept at 550°C and 84.9MPa with a life of around 60 000h, Figs. 3a-3d show these predicted distributions of chain lengths at progressive life fractions, together with observed values. Observations show increased numbers of shorter chains and decreased numbers of longer chain, compared with the uniform damage hypothesis. This effect is confirmed by Figs. 4,5 where the observed number and average lengths of chains are compared with the uniform damage prediction. All these findings are consistent with a degree of damage localisation.

Whilst counting damaged grain boundaries in each Chokshi field - as for the A^*-parameter - is more time consuming, it allows more detailed investigation of damage inhomogeneity. Under a uniform damage hypothesis, the average number of damaged boundaries in each field is given by (ref.1):

$$D_{Ch} = N_{Ch}.A_l.8/\pi^2 \tag{8}$$

and the probability of a given number of damaged boundaries is:

$$\left(\frac{N_{Ch}!}{D_{Ch}!.(N_{Ch}-D_{Ch})!}\right).\left(A_l.8/\pi^2\right)^{D_{Ch}}.(1-A_l.8/\pi^2)^{(N_{Ch}-D_{Ch})} \tag{9}$$

Figures 6a,b show the damage levels observed in successive Chokshi fields along the A-parameter scanning line. For life fractions of 0.7 and greater, clear periodicity is seen. It is also apparent that the individual damage levels are significantly greater than would be predicted on a uniform damage hypothesis. Indeed, the prediction corresponds broadly with the minimum observed levels. Figure 7 compares average Chokshi field damage levels with the binomial prediction, confirming this observation. Finally, Fig. 8 shows the observed and predicted cumulative probability distributions, according to equation 9. It is clear that, for each of the four life fractions studied, the whole observed damage distribution lies at higher levels than would be consistent with uniform damage.

4 Conclusions

- Damage inhomogeneity can explain why failure is often observed at lower A-parameter values than are predicted using standard continuum damage mechanics models.
- The Kachanov-Rabotnov model can be consistently extended to describe damage localisation within a cohesion section.
- Observations show both damage concentration in a cohesion section and damage periodicity perpendicular to it.
- Extensions of the classical A- and A^*-parameters allow quantification of damage inhomogeneity, by comparison with the binomial statistics expected under a uniform damage hypothesis.
- Further work is required to link the theoretical treatment to the quantification methods.

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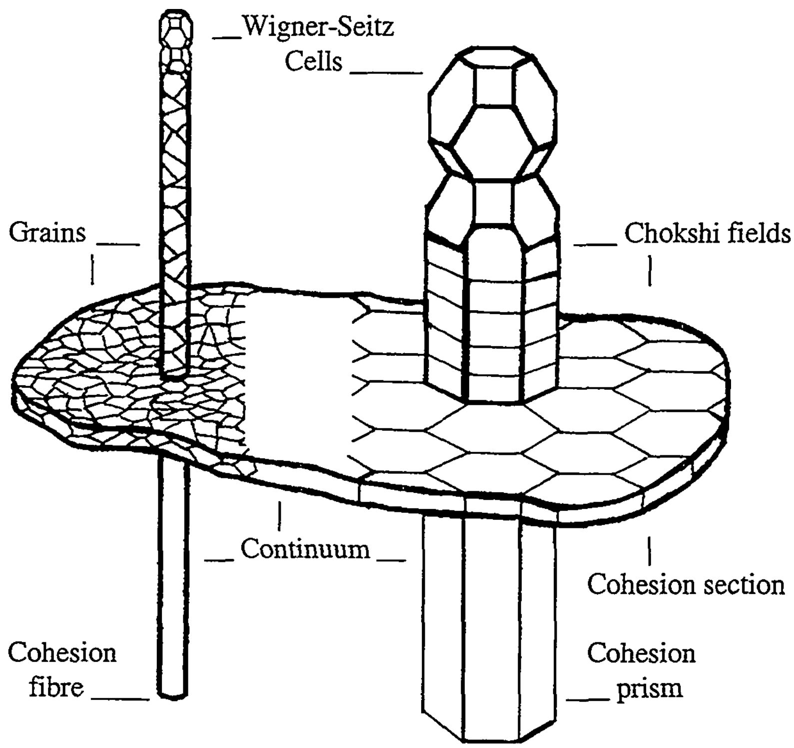
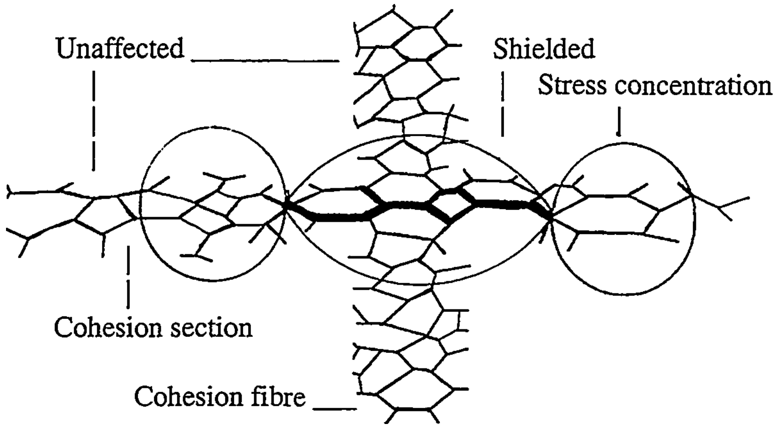


Fig. 1. Continuum and discrete structures for an isotropic material under predominantly uniaxial loading.



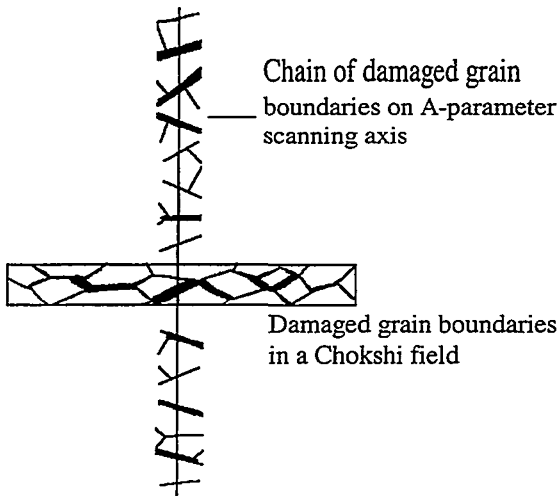


Fig. 2. Damage localisation - effects and quantification.

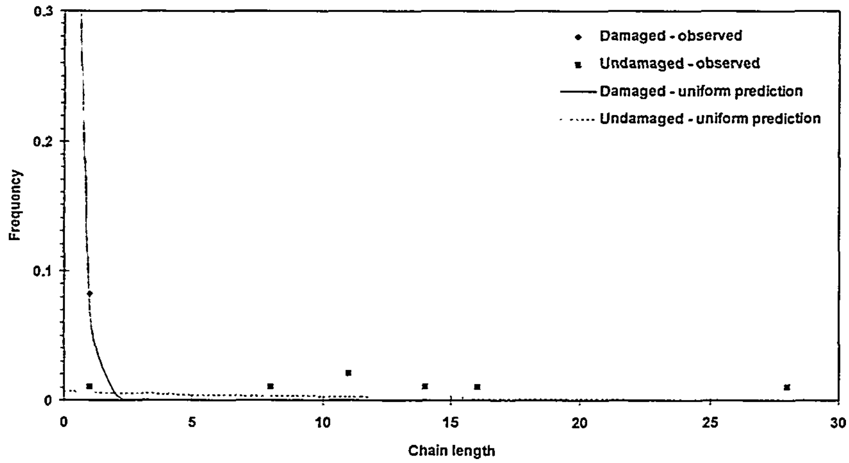


Fig. 3a Distribution of chain lengths, LF = 0.5

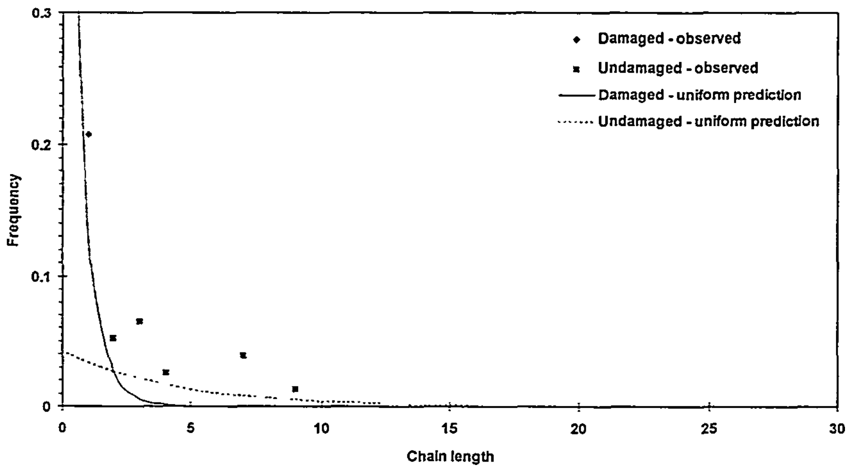


Fig. 3b. Distribution of chain lengths, LF = 0.7.

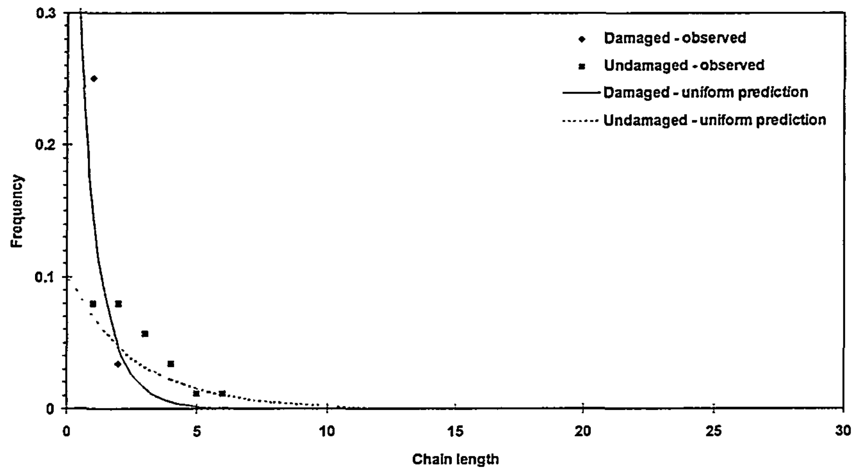


Fig 3c. Distribution of chain lengths, LF = 0.9.

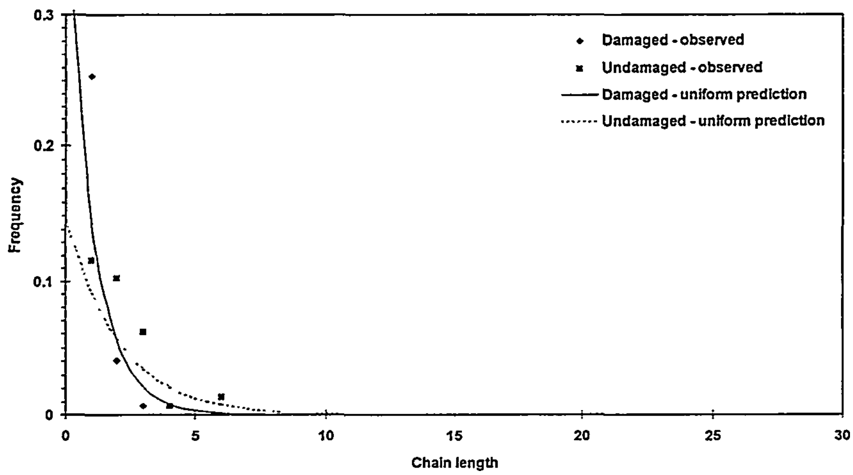


Fig. 3d. Distribution of chain lengths, LF = 1.0.

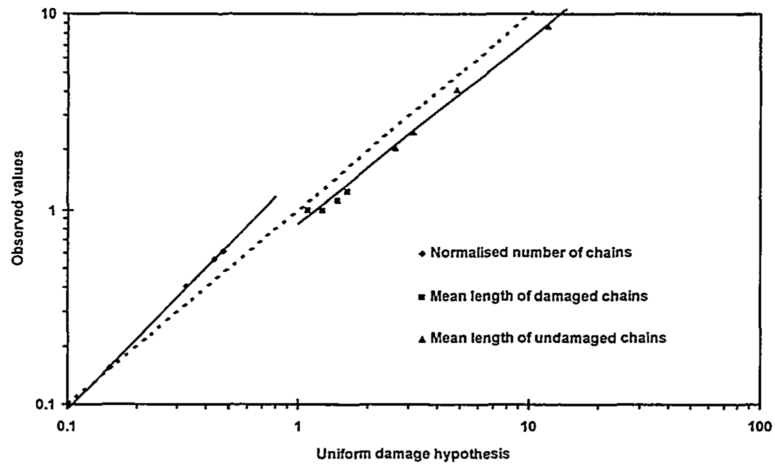


Fig. 4. Distributions of number and average length of chains.

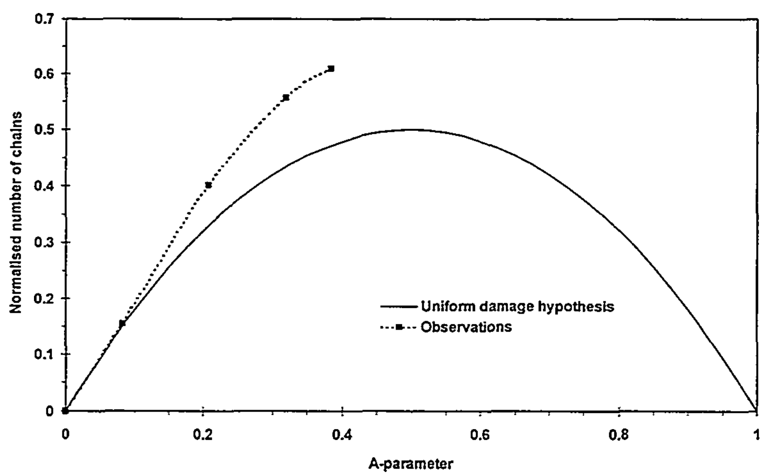


Fig. 5. Relationship between A-parameter and number of chains of damaged and undamaged grain boundaries.

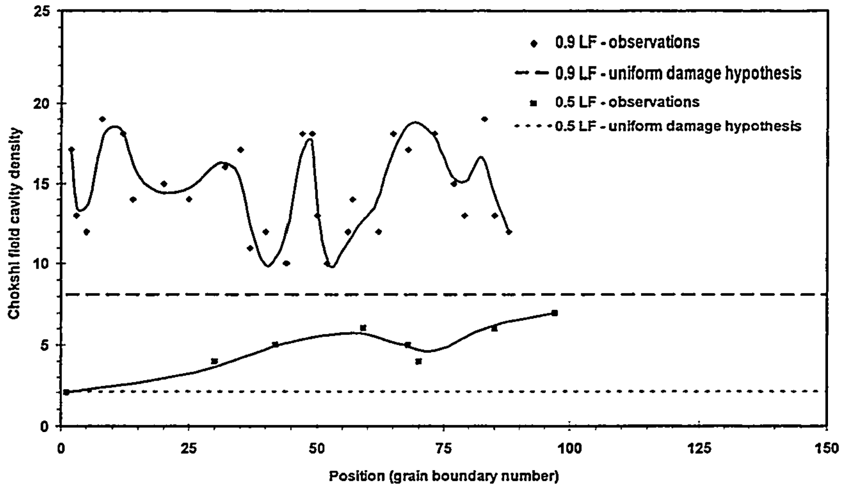


Fig. 6a.Periodicity of damage in Chokshi fields at LF = 0.5 and 0.9.

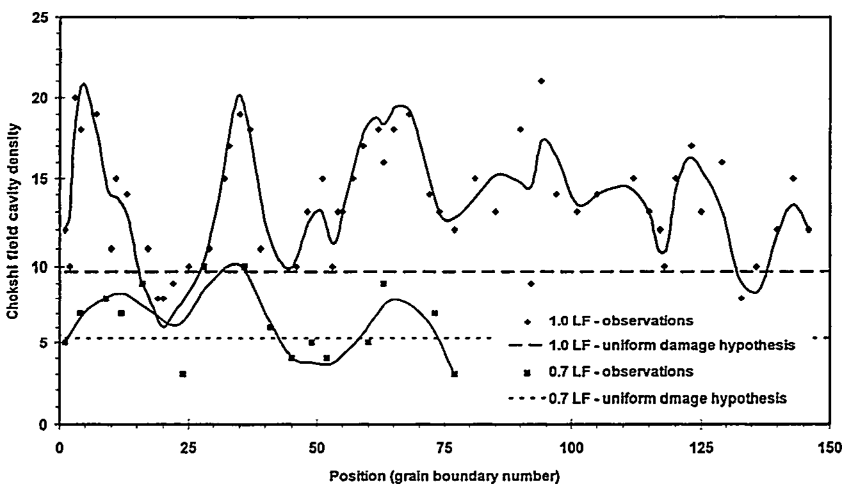


Fig. 6b.Periodicity of damage in Chokshi fields at LF = 0.7 and 1.0.

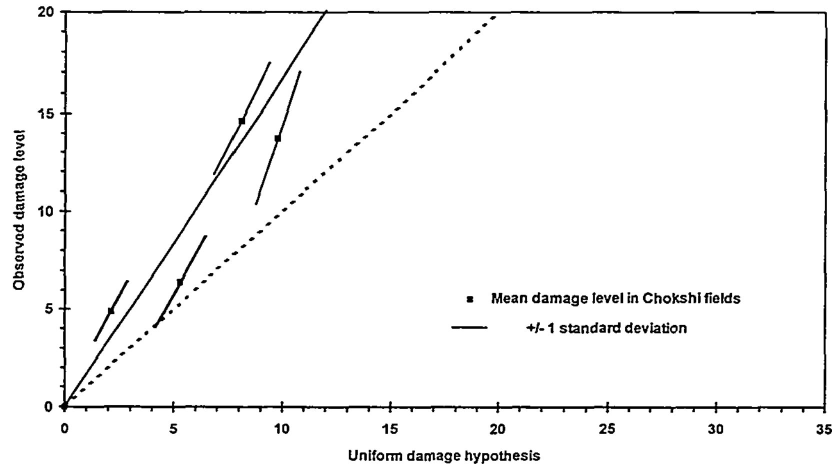


Fig. 7. Mean Chokshi field damage levels.

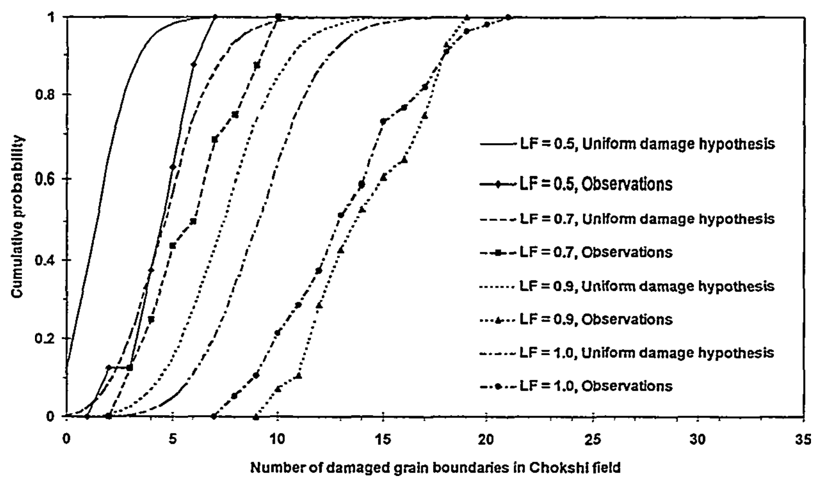


Fig. 8. Distribution of Chokshi field damage levels.

MODELLING OF CREEP DAMAGE DEVELOPMENT IN FERRITIC STEELS

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ABSTRACT

The physical creep damage, which is observed in fossil-fired power plants, is mainly due to the formation of cavities and their interaction. Wu and Sandström have previously demonstrated that both the nucleation and growth of creep cavities can be described by power functions in strain for low alloy and 12% CrMoV creep resistant steels. It possible to show that the physical creep damage is proportional to the product of the number of cavities and their area. Hence, the physical creep damage can also be expressed in terms of the creep strain. In the present paper this physical creep damage is connected to the empirical creep damage classes (1-5) introduced by Neubauer. A creep strain-time function proposed by Sandström and Kondyr, which is known to be applicable to low alloy and 12% CrMoV creep resistant steels, is used to describe tertiary creep. With this creep strain - time model the residual lifetime can be predicted from the observed damage. For a given damage class the remaining life is directly proportional to the service time. An expression for the time to the next inspection is proposed. This expression is a function of fraction of the total allowed damage, which is consumed till the next inspection.

Keywords: creep damage, cavitation, residual life

1 INTRODUCTION

Observation of creep cavitation has been used for many years to estimate the residual lifetime of components in fossil-fired power plants. The cavities have been observed with the help of replicas, which can be applied non-destructively. A common way of classifying the damage is to use the type of rating originally introduced by Neubauer. Typically five classes of damage are considered. 1. No cavities, 2. Single cavities, 3. Strings of cavities, 4. Microcracks and 5. Macrocracks. Each damage rating has also been associated with a maximum time to the next inspection. Such information is available in previous NORDTEST reports. Although this approach has worked very well in practice and few failures have been reported it must be recognised that it is entirely empirical.

Attempts have been made to improve this situation by applying models for the development of the creep damage for example using the Kachanov-Rabotnov model. The models applied have however all been phenomenological in nature. They can fit observation but in general they can not be used for extrapolation. In recent years physically based models for the initiation and growth of cavities have been established. These models can describe the initiation and growth of cavities for low alloy and 12% CrMoV creep resistant steels. Since good representations of the creep strain-time behaviour are available, the time dependence of the cavitation can also be described. The missing link in the past has been the absence of a clear connection between the empirical damage representation and the amount of cavitation. It is the *purpose* of the present paper to propose such a link, to express the damage rating in terms of the cavitation and to use this relation to predict the remaining lifetime from creep cavity observations.

2 NOMINAL CREEP DAMAGE

A range of models can describe the creep strain behaviour of ferritic steels as well as 12% CrMoV steels. In the present paper a model set up by Sandström and Kondyr [1], [2], [3] is used. It can accurately represent the creep curves with a limited number of parameters. The creep rate $\dot{\varepsilon}$ is given by the following expression

$$\dot{\varepsilon} = A\sigma^n e^{B\varepsilon} \tag{1}$$

where ε is the strain, σ the stress and n the Norton exponent. A and B are constants, which can approximately be determined from the following expressions.

$$B = 5.6/\varepsilon_R \tag{2}$$

$$A = 1/Bt_R\sigma^n \tag{3}$$

ε_R and t_R are the rupture strain and rupture time respectively. Eq. (4) takes the form of the Monkman-Grant relation. Eq. (1) is associated with the following time dependence

$$\varepsilon = \frac{1}{B}\ln\left[\frac{1}{\exp(-B\varepsilon_0) - BA\sigma^n(t-t_0)}\right] \tag{4}$$

The rupture time t_R is not necessarily the design life of the component in question. In fact t_R is assumed to take local values. Thus the rupture time can vary for example across a weldment. The actual value of t_R has to be assessed from the appearance of the creep damage. Since the life of components is frequently much longer than the overall design life of a plant the (local) values of t_R are typically exceeding the design life as well.

Eq. (1) has a form which is consistent with the Kachanov - Rabotnov damage equations [4], [5], [6]. The nominal damage function ω is related to the strain in Eq. (5) as

$$(1-\omega)^m = e^{-B\varepsilon} \tag{5}$$

Since the constant m does not enter Eqs. (1) and (4) for the strain rate and strain, it can take arbitrary values. The concept nominal damage is used here to emphasise that the Kachanov - Rabotnov damage function ω does not correspond directly to the physically observed creep damage.

3 PHYSICAL CREEP DAMAGE

The available literature on creep cavitation in ferritic and 12%CrMoV steels has recently been surveyed [6], [7]. It is found that the nucleation and growth of cavities can approximately be described by

$$N = C_N \varepsilon^{\nu} \tag{6}$$

$$R = C_R \varepsilon^{\rho} \tag{7}$$

where C_N, C_R, ν, and ρ are constants. ν and ρ take values in the range 0.3-1 and 0.35-0.75 respectively. In the former cases the exponents are typically at the upper end of the range, in the latter at the lower end. Data for the cavity radius for 1Cr 0.5Mo is illustrated in Fig. 1 [7].

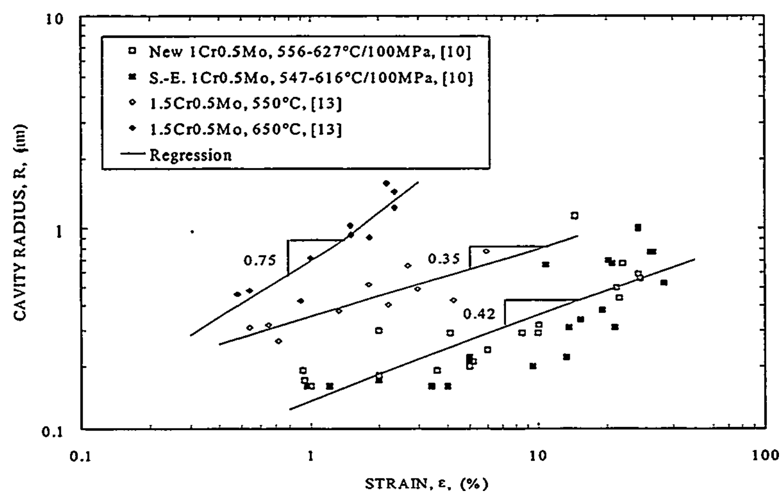

Fig. 1. Cavity radius R as a function of creep strain for the steel 1Cr 0.5Mo. From [7].

The nucleation and growth of cavities can also be represented with time dependent exponentials in much the same way as in Eqs. (6) and (7). The temperature dependence of the constants is however considerably larger than in Eqs. (6) and (7). Hence the nucleation and growth of cavities are believed to be closely linked to the creep strain.

Intuitively the influence of the damage on the mechanical properties is related to the cavitated grain boundary area, which is proportional to the product $N R^2$. This product is assumed to represent the physical damage D.

$$D \propto N R^2 \tag{8}$$

This physical damage D promotes grain boundary decohesion. Cocks and Ashby have studied the influence of power-law creep on intergranular fracture with the help of a micromechanical model [8]. From their results a damage function can be derived, namely

$$D_{CA} = 8 N R^2$$

Thus Eq. (8) is fully consistent with the micromechanical model. Inserting (6) and (7) into Eq. (8) gives

$$D = C_D \varepsilon^{\delta} \tag{9}$$

where C_D and δ are constants and δ is 1 to 1.5. Since the damage is assumed to be unity at rupture, Eq. (9) can also be written as

$$D = \left(\frac{\varepsilon}{\varepsilon_R} \right)^{\delta} \tag{10}$$

4 CLASSIFICATION OF CREEP DAMAGE

Neubauer introduced a damage rating from 1 to 5 according to the morphology of the creep cavitation. The damage rating N_D should be closely connected to the amount of physical damage. An exponential relation between the two types of damage is assumed

$$N_D = 5D^{\gamma} + 1 = 5\left(\frac{\varepsilon}{\varepsilon_R} \right)^{\delta\gamma} + 1 \tag{11}$$

where γ is a constant. In this way the damage rating is also expressed in terms of an exponential in strain, which is natural. According to Eq. (11) the damage rating is 6 at rupture, i.e. the maximum value 5 appears slightly before rupture. The rating 5 is assumed to be associated with the formation of macrocracks. Rating 6 can be said to represent the final failure. Eq. (11) generalises the damage classification according to Neubauer in the sense that the damage can take non-integer values. The consumed strain fraction

$\varepsilon/\varepsilon_R$ is determined using Eq. (11) and the consumed life fraction (time fraction) is calculated with Eq. (12).

$$\frac{t}{t_R} = 1 - e^{-B\varepsilon} \qquad (12)$$

The only material parameters entering the expressions for the physical damage (10) and the damage classification (11) are γ and δ. The value of δ has been given above to about unity. The value of γ is fixed in the following way. It has been demonstrated both for ferritic steels and 12%CrMoV steels that cavities at significant numbers (rating 2) start to appear at a strain which is about 4% of the rupture strain [6]. This gives $\gamma\delta = 0.5$ and with $\delta = 1$ the value of γ becomes 0.5. These values are based on laboratory data for parent materials. However, the model will also be used for microstructures in weldments, which might possibly be represented by other values of $\gamma\delta$. Thus the influence of the product $\gamma\delta$ on the results will be analysed.

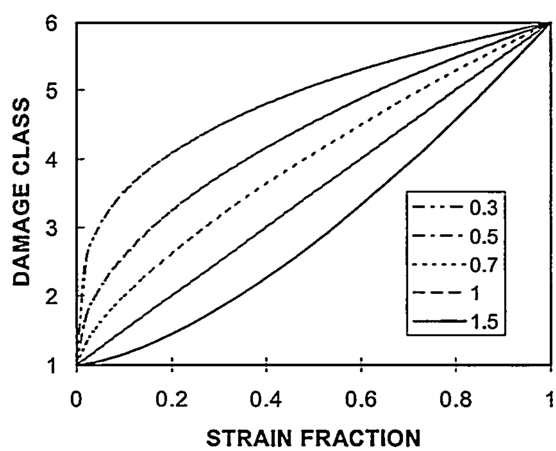

Fig. 2. Damage class as a function of the strain fraction to failure $\varepsilon/\varepsilon_R$ according to Eq. (11) for $\gamma\delta = 0.3$, 0.5, 0.7, 1.0 and 1.5.

In Fig. 2 and Fig. 3 the damage class N_D is given as a function of the strain life fraction $\varepsilon/\varepsilon_R$ and as a function of the time life fraction t/t_R respectively. For $\gamma\delta = 1$ the damage class versus strain relation is linear illustrating the close connection between the two parameters. At small values of $\gamma\delta = 0.3$ the damage class increases very rapidly both at small strains and times. This rapid increase is not consistent with damage observations in fossil fired power plants for parent metal, HAZ or weld metal. At large values of $\gamma\delta = 1$ and 1.5 the damage class increases very rapidly at large times in a way, which sometimes is in agreement with findings in plants. It must be concluded that $\gamma\delta$ must be larger than 0.3. A realistic range is $0.5 \leq \gamma\delta \leq 1.5$ with $\gamma\delta = 0.5$ being the most well documented case. This value will primarily be used in the analysis.

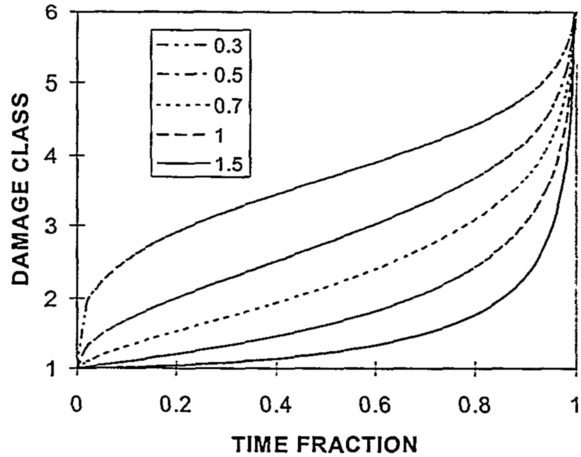

Fig. 3. Damage class as a function of the time fraction to failure t/t_R according to Eqs. (11) and (12) for $\gamma\delta = 0.3$, 0.5, 0.7, 1.0 and 1.5.

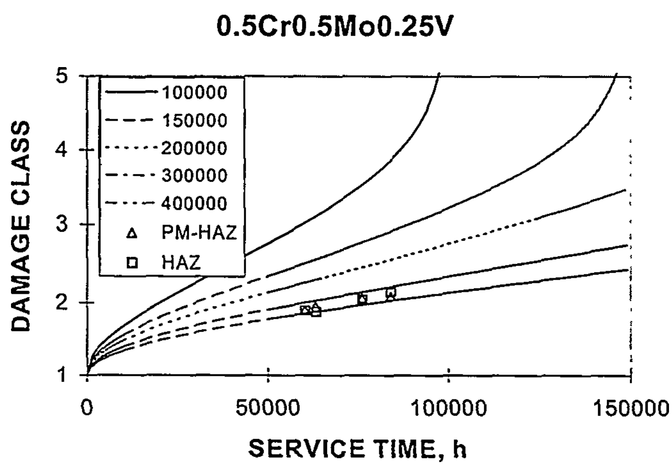

Fig. 4. Damage class as a function of service time at the rupture times 100000, 150000, 200000, 300000 and 400000 h according to Eqs. (11) and (12) for $\gamma\delta = 0.5$. A comparison is made to observed damage in main steam pipe components taken as averages over 8 positions. 0.5Cr0.5Mo0.25V.

A comparison with observed creep damage in a Swedish power plant is illustrated in Fig. 4. The observed creep damage is given as a function of service time together with the model values for the damage. Damage in the HAZ or in the parent metal adjacent to the HAZ is shown for some main steam pipe components in 0.5Cr0.5Mo0.25V. Little variation between components and positions was observed and the average is presented. No damage development was found in the weld metal. The damage development is clearly consistent with the model for a rupture time of about 350000 h.

There are however data which require higher $\gamma\delta$ values than 0.5. Such data are for example given in [9] for 0.5Cr0.5Mo0.25V. This type of data will be analysed in a forthcoming paper.

5 REMAINING LIFE TIME

With the help of Eqs. (11) and (12) the rupture time can be estimated from the service time and the damage classification

$$t_R = \frac{t_{service}}{1 - e^{-5.6((N_D - 1)/5)^{1/(\delta\gamma)}}} \qquad (13)$$

where N_D is the observed damage rating. From Eq. (13) an expression for the remaining lifetime t_{rem} can be found from an observed damage rating.

$$t_{rem} = t_{service}\left[-1 + 1/\left(1 - e^{-5.6((N_D - 1)/5)^{1/(\delta\gamma)}}\right)\right] \qquad (14)$$

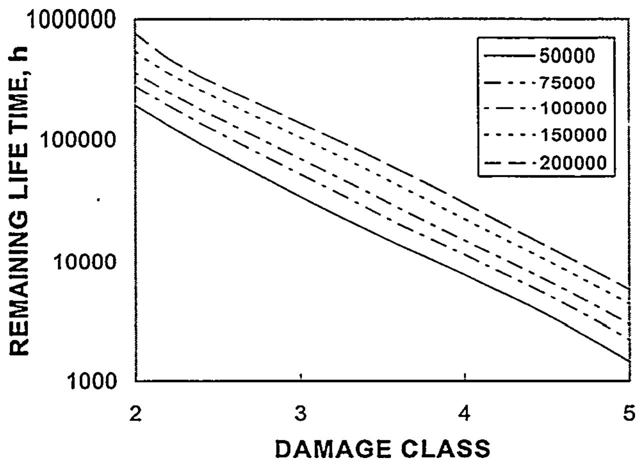

Fig. 5. Remaining life versus damage class at the service times 50000, 75000, 100000, 150000, and 20000 h following Eq.(13).

This equation is illustrated in Fig. 5, where the remaining life is shown versus damage class. It can seen from Fig. 5 that the logarithm of the remaining life is approximately linear as a function of the damage class. For a given damage class the remaining life is directly proportional to the service time. Thus a remaining life factor $t_{rem}/t_{service}$ can be introduced, which is independent of the service time $t_{service}$. By multiplying this factor by the service time the remaining life is obtained. It can be shown that more than two thirds, less than half and slightly more than 10% of the life remain for a damage class of 2, 3 and 4 respectively for $\gamma\delta = 0.5$.

6 TIME TO NEXT INSPECTION

It is assumed that the time t_{inspec} for the next inspection is no later than when half of the remaining damage has been consumed.

$$\frac{t_{inspec}}{t_R} = 1 - e^{-5.6((N_D+5-2)/10)^{1/(\delta\gamma)}} \tag{15}$$

All of the remaining life is consumed when N_D has reached 5. Dividing Eq. (15) with (13) gives

$$\Delta t_{inspec} = t_{service}\left(\frac{1-e^{-5.6((N_D+5-2)/10)^{1/(\delta\gamma)}}}{1-e^{-5.6((N_D-1)/5)^{1/(\delta\gamma)}}} - 1\right) \tag{16}$$

where $\Delta t_{inspec} = t_{inspec} - t_{service}$ is the maximum time to the next inspection.

After a metallographic investigation the basic assumption made above is that half of the potential damage development should be left at the time of the next inspection. More precisely the damage class at the next inspection $N_{D\,i+1}$ should be

$$N_{D\,i+1} = (N_{D\,i} + 5)/2 \tag{17}$$

where $N_{D\,i}$ is the observed damage class at the present investigation. The available damage is fully consumed when $N_D = 5$. Expression (17) has been used when deriving Eqs. (15) and (16). For $\gamma\delta = 0.5$ a damage class of 2, 3 and 4 corresponds to inspection at about 70%, 80% and 90% of the rupture time, respectively. The time to next inspection as a function of damage class after different service times is shown in Fig. 6. These times are also given in Table 1. The proposed times to next inspection are 46, 20 and 8% of the service time for a damage class of 3, 3.5 and 4 respectively. According to the model the proposed times to next inspection are proportional to the service time.

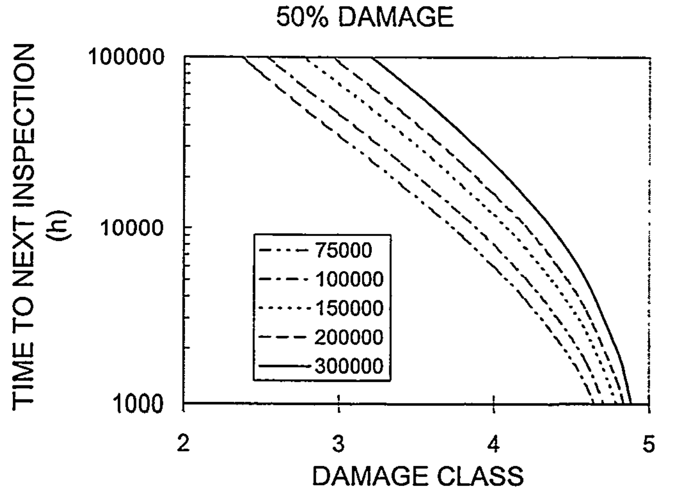

Fig. 6. The proposed time to next inspection as function of damage class, Eq. (16) for the rupture times 75000, 100000, 150000, 200000 and 300000 h. $\gamma\delta = 0.5$. 50% of remaining damage consumed.

Table 1. Time to next inspection (Eq. (16), h).

Damage class	t_{serv} (h) 75000	t_{serv} (h) 100000	t_{serv} (h) 150000	t_{serv} (h) 200000	Proposed Nordtest 0.5CrMoV	Proposed Nordtest 1Cr0.5Mo	Proposed Nordtest 2.25Cr1Mo
2	206562	275416	413124	550832	30000	40000	50000
2.5	79629	106172	159259	212345	15-20000	20-25000	25-30000
3	34853	46470	69706	92941	15-20000	20-25000	25-30000
3.5	15205	20274	30410	40547	10000	10-15000	10-15000
4	5959	7946	11919	15891	10000	10-15000	10-15000
4.5	1720	2294	3440	4587	5000	5-10000	5-10000
5	0	0	0	0		0	0

$\gamma\delta = 0.5$; Nordtest values from [10]

The model values for the time to the next inspection are compared the values given by NORDTEST in their recent survey [10]. The NORDTEST values depend on the damage classification and somewhat on the material, but not on the expired service time. The NORDTEST values are in general shorter than the model values except at higher damage (> 3.5) and not too long service times. The recommendation from this paper is that the shorter of the two times should be applied in practice. The argument behind this conclusion is the following. It is difficult to find any reasons why the model would underestimate the remaining lifetime. On the other hand the values in Fig. 5 and Fig. 6 can overestimated the time to the next inspection: (i) Higher $\gamma\delta$ gives shorter times. (ii) The presence of system stresses can give rise to rapid damage formation, although plant operators nowadays have in general a good control of hanger adjustment, etc. to minimise the system stresses.

7 CONCLUSIONS

- Since both the nucleation and growth of creep cavities can be described by a power function in strain, the physical creep damage can be modelled as a function of creep strain. It has also been shown that the damage rating introduced by Neubauer can after generalisation be described in the same way.
- According to the Sandström-Kondyr model the strain fraction - time fraction curve is independent of material for low alloy and 12% CrMoV creep resistant steels. With this creep strain - time model the residual lifetime can be predicted from the observed damage. The logarithm of the remaining life is approximately a linear function of the damage class. For a given damage class the remaining life is directly proportional to the service time.
- Assuming that the creep damage at the next inspection should be intermediate to the observed damage and that corresponding to a damage class of 5, the time to the inspection has been modelled. The proposed times to next inspection are 46, 20 and 8% of the service time for a damage class of 3, 3.5, and 4 respectively.
- The model predicts longer times to the next inspection than according to the Nordtest guidelines at low damage classes but shorter times at larger damage. At lower damage classes it is recommended that the Nordtest values are used, since for example the effect of system stresses has not been taken into account in the model. However at higher damage classes it is recommended that the model values are applied.

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Development of Creep Damage Assessment System for Aged Thermal Power Plant

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Abstract

IHI has developed the Creep Damage Assessment System to identify voids by processing an image observed by a small laser microscope with an advanced image processing technique jointly with Chugoku Electric Power Co., Inc. The result can be obtained immediately on the spot. Application tests of the system at the Unit No.3 boiler of the Kudamatsu Power Station showed good operability, adaptability to the environment, and accuracy. The new system can easily indicate damage conditions in parts during the periodical inspection, allowing rapid maintenance. Time reduction required for assessment and increased reliability of equipment can be also achieved.

1 Introduction

About 80% of the nation's rapidly aging thermal power plants are 20 years old with some plants exceeding 250 000 hours of cumulative operation. It is therefore increasingly important to secure the reliability of the equipment.
At the welded portion of a high-temperature components of the boiler of thermal power plants, a very small hole of about 1 μm called creep void is made in the metal structure due to prolonged use and will grow to a crack in due course to destroy the member. By the conventional void area rating method(1), the replica sampled at the site was taken back to the laboratory and the extent of damage was assessed by observing the void condition through

the scanning electronic microscope. This method, however, has such problems that the void identification requires a specialist and it is impossible to evaluate soundness during the periodical inspection period because the assessment takes time. To solve such problems, therefore, the authors developed a diagnostic system that can quickly assess the extent of damage at the site by directly observing the portion in question through a small laser microscope and making automatic recognition of the void through image processing, jointly with Chugoku Electric Power Co., Inc. The following outlines the system.

2 Creep damage assessment system

2.1 Features of system

This system has the following features.

(1) It is possible to directly observe the portion in question and check the condition of the metal structure at the site using a small laser microscope.

(2) It is possible to conduct the diagnosis through the automatic recogni tion of the void by the image processing technique developed by IHI without depending on a specialist, thus preventing the variance in diagnosis that result from personal error.

(3) Since the diagnostic result can be quickly obtained on the spot, proper preventive maintenance can be conducted during the periodical inspection.

(4) As to a narrow portion that cannot be directly observed, the replica is sampled and observed through the microscope, thereby obtaining the diagnosis result on the spot, as in the case of direct observation.

(5) Since such data as images observed and diagnostic ressults can be automatically saved, it is not necessary to store the replicas as in the conventional method.

2.2 System configuration

As shown in Fig. 1, the components are installed inside and outside the boiler furnace. The equipment inside consists of the small laser microscope, jig controller and jig driver to operate and control the movement of field of view, etc. The equipment outside consists of the image processing device to automatically diagnose the image observed and assess the extent of damage, microscope monitor, etc. The small laser microscope equipment is composed of the microscope and the fixed jig. This microscope is a new type of microscope that images the observed surface by scanning the laser beam, and it is possible to obtain a clear FSM (Focus Scan Memory) image focused over the entire field of observation view by storing/synthesizing the real-time image while moving the object lens along the focal axis as well as the real-time image showing only the focused portion. It has a resolution of 0.30μm, sufficient performance for detecting the void. By taking environment, including vibration and dust, into consideration, a compact and light microscope superior in dustproofing as shown in Fig. 2 was developed. The fixed jig comes in two types, one to directly observe the portion in question and the other to observe the replica sampled. The fixed jig for direct observation is made small and light so as to be held with one hand to facilitate the operation on the spot, and it adopts a belt to clamp so as to be installed easily by two persons. The movement of the field of view of the microscope after the jig is fixed can be remote-controlled from inside and outside the furnace by means of the electrical three degrees of freedom cartesian moving mechanism installed to the jig.

2.3 System functions

The image processing device, the nucleus of this system, has an automatic assessment function, manual assessment function, correcting assessment function that can correct void recognition results, etc. Here the automatic assessment function is explained.

Fig. 3 shows the processing flow of the automatic assessment. First, the field of view of the microscope is set at the assessment start position and the FSM image at that position is generated and displayed on the microscope monitor. The generated image is inputted to the image processing device and the image processing is done using the automatic void recognition technique described later. From the area of the void recognized, the void area per image is calculated. After processing for one image sheet is completed, to assess the next image, the field of view is automatically moved in such a way that the image processing range will be continuous.

The above series of processing is continuously done until it reaches about 50 sheets equivalent to the assessment area which is about $1mm^2$. After the processing is completed for all the images, the total void area of all the images is calculated and the calibration curve of damage is drawn as shown in Fig. 4, and the creep damage value is determined.

Finally, the remaining life is calculated from the creep damage value and the cumulative operation time of the boiler and displayed on the screen to complete the assessment. These assessment results, together with the image data, are automatically saved in the magneto optical disk and can be read at any time.

3 Automatic void recognition method

Fig. 5 shows the processing flow of automatic void recognition. First of all, the input image is normalized. This is to convert the density histogram of the input image so as to achieve a constant average value and dispersion, and the void and grain boundary densities are corrected to be in almost the same range. This makes it possible to almost fix the parameters in the subsequent processing and achieve the automation. The normalized image is subjected to the following void candidate extracting and crystal grain boundary extracting. Finally the results of these processings are combined and the void candidates existing on the crystal grain boundary are extracted as true voids.

3.1 Void candidate extracting

The void picked up by the laser microscope has such a character that its center is very dark and its periphery is relatively light. For this reason, if the thresholding value is decreased, only the center portion of the void area is extracted, and if it is increased, the entire void area can be extracted, but many noise areas are also extracted. In this method, therefore, the 2-phase threshold as shown in Fig. 6 was adopted so that the void candidate area could be securely extracted while minimizing the noise extraction.

3.2 Crystal grain boundary extracting

The crystal grain boundary has no fixed pattern, and it has a complicated curved shape. The grain boundary is intermittent and many noises of quasi grain boundaries and abrasions exist, and so it is difficult to detect the grain boundary by just combining the conventional image processing techniques. After the grain boundary candidates are extracted by the sequential region growing method, therefore, a curve is expressed with multiple linear segments through the break line vector process. Thus, the geometric information of the grain boundary candidates is described within the computer and can be processed as signals. From the linear segments described, all the segments longer than a certain length are extracted as the base segments, and the linear segments are connected on the basis of the fitness to straight line and geometrical continuity. This makes it possible to eliminate the noises and extract one continuous grain boundary. As the method to connect the linear segments, two approaches were used: the global search method based on the fitness to straight line and the local search method based on the geometrical continuity. The following explains the sequential region growing method, global search method, and local search method.

(1) Sequential region growing method

In this method, the grain boundary candidate area is divided into several density ranges on the basis of the multi-phase density threshold, and if the divided areas are adjacent to the nuclear area (darkest density area) securely judged as the grain boundary, they are sequentially integrated as the grain boundary area. By repeating this processing, it is possible to achieve a good growing of the grain boundary area while avoiding the extraction of noise areas.

(2) Global search method

In this method, even if multiple linear segments are widely disconnected, they are connected and extracted as the grain boundary if they form one straight line from the macro viewpoint. For each base segment, judgment is made if it is possible to form a straight line in pair with other linear segment, and if it is possible, a straight line is formed by the method of least squares, and it is hypothesized that the grain boundary exist on the straight line (Fig. 7-(a)). And all the linear segments existing on the straight line are extracted as candidate segments (Fig. 7-(b)), and they are connected into one continuous grain boundary (Fig. 7-(c)).

(3) Local search method

By the global search method, it is possible to extract grain boundaries existing on the same straight line but it is impossible to extract a curved grain boundary. In this method, linear segments existing near and continuous in direction as seen locally are sequentially connected. As shown in Fig. 8-(a), linear segments parallel to the base segment and in the width range W are taken as candidate segments. An end point of the base segment is made the searching point, and of the candidate segments having their end points within the circle of radius r from this searching point, the segment near the base segment and in the same direction is connected with the base segment. The end of the segment connected is made the next searching point and the same processing is thus repeated until there is no more segment. The segments thus connected are extracted as the grain boundary (Fig. 8-(b)).

3.3 Void recognition results

Fig. 9 shows the results of extracting tests conducted against the laser microscope image of actual voids. (a) of the figure shows the original image and (b) - (d) the results of extracting void candidates, grain boundaries, and voids respectively. The red, green, and blue in Fig. 9-(d) indicate void, noise, and grain boundary respectively, and it is known that the voids on the grain boundary are extracted well.

4 Actual machine application test

The actual machine application tests of this system were conducted at the Kudamatsu P/S unit-3 boiler of Chugoku Electric Power Co., Inc. The portions subjected to the assessment were the circumferential joint of the header at the outlet of the final super heater and the stub weld.

Fig. 10 shows the installed condition of the small laser microscope system. This system can be operated by two persons, and it can be well applied to such narrow portions as stub weld as well sa the header circumferential joint, and clear structure images were obtained at all the places through direct observation. As to places that cannot be directly observed, it was confirmed that the assessment could be made on the spot by observing the replicas sampled through this microscope. The results of measuring the working time revealed the prospect of being able to reduce the mandays required for the assessment by about 60% by adopting this system in comparison with the conventional method. If work accompanied by impulsive force is done very near, the effect of the vibration cannot be avoided, but it was confirmed that normal peripheral working and dust posed no problem. The assessments at the same places of the header/stub were made using this system and the conventional method, and a comparison of the results confirmed that the assessment results of this system are adequate.

5 Conclusion

By the void area rating method put to practical use as a non-destructive damage measuring method of aged equipment, the authors developed the creep damage assessment system with which the assessment results can be obtained on the spot by directly observing the portion in question with a small laser microscope system and using the automatic void recognition technique through the image processing, jointly with Chugoku Electric Power Co., Inc. The actual machine application tests of this system were conducted at the Kudamatsu P/S unit-3 boiler of Chugoku Electric Power Co., Inc., verifying good operability, applicability to the environment, assessment accuracy, etc. Since it is possible to grasp the damage of portions during the periodical inspection and conduct quick maintenance by applying this system, we believe it can contribute to a large reduction in assessment period and improved reliability of the equipment.

We intend to further improve this system by repeating the assessments with actual machines in the future.

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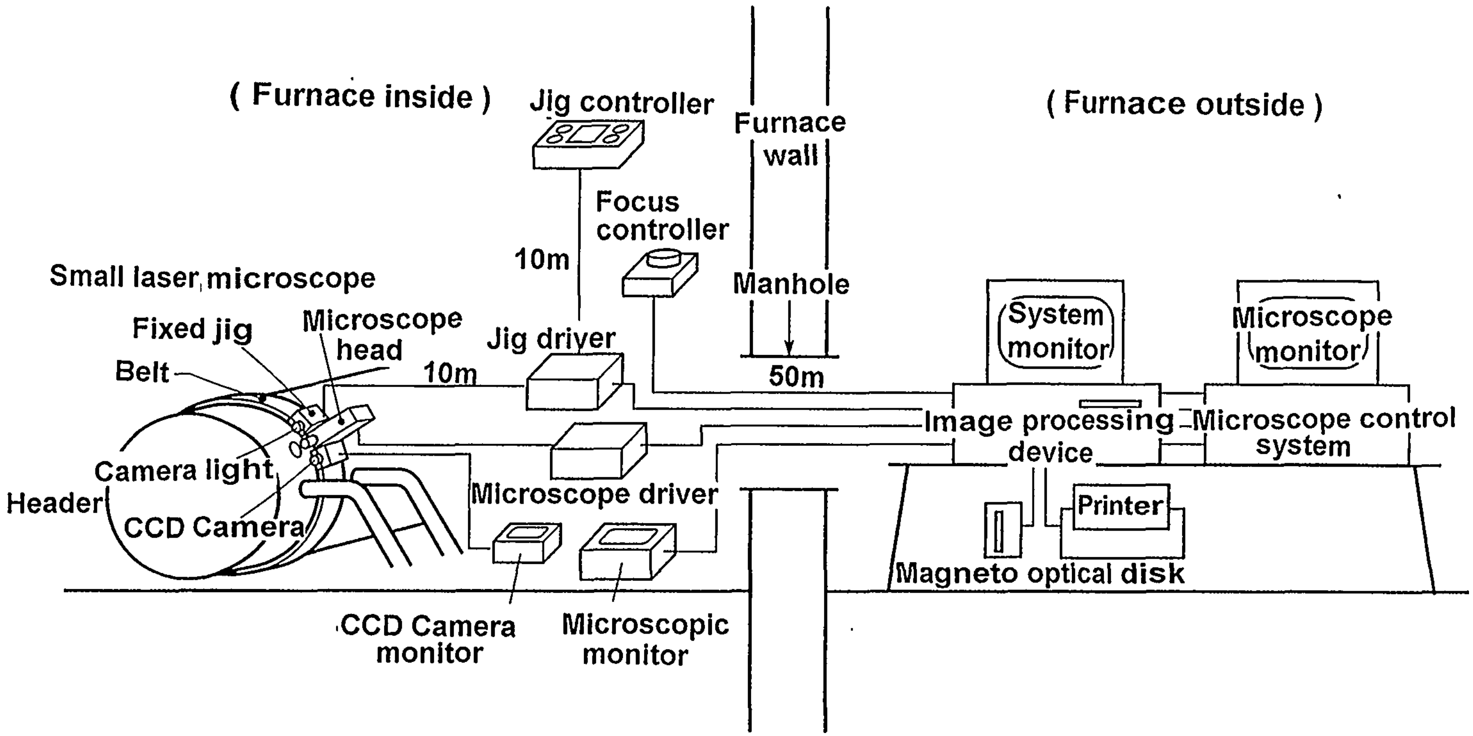
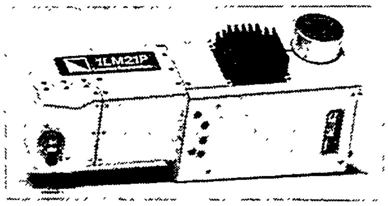


Fig.1. System configuration.



Light source	Semiconductor laser
Dimensions	131(Height)×103(Width)×358(Length)mm
Weight	5.0 kg
Magnification	1 250 times
Resolution	0.30 μm

Fig.2. General view and specification of small laser microscope.

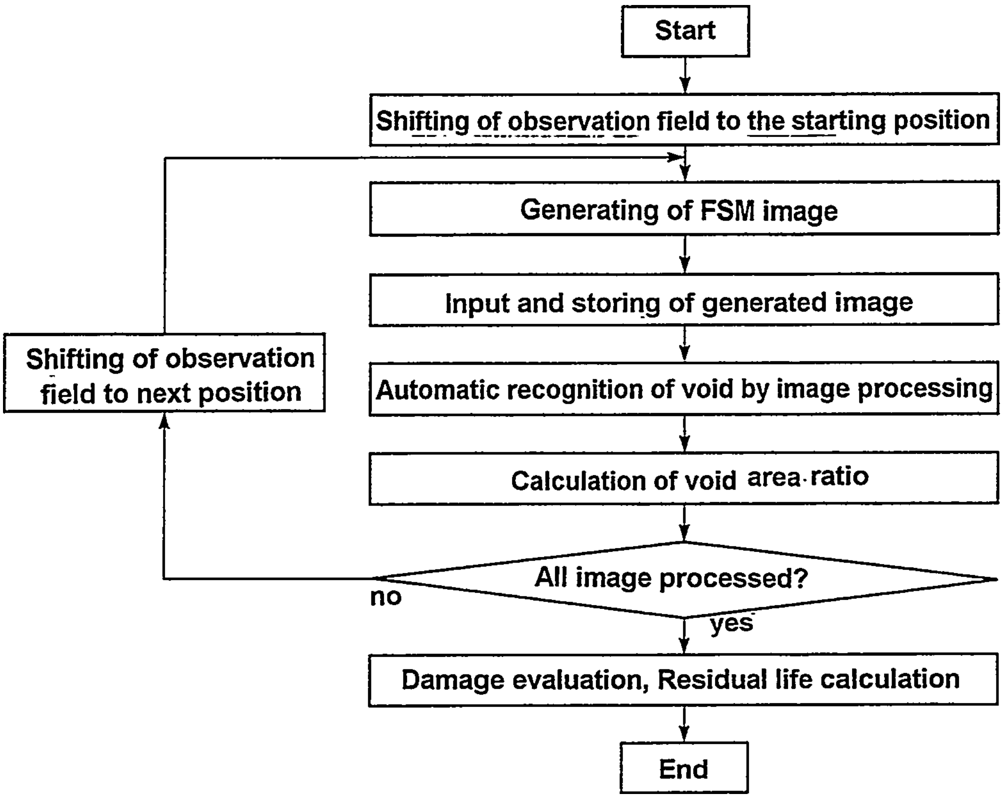


Fig.3. Processing flow of automatic creep damage assessment.

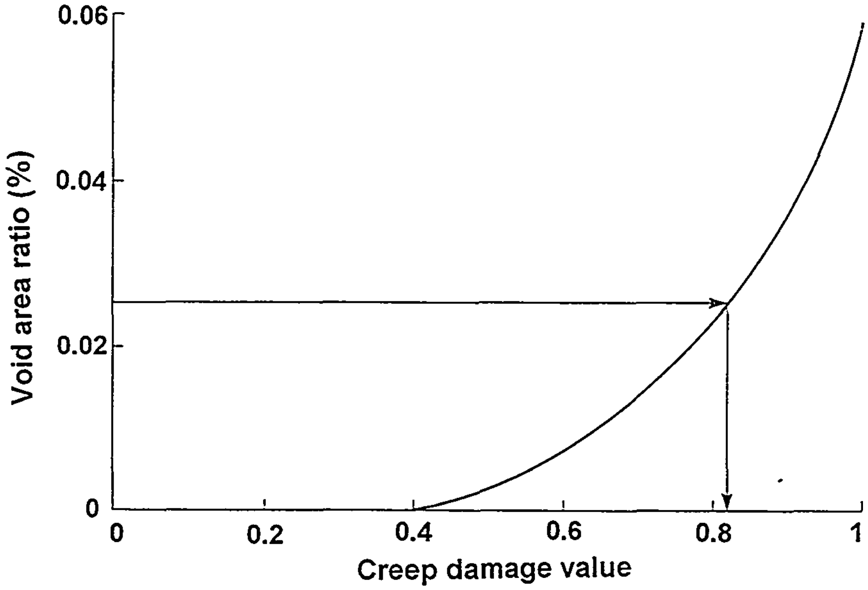


Fig.4. Calibration curve of creep damage.

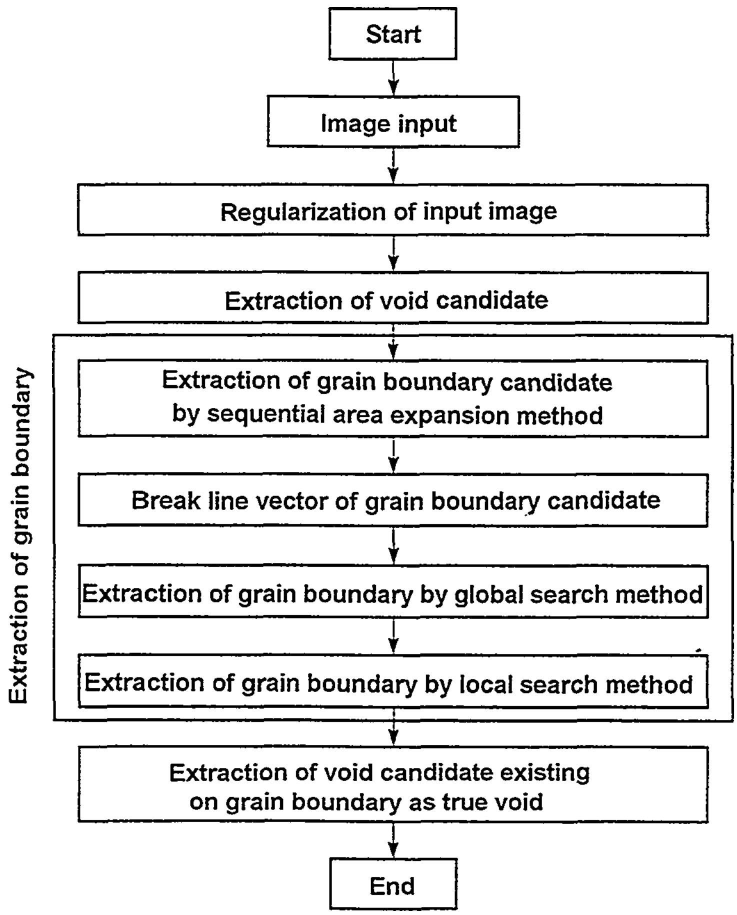


Fig.5. Processing flow of void recognition.

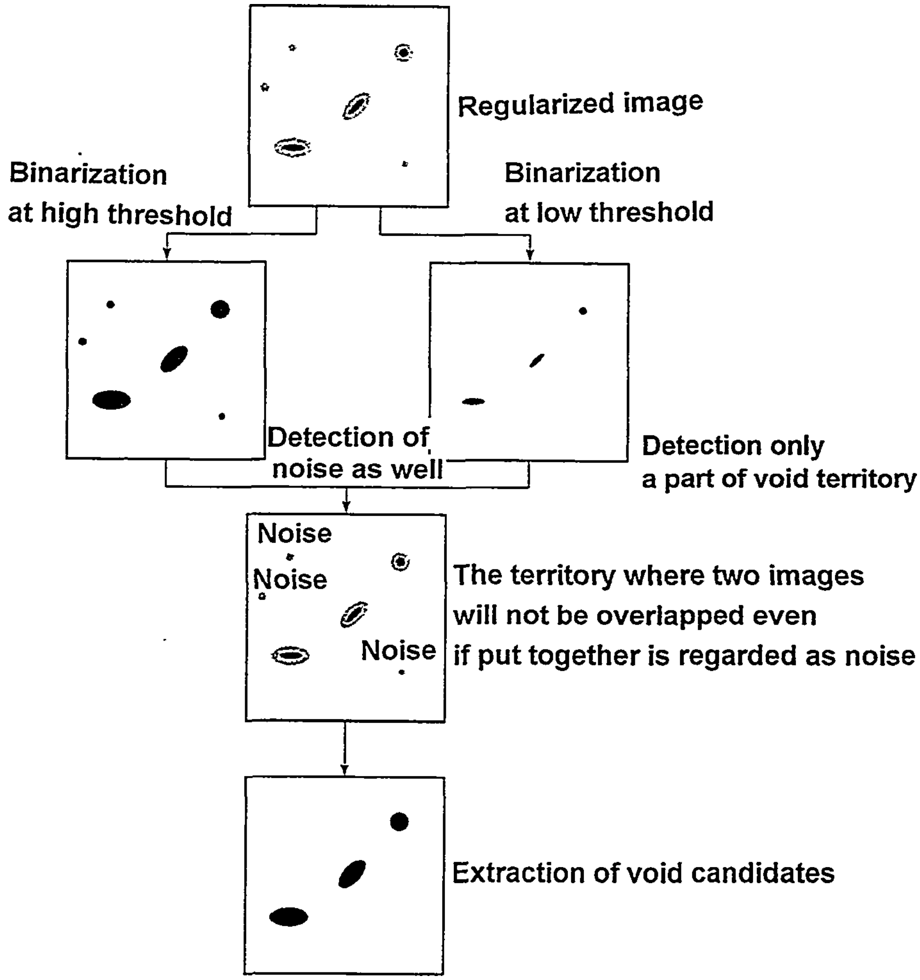


Fig.6. Process of extracting void candidates.

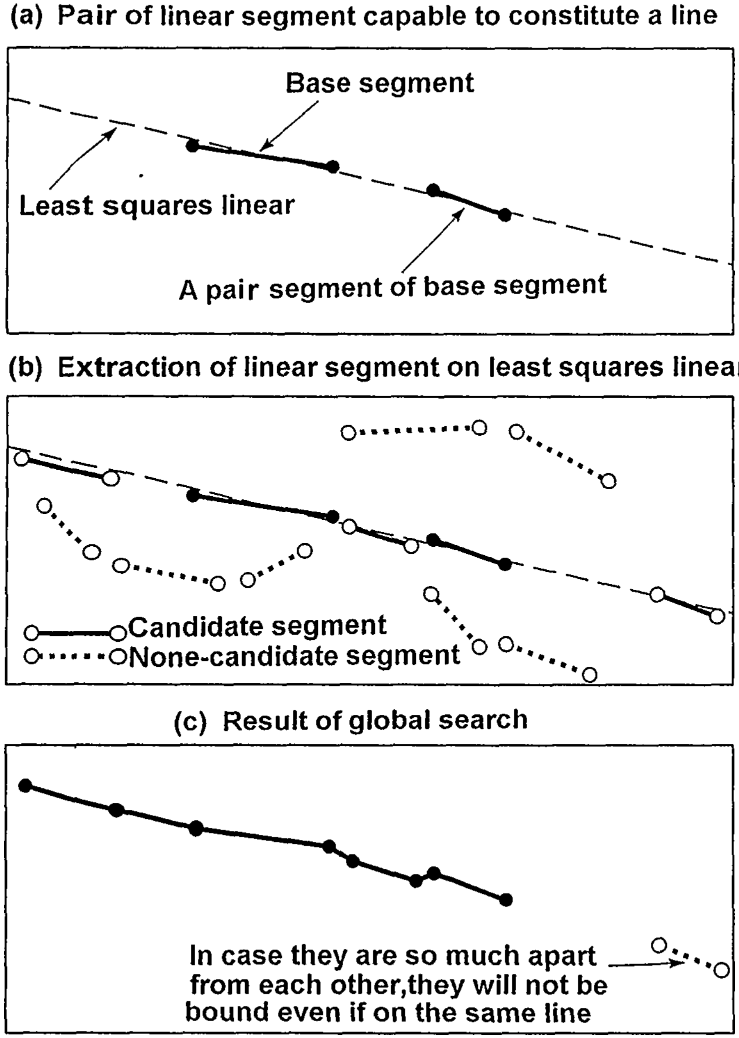


Fig.7. Extracting grain boundary based on the global search method

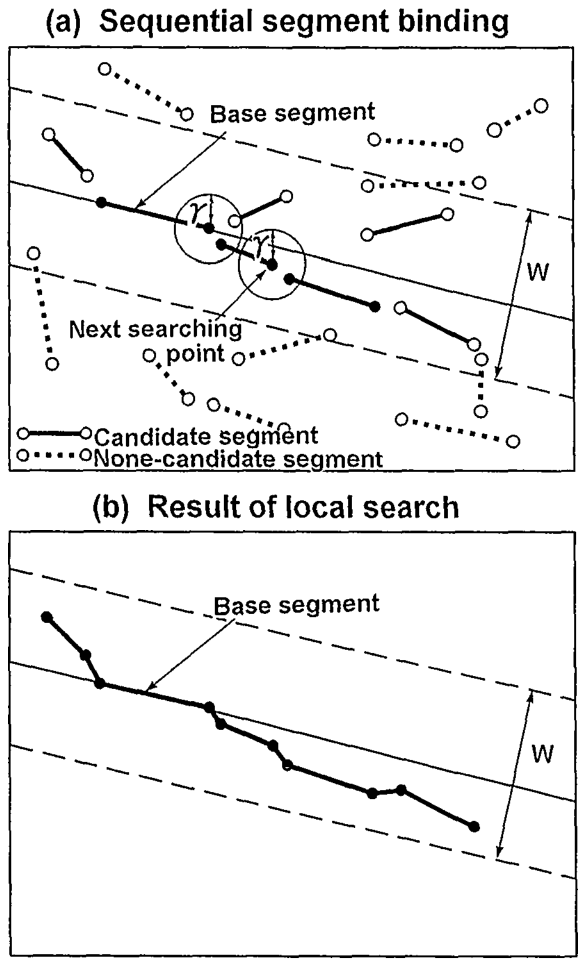


Fig.8. Extracting grain boundary based on the local search method

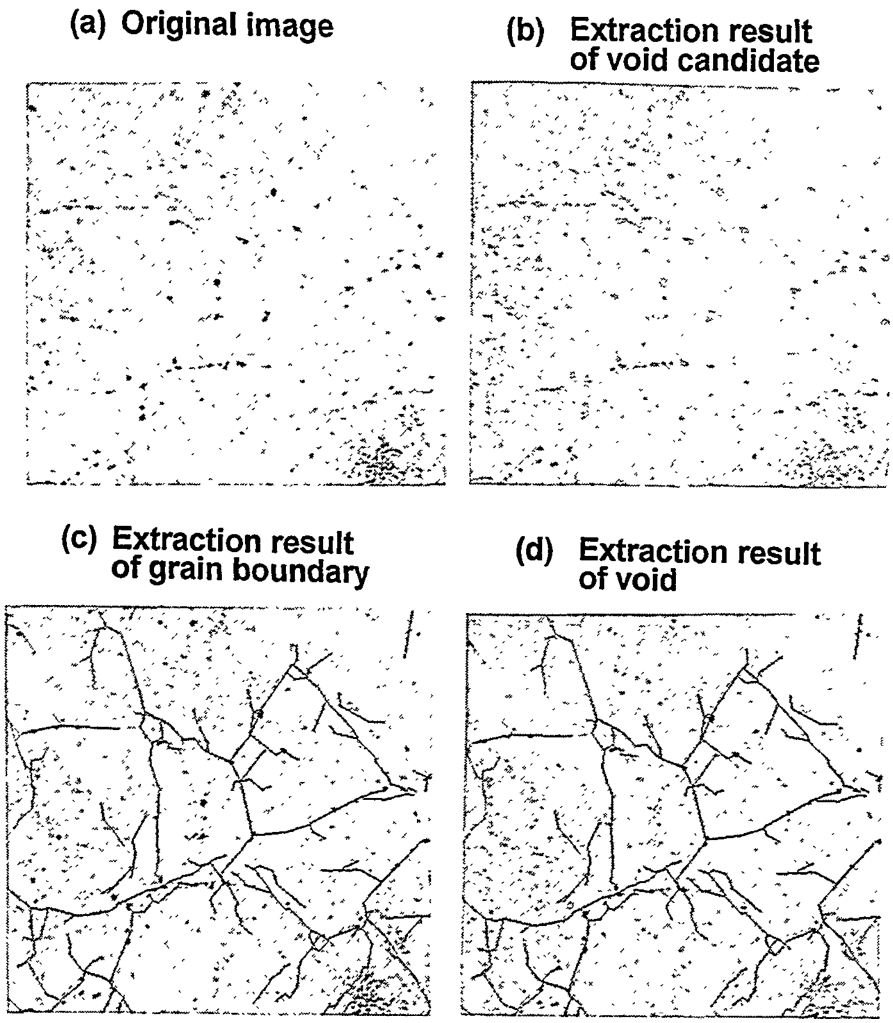


Fig.9. Example of void recognition process.

(a) Outer view of small laser microscope equipment

(b) Microscope objective lens part

Fig.10. General view of observation at header-stub welded part by laser microscope.

PREDICTION OF MATERIAL CREEP BEHAVIOUR FOR STRAIN BASED LIFE ASSESSMENT APPLICATIONS

J.H. Rantala[#], R.C. Hurst[#], F. Bregani*

Abstract

In this work the idea of using constant load uniaxial creep test results instead of constant stress results for developing a CDM creep model for the P92 material is demonstrated. Due to limited availability of creep test results this work is based on incomplete test data and a general stress rupture line. In spite of these limitations a material creep model was developed for use in a FE analysis.

Using P91 material as an example, a method is proposed to account for differences in strain evolution as a function of stress which normally manifests itself as lower strain values at low stresses in a normalised time-strain plot. This allows the CDM model to be used both in FE analysis and in strain-based life assessment engineering calculations.

1 Introduction

The development of the CDM creep model for the P92 material was performed as a contribution to the LICON project, "A METHODOLOGY FOR LIFE PREDICTION AND CONDITION ASSESSMENT FOR WELDS OF REFURBISHED AND NEW STEAM CYCLE PLANTS", (BRPR-CT96-0354). In the project a longitudinally welded test component (OD 245*21 mm) will be tested at 625°C and JRC will perform a FE analysis to predict the damage behaviour of the vessel. For this purpose the CDM model was used to produce a material model to be used in the FE analysis.

Unfortunately, at the time of preparing this paper, the creep test results of P92 at 625°C were not yet available to the authors. Within another programme Mannesmann Forschungsinstitut had a isothermal constant load test series running with the test at the highest stress approaching rupture. This data in combination with the rupture information from ASME was the

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absolute minimum requirement for the CDM creep model development. Because the creep tests had not yet reached rupture, the rupture strains had also to be estimated. It was assumed that the rupture strains of P92 at 625°C would be similar to P91 values at 600°C. Obviously, taking all these shortcomings and assumptions into account, the accuracy of the prediction is restricted, but on the other hand this demonstrates the applicability of the model when only limited amount of basic creep data is available.

1.1 CDM modelling based on Constant Load data

The Continuum Damage Mechanics (CDM) creep model was originally developed for application to data obtained from tests carried out under constant stress conditions. Consequently the normal route for determining the model parameters has been to perform a series of constant stress (CS) creep tests, to do the CDM fitting for the curves and then use the parameters for predicting either constant load (CL) or multiaxial behaviour. In this paper a different approach is proposed which is based on using only CL data.

Using CL data instead of CS data is interesting for the following reasons:

- CL data is normally available for all existing materials at temperatures of interest and can be easily generated for new materials
- CS data is not generally available in sufficient amounts
- Performing additional CS tests appears to be more expensive than CL tests
- Predictions based on a small CS data set may result in modelling the scatter of the experimental facility instead of modelling the true material behaviour
- CL data is used as a basis for design calculations.

For this work a MS Excel based macro "solver" was developed which numerically integrates the strain rates to strain using a time hardening algorithm and calculates the stresses and strains in multiaxial stress situations. This solver is designed to predict the multiaxial behaviour of tubular specimens, which are loaded under combined internal pressure and axial tension.

The traditional route of CDM model development and the proposed route are schematically described in Fig. 1. In the traditional case the fitting takes place in the very beginning of the exercise while in the proposed route the initial CL fitting serves only as a starting point providing "initial guesses" of the CDM parameters which are entered into the multiaxial solver, which then predicts the uniaxial CL curves as a special case of multiaxial stress state. These predicted CL curves are compared with the experimental ones and the parameters are modified semi-manually such that after a few iteration rounds a good fit is reached. Then the parameter set can be verified using a set of multiaxial small scale model component tests. The testing facility of JRC in Petten allows tubular components to be loaded under combined internal pressure and axial tension. The combined loading tests have been reported elsewhere by Hurst et al. (1) and are not included in this study.

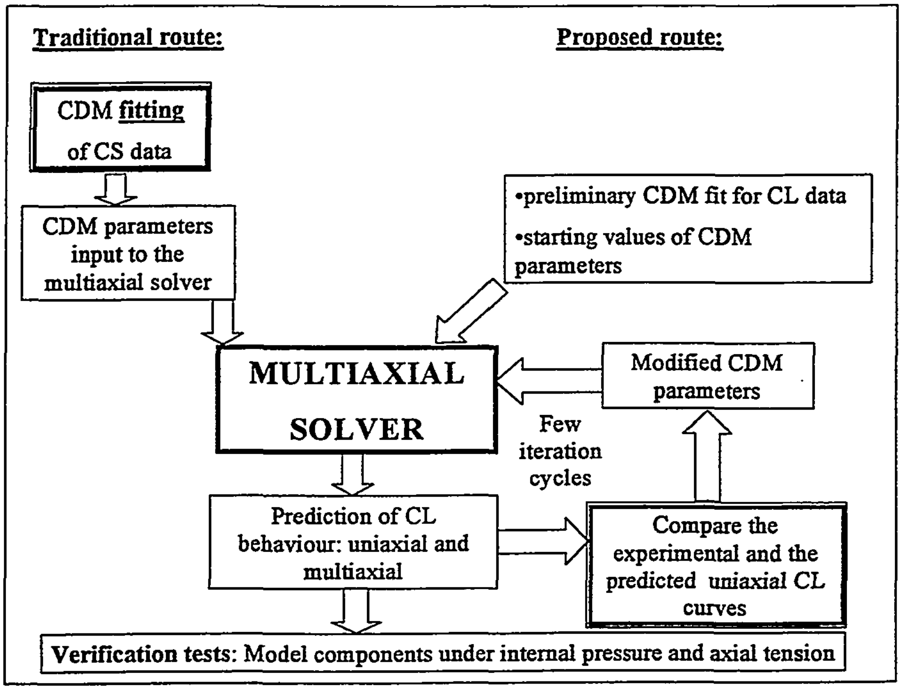

Fig. 1. Schematic presentation of the traditional and the proposed way of developing a CDM creep model.

1.2 The CDM creep model

The basic constitutive equations of the constant stress CDM model are (2):

$$\frac{d\varepsilon}{dt} = K\left(\frac{\sigma}{1-\omega}\right)^n t^{-m} \tag{1}$$

$$\frac{d\omega}{dt} = A\frac{\sigma^\nu}{(1-\omega)^\phi} t^{-m} \tag{2}$$

where t = time, ω = damage parameter
σ = applied stress
m,n, ϕ, ν, K, A = CDM model parameters

In these equations the time component relates to the primary part of a general creep curve while the tertiary creep is introduced by the damage term.

Under multiaxial state of stress the following equations are used to calculate the strain rates and damage rates:

$$\dot{\varepsilon}_1 = \frac{K\sigma_{MSDC}^{n-1}(\sigma_1 - 0.5(\sigma_2 + \sigma_3))}{(1-\omega)^n} t^{-m} \tag{3}$$

$$\dot{\omega} = A\frac{\sigma_{MSRC}^{\nu}}{(1-\omega)^{\phi}} t^{-m} \tag{4}$$

MSDC = Multiaxial stress rupture criterion
MSRC = Multiaxial stress deformation criterion

1.3 Application of the proposed route

Availability of P92 creep curves at 625°C proved to be a problem. Fortunately Mannesmann Forschungsinstitut made the results of four constant load creep tests at 625°C available, all of them still running at stresses of 80, 100, 120 and 140 MPa. The normalised creep curves are presented in Fig. 2 (for clarity only the tests at 140 and 120 MPa). Only the test at 140 MPa has progressed beyond the secondary creep stage. For the

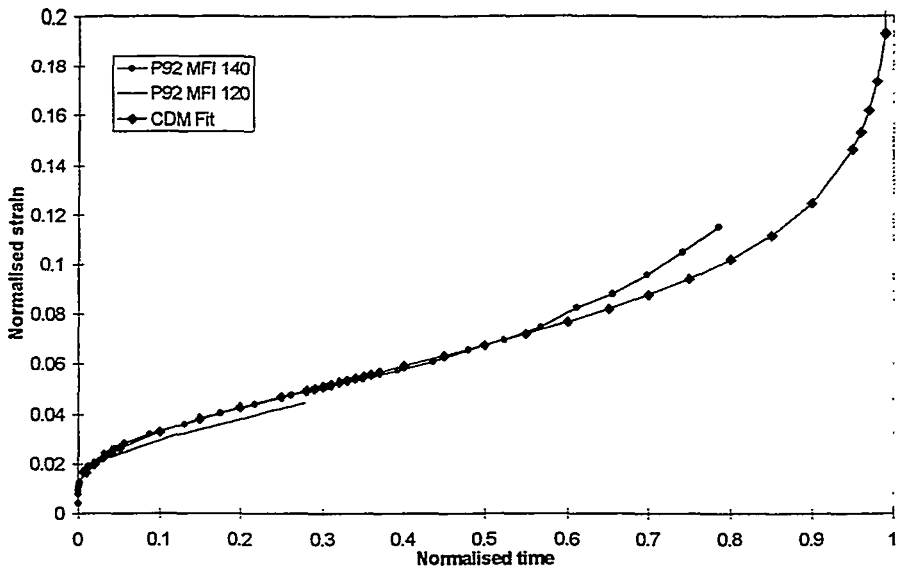

Fig. 2. The normalised P92 CL creep curves and the initial CDM fit.

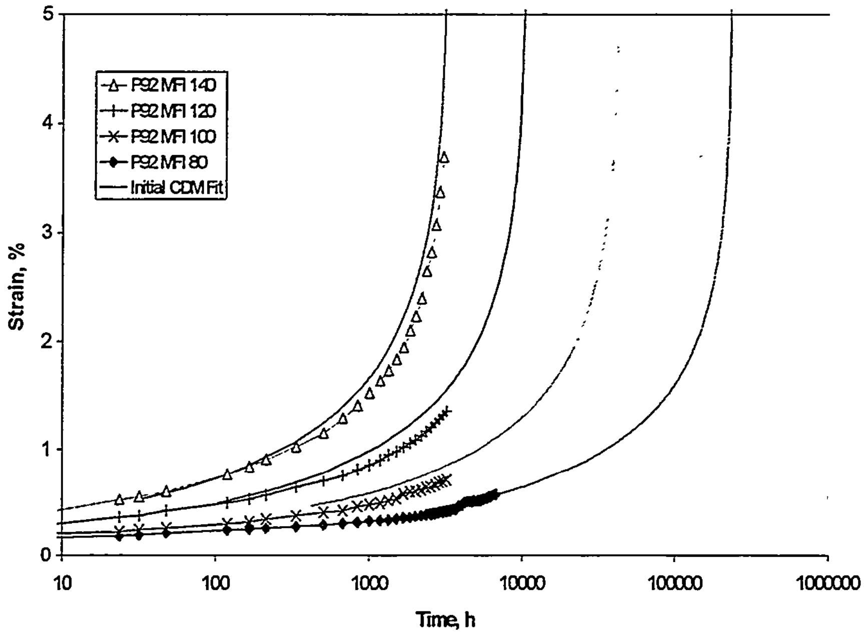

Fig. 3. Uniaxial P92 CL creep curves (lines with markers) and the initial CDM fitted curves (solid lines), note logarithmic time.

purposes of this analysis a rupture time of 3850 h was estimated for this test. The test at 120 MPa had progressed to a life fraction of 0.25 using the ASME rupture mean line as a basis of the rupture time prediction. The tests at 80 and 100 MPa were only at a life fraction of about 0.05. An initial CDM fit based on this CL data was performed and the parameters m, n and ϕ were manually adjusted such that the shape of the normalised creep curve and the fitted curve in Fig. 2 would match. It is normal that the fitted curve slightly underestimates the strain values at life fractions beyond 0.6. The individual CL creep curves and the fitted curves are presented in Fig 3 versus logarithmic time.

The CDM parameters obtained from this initial CL fit are not theoretically correct, because they are based on CL data instead of CS data. This is done deliberately because they will only serve as an initial input to the multiaxial solver, which will predict the CL behaviour using the time hardening algorithm. The predictions of CL creep curves are compared with the experimental ones and as the second phase of the fitting procedure the CDM parameters ν, K and A are modified iteratively such that the predicted stress-rupture curve becomes identical with the experimental trendline and the predicted CL curves match the experimental ones. The predicted failure strain was used as a basis for the cut-off point for calculation of failure time. The ASME rupture mean line and the predicted rupture mean line are completely overlapping in the stress-rupture plot in Fig. 4. The estimated rupture time of 3850 h for the test at 140 MPa is slightly above the mean line. The predicted CL curves are plotted together with the experimental curves in Fig. 5. The predicted creep curves versus normalised time are presented in Fig. 6. The vertical spacing of the predicted creep curves at different stresses in this figure is dependent on the assumed failure strains. As none of the experimental curves had reached failure, it was assumed that the failure strain will be 26% at 80 MPa and 32% at 140 MPa.

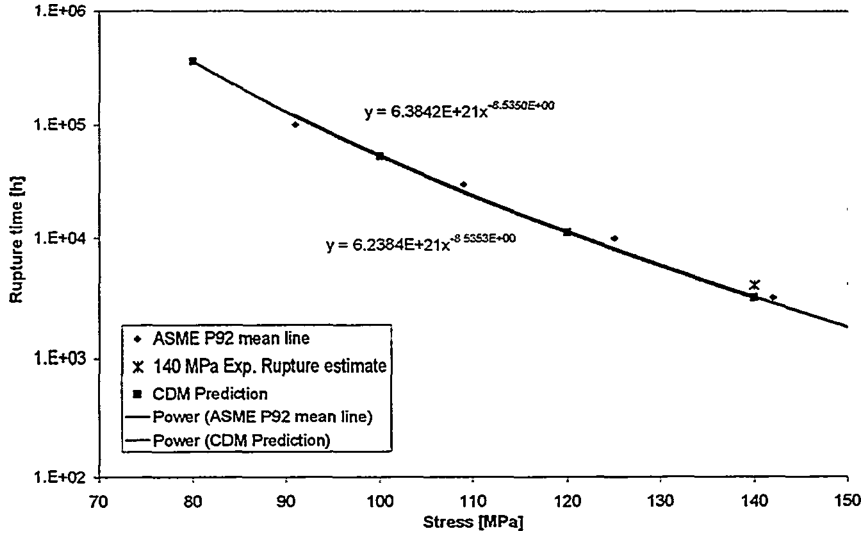

Fig. 4. Stress rupture plot of ASME uniaxial P92 CL data (squares) and the power law fit. The predicted trendline is overlapping with the experimental one.

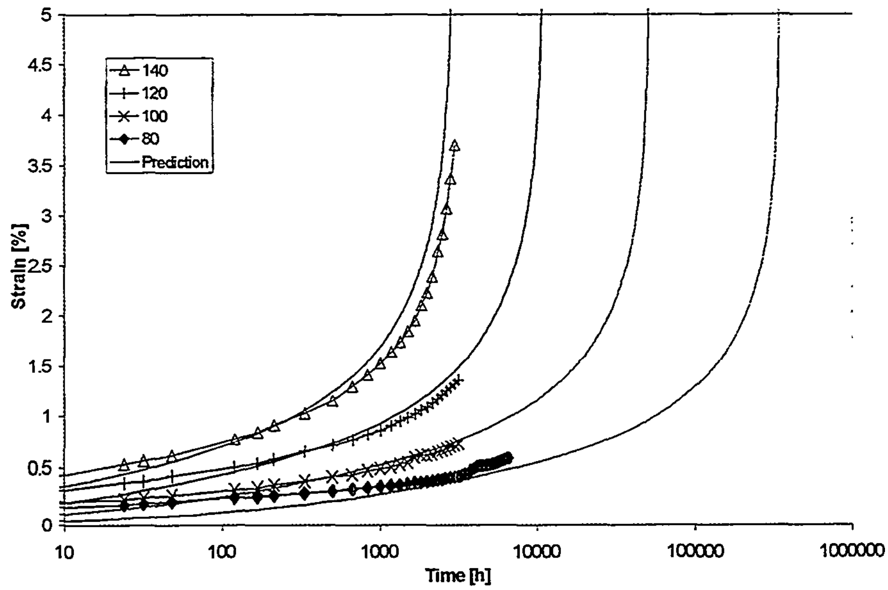

Fig. 5. Predicted P92 CL CDM curves and the experimental curves.

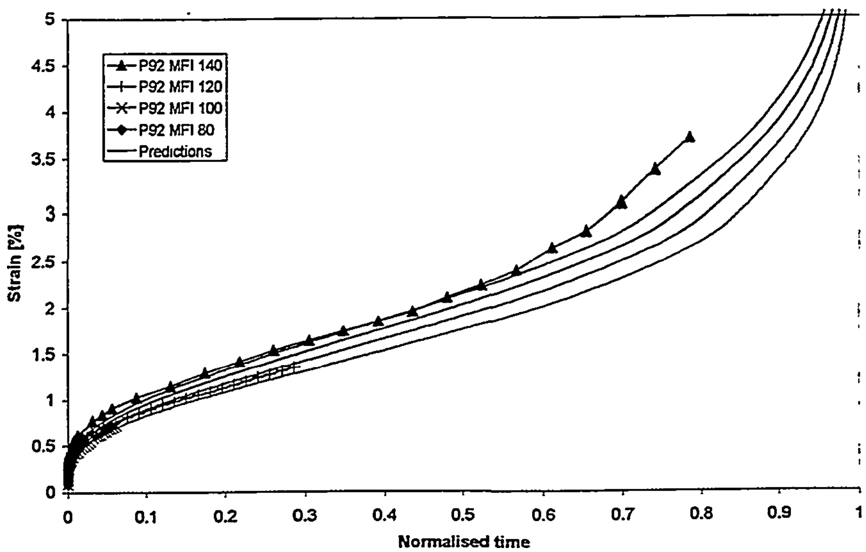

Fig. 6. Experimental P92 CL creep strains versus normalised time with multiaxial CDM predictions at stresses 140 (top curve), 120, 100 and 80 MPa (bottom).

It is likely that these assumptions of failure strain have to be revised on the basis of the actual rupture strain data.

The CDM model developed will be used as a material model in the ABAQUS FE analysis which will be performed to evaluate the creep and damage behaviour of the LICON P92 test vessel.

2 Accounting for the stress dependency of strain development

The CDM theory has one serious drawback if it is intended to be used for strain-based life predictions in plant. Namely the CDM model predicts only one shape for the normalised creep curve while the experimental creep curves show a clear stress dependency of strain development, as shown in Fig. 7, which is based on an earlier study on the creep behaviour of P91 steel for the Italian ENEL power company (1, 3). This can also be seen in the CDM equations, which have been reported elsewhere (1), which show that the equations of strain and damage are a function of only life fraction, but not stress. As a consequence of this the CDM model would predict too high strain values at service stress levels, which would lead to excessive conservatism in life predictions. One example is demonstrated in Fig. 8, where the P91 CDM prediction is biased to give reasonably good strain predictions at the lowest stress, but on the other hand the strain values at higher stresses are clearly underestimated early on in the curve.

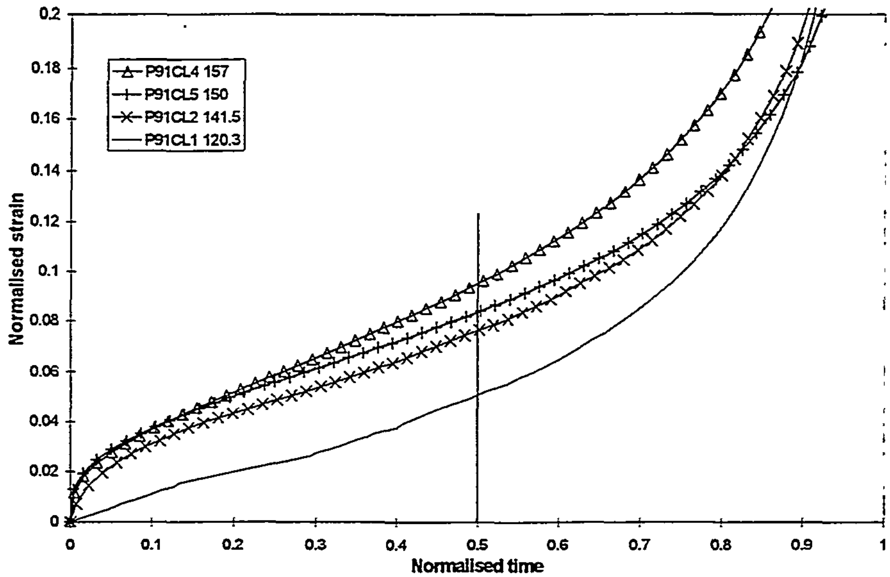

Fig. 7. Normalised P91 experimental creep curves demonstrating the stress dependency of strain development.

This shortcoming can be corrected by introducing the concept of "half life strain" which is the strain value at the life fraction t/t_f=0.5, see Fig. 7. It is commonly observed in creep testing that the amount of primary creep is higher at high stresses. A series of tests at different stress levels produces typically a bunch of curves with the tests at higher stress appearing above the lower stress result.

The proposed method is to modify the measured failure strains such that failure strains are proportional to the "half life strain". In this particular example the half life strains were multiplied by a factor of 10.57 such that the failure strain at the highest stress retains its value, but the predicted failure strains at low stresses, by definition, are clearly underestimated. This should not have any serious effect in the practical life assessment cases because components will be replaced or repaired well before failure. Accuracy of the strain development is more important than the final value of strain at rupture, especially if the component life assessment is based on strain measurement.

The strain predictions were then calculated using the multiaxial solver and without doing any further modifications or iterations other than using the multiple of half life strains instead of measured failure strains, the results shown in Fig. 9 were achieved. These results show that by deliberately sacrificing the accuracy of failure strain, the predicted strain values during secondary creep are accurate over the whole stress range and that the concept of half life strain enables the stress dependency of the strain development to be modelled more precisely.

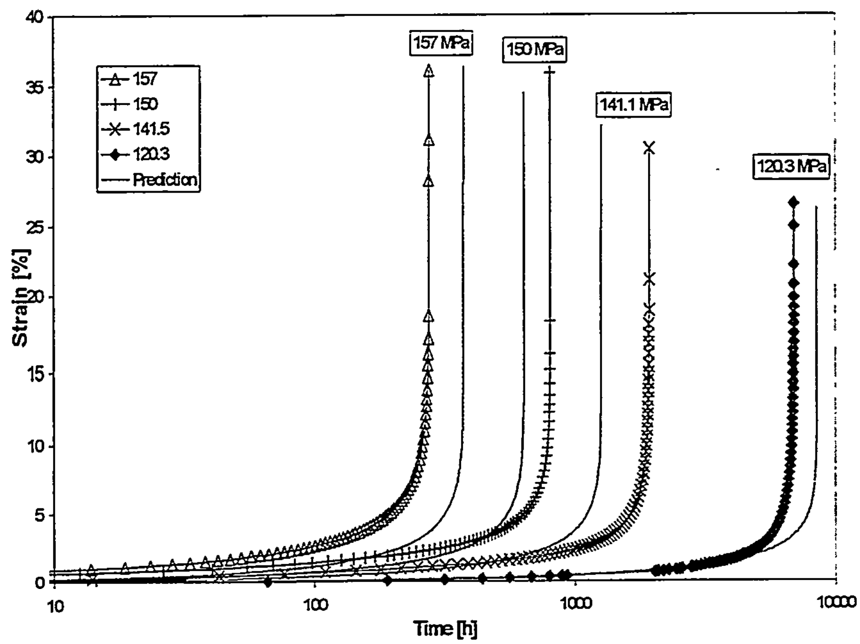

Fig. 8. Uniaxial P91 CL creep curves (lines with markers) and the predicted curves (solid lines), note logarithmic time.

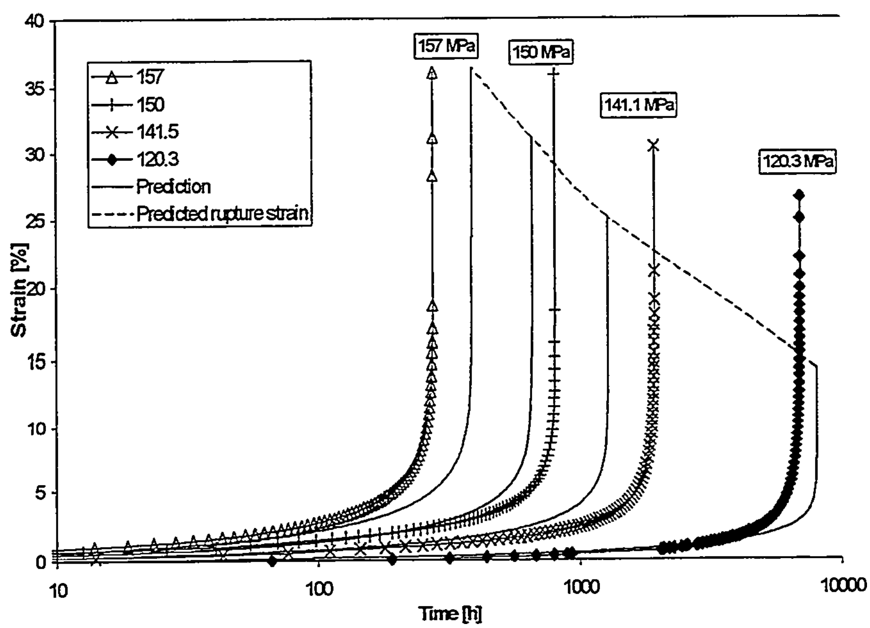

Fig. 9. Experimental and predicted CDM creep curves using the half life strain concept. Note the improved accuracy of strain predictions compared with Fig. 8.

3 Acknowledgements

Mannesmann Forschungsinstitut is acknowledged for provision of the ongoing P92 creep test results. The ENEL company is gratefully acknowledged for the research contract 2RTRI0015 and for their interest in using the CDM models.

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CREEP CRACK GROWTH IN A REACTOR PRESSURE VESSEL STEEL AT 360°C

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ABSTRACT

Plain creep (PC) and creep crack growth (CCG) tests at 360°C and post metallography were carried out on a low alloy reactor pressure vessel steel (ASTM A508 class 2) with different microstructures. Lives for the CCG tests were shorter than those for the PC tests and this is more pronounced for simulated heat affected zone microstructure than for the parent metal at longer lives. For the CCG tests, after initiation, the cracks grew constantly and intergranularly before they accelerated to approach rupture. The creep crack growth rate is well described by C*. The relations between reference stress, failure time and steady crack growth rate are presented for the CCG tests. It is demonstrated that the failure stress due to CCG is considerably lower than the yield stress at 360°. Consequently, the CCG will control the static strength of a reactor vessel.

Keywords *Low alloy Reactor pressure vessel steel, creep, creep crack growth, simulated heat affected zone, intergranular*

1 INTRODUCTION

Investigations on the creep crack growth (CCG) behaviour in low alloy C-Mn steels [1-3] at 360°C have been carried out since failures occurred in the pipework systems of fossil-fueled power plant after service lives from 8,000 to 100,000 hours [4]. Analyses of the failures showed that mm-sized defects such as laps, hammer blow marks or shallow notches [2], which may have resulted in stress concentration [5], acted as a crack starter. Subsequent crack growth led to final brittle failure [5].

At such low temperature as 360°C, being below the limit temperature for creep of about 430°C for these steels, design stresses in power generating application are actually based on tensile properties, and creep process is generally considered to be of little importance [6]. Somewhat surprisingly, the mechanism of cracking was eventually identified as being creep [2].

The quest for a parameter to correlate CCG rates has made it possible to develop C*, an energy rate line integral characterising uniquely the crack tip stress and strain rate field for cracked bodies deforming under steady-state creep conditions (or power-law creep obeying Norton's law), c.f. Refs. [7-11]. Being analogous to the J-integral, C* is a modification of the J-integral where strain and displacement in J-integral are replaced by their rates in C*.

The following expression is now well accepted for the estimation of C* in the case of compact tension (CT) specimen [11]

$$C^* = \frac{P \cdot \dot{\Delta}_c}{B(W-a)}\left[\frac{n}{n+1}\left(2+0.522\frac{W-a}{W}\right)\right] \quad (1)$$

where C* is in MPa m/h, P is the applied load in N, $\dot{\Delta}_c$ the load line displacement rate due to creep in mm/h, n the stress index in Norton's law, W the width of the CT specimen in mm, B the CT specimen thickness in mm and a the crack length in mm.

The *aims* of the present work are to investigate whether CCG occurs in a low alloy reactor pressure vessel steel at 360°C, to study CCG behaviour and to examine the effects of microstructure on CCG and failure.

2 EXPERIMENTAL

2.1 Material And Heat Treatment

A low alloy reactor pressure vessel steel (ASTM A508 Class 2) was used in the study. Chemical compositions in as-received condition, satisfied with the requirements of ASTM [12], are shown in Table 1.

Table 1. Chemical compositions (wt%).

Material	C	Si	Mn	S	P	Cr	Mo	Ni	V
As-received	0.19	0.29	0.69	0.0087	0.012	0.35	0.63	0.84	<0.001
ASTM A508 Class 2	≤0.27	0.15-0.40	0.50-1.00	≤0.025	≤0.025	0.25-0.45	0.55-0.70	0.50-1.00	≤0.05

To simulate microstructure in the coarse grained heat affected zone across a weld, the steel was furnace heat treated at 1150°C for 30 minutes followed by boiling water cooling. Then, the steel was tempered at 640°C for two hours followed by furnace cooling. The microstructures are composed of bainite and ferrite in the as-received condition and tempered martensite in the simulated heat affected zone (SHAZ) microstructure. The hardness and grain size in the as-received condition are about 161 to 185 (HV10) and about 16.4 to 20.8 μm, respectively. They increase to 429.4 (HV10) and about 131 to 144.3 μm, respectively, after heat treating and tempering.

2.2 Plain Creep And Compact Tension Samples

A series of plain creep (PC) samples, designated PCS, was taken from SHAZ microstructure. The samples are cylindrical with threaded ends with 5 mm diameter and 55.5 mm gauge length.

Two series of compact tension (CT) samples were considered for CCG tests. One series, designated CTA, was taken from the as-received material and another, designated CTS, from SHAZ microstructure. Geometry of the CT samples is given in Ref. 13. The spark machined notch has a root radius of 0.15 mm. The notch is oriented along the transverse section of the bar, which allows the crack to grow in the radius direction.

2.3 Creep And Crack Growth Tests

By using single specimen, uniaxial constant load creep testing machines the PC samples were tested to rupture at 360°C in air at various stresses from 685 MPa to 730 MPa. The tensile stress at 360°C is 775 MPa.

The reference stress applied on the CT specimens, σ_{ref} in MPa, is calculated according to

$$\sigma_{ref} = \frac{P}{m \cdot B_{eq} \cdot W} \qquad (2)$$

where $$m = -(1+\gamma(\frac{a}{W})) + \sqrt{(1+\gamma)(\gamma(\frac{a}{W})^2+1)} \qquad (2a)$$

and $$B_{eq} = B - \frac{(B-B_n)^2}{B} \qquad (2b)$$

and $$\gamma = \frac{2}{\sqrt{3}} \qquad (2c)$$

where B_n is the net thickness between side grooves of CT specimen in mm.

The CT specimens were tested at 360°C at various σ_{ref}. The σ_{ref} causing instantaneous failure for series CTA and CTS was 519 MPa and 771 MPa, respectively. It should be noticed that the maximum service temperature of this material in boiling and pressurised water reactors is about 320°C. Slightly higher test temperature was chosen to shorten the test duration and to enhance the CCG effect.

The CCG tests followed fully the instructions described by the standard ASTM E 1457 [14]. The tests were conducted in air and progressed to final rupture by using the constant-load method. The direct current potential drop (PD) method was used to monitor crack progress and an extensometer was used to measure load line displacement (LLD). For detailed description of PD method and assembly, the reader is referred to Ref. 13.

The PD output and the LLD for the CT specimens, the creep strain for the PC specimens as well as temperatures were recorded periodically by a logger. The maximum temperature variations with time were controlled within ±2°C of the testing temperatures.

2.4 Post Metallography

Some PC and CT specimens were metallographically examined using light optical microscope (LOM). The mid-thickness of the specimens which is perpendicular to the fracture were sectioned, ground and polished to 1 µm before etched in 4% nital. Fractography was performed on some ruptured CT specimens using scanning electron microscopy (SEM).

The maximum accumulated crack growth length at rupture Δa_{max} on the CT specimens was measured using stereo microscope.

3 RESULTS

3.1 Plain Creep (PC) Tests

All creep curves show insignificant primary creep, dominant secondary creep and pronounced tertiary creep. Creep ductilities in terms of elongation and reduction of area at rupture decrease with increasing time to failure t_R, e.g. elongation decreases from 10% to 8% and reduction of area form 60% to 40% as t_R increases from 0.1 hour to 1609 hours. t_R versus stress σ is given in Fig. 1. It is seen that t_R is sensitive to the stress reduction. As σ is reduced 10 MPa from 700 MPa to 690 MPa, t_R increases from 93 hours to 1609 hours, see Fig. 1. t_R increases linearly with decreasing σ and this relation can be described as

$$t_R = \eta' \sigma^{-\eta} \qquad (3)$$

where η' and η are constants and η is about 168. Also, minimum creep rate $\dot{\varepsilon}_{min}$ decreases with decreasing σ and this follows the Norton's law. The stress index n in the Norton's law takes the value of about 231.

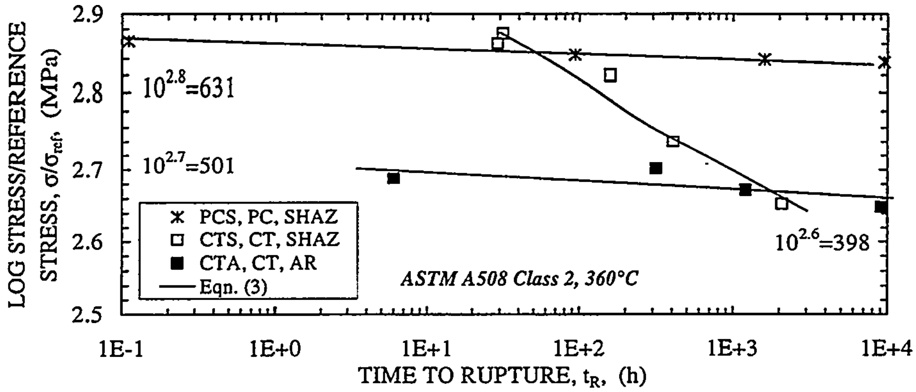

Fig. 1. Log σ or log σ_{ref} versus t_R. PC means plain creep, CT compact tension, SHAZ simulated heat affected zone, and AR as-received.

3.2 Creep Crack Growth (CCG) Tests

t_R as a function of σ_{ref} for CCG test is also given in Fig. 1. In comparison to the PC test results, it can be seen from Fig. 1 that

i) t_R for series CTS is nearly the same as that for series PCS at higher stresses. However, series CTS gives greatly shorter t_R than series PCS at lower stresses.

ii) t_R for series CTA is considerably shorter than that for series PCS. This trend is independent of stresses.

iii) series CTA gives shorter t_R than series CTS at higher σ_{ref}. But, this tends to be reversed at lower σ_{ref}, or longer t_R.

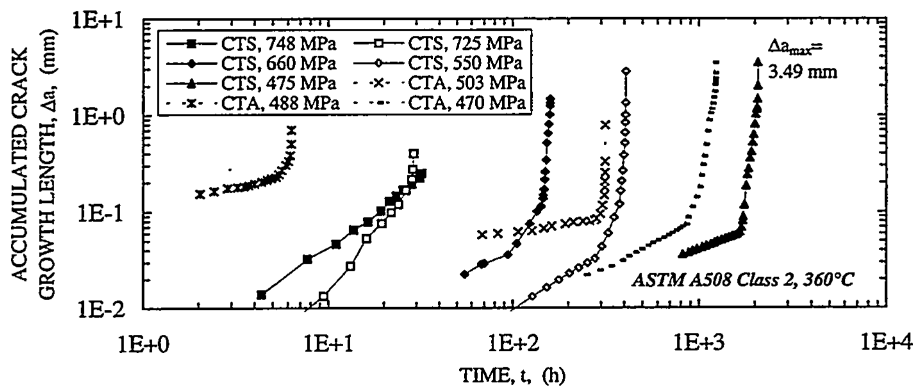

Fig. 2. Δa as a function of t. The highest Δa for each test refers to the measured maximum accumulated crack length at rupture Δa_{max}.

The same relation as eqn. (3) is also found in the CCG tests, see Fig. 1. For instance, the indexes over σ_{ref} are 8.3 for series CTS and 41 for series CTA, respectively. They are much smaller than that for the PC test.

The accumulated crack growth length Δa as a function of time t for the CCG tests is shown in Fig. 2. Δa is calculated according to [14-16]

$$\Delta a = \frac{2W}{\pi}\cos^{-1}\left\{\frac{\cosh(\pi Y_0/2W)}{\cosh\left[\frac{V}{V_0}\cosh^{-1}\left(\frac{\cosh(\pi Y_0/2W)}{\cos(\pi a_0/2W)}\right)\right]}\right\} - a \quad (4)$$

where a is the crack length in mm with respect to the initial voltage V_0 at t=0, V the output voltage at time t and Y_0 the half distance between the output voltage leads in mm. The maximum accumulated crack growth length at rupture Δa_{max} given in Fig. 2 is the measured value. Δa_{max} was determined by observing fracture surface where the crack growth zone was to some extend oxidised and fracture patterns were different in different zones. It is clear from Fig. 2 that after initiation the crack propagated steadily before it accelerated to approach the final rupture. Significant crack growth took place at later stage of the tests. Δa_{max} increases with increasing time. These are true for both series.

Crack growth rate $\dot{a}$ (da/dt) as a function of Δa is exhibited in Fig. 3. $\dot{a}$ is simply the slope of a straight line connecting two adjacent data points (Δa_{i+1} and Δa_i and corresponding time t_{i+1} and t_i) on the Δa-t curves and can be defined as

$$\dot{a} = \frac{\Delta a_{i+1} - \Delta a_i}{t_{i+1} - t_i} \quad (5)$$

It is apparent from Fig. 3 that at the same Δa, the higher σ_{ref} give higher $\dot{a}$ values. This is true for the steady crack growth rate $\dot{a}_s$ (da/dt$_s$) as well. For tests at lower σ_{ref}, $\dot{a}$ is nearly constant when Δa is small. As soon as Δa exceeds a threshold value, $\dot{a}$ increases fairly linearly with increasing Δa.

The power-law relation between $\dot{a}$ and Δa in Fig. 3 can be described by

$$\dot{a} = \xi' \Delta a^{\xi} \quad (6)$$

where ξ' and ξ are empirically determined constants. ξ takes values from about 1 to 5. ξ decreases with increasing t_R for series CTA. ξ increases with increasing t_R for series CTS.

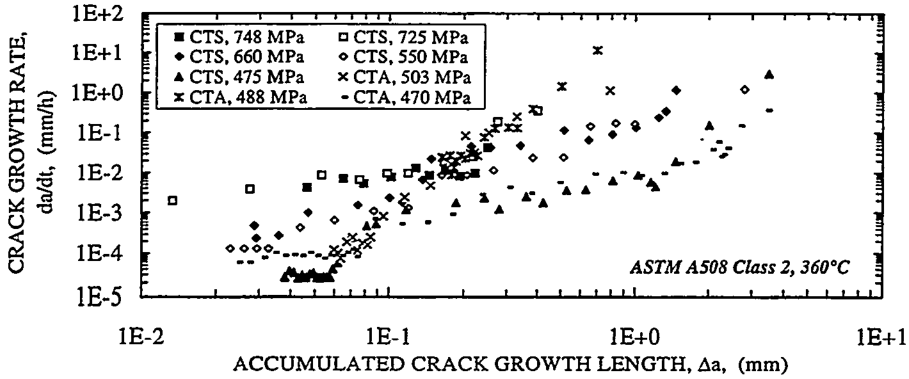

Fig. 3. $\dot{a}$ *(da/dt) as a function of Δa.*

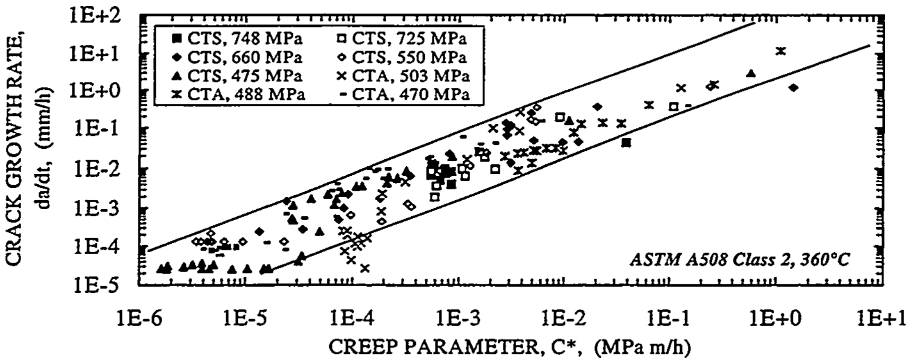

Fig. 4. $\dot{a}$ *(da/dt) as a function of C*.*

$\dot{a}$ as a function of creep parameter C* is displayed in Fig. 4. Calculation of C* is based on eqn. (1). The load line displacement rate, $\dot{\Delta}_c$, is calculated in a similar way to eqn. (5), where Δa is replaced by Δδ.

Regardless of σ_{ref} and microstructure, $\dot{a}$ falls in a narrow band, see Fig. 4. $\dot{a}$ increases linearly with increasing C* and this relation takes the form of

$$\dot{a} = D_0 (C^*)^{\phi} \qquad (7)$$

where D_0 and ϕ are constants. The values of ϕ are between 0.5 to 1 for series CTS and slightly larger than unity for series CTA.

Steady crack growth rate $\dot{a}_s$ is shown as a function of σ_{ref} in Fig. 5. $\dot{a}_s$ decreases linearly with σ_{ref} and this power-law relation takes the form of

$$\dot{a}_s = \nu' (\sigma_{ref})^{\nu} \qquad (8)$$

where ν' and ν are constant and stress index, respectively. ν is 61 for series CTA and 11 for series CTS.

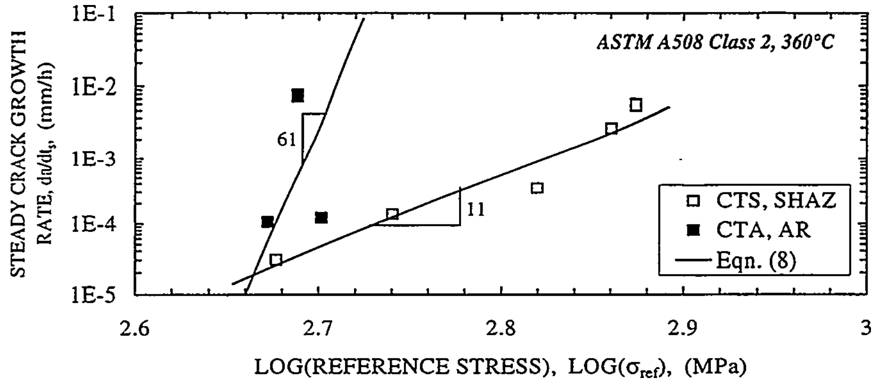

Fig. 5. $\dot{a}_s$ *(da/dt$_s$) as a function of log σ_{ref}. Eqn (8) is included.*

$\dot{a}_s$ is plotted against t_R in Fig. 6. Fig. 6 includes also series PCS where t_R is plotted against $\dot{\varepsilon}_{min}$. The $\dot{a}_s / \dot{\varepsilon}_{min}$-$t_R$ relations are reasonably linear. At the same t_R, $\dot{\varepsilon}_{min}$ for series PCS is about one order of magnitude smaller than $\dot{a}_s$ for CCG series. For the CCG series, effect of microstructure on the $\dot{a}_s$-t_R relation is limited. The power-law $\dot{a}_s$-t_R relation for the CCG series and the power-law $\dot{\varepsilon}_{min}$-t_R relation for the PC series PCS propose

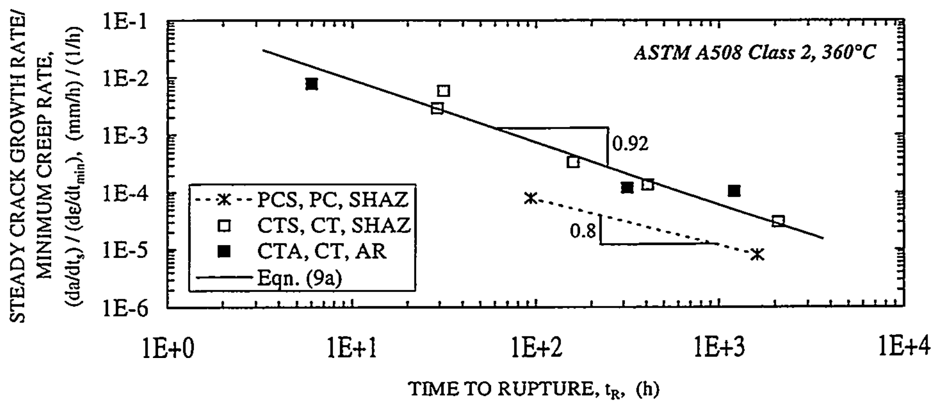

Fig. 6. $\dot{a}_s$ *or* $\dot{\varepsilon}_{min}$ *(da/dt$_s$ or dε/dt$_{min}$) versus t_R. Eqn (9a) is included.*

$$\dot{a}_s \cdot t_R^{\beta_{CCG}} = C_{CCG} \qquad (9a)$$

$$\dot{\varepsilon}_{min} \cdot t_R^{\beta_{PC}} = C_{PC} \qquad (9b)$$

where C_{CCG}, C_{PC}, β_{CCG} and β_{PC} are constants. β_{PC} and C_{PC} for series PCS take the values of 0.8 and 0.003, respectively. β_{CCG} and C_{CCG} for series CTS and CTA take the values of 0.92 and 0.068, respectively.

3.3 Post Metallography

For the PC samples necking appeared prior to the rupture. Grains adjacent to the fracture were elongated along the stress direction and the rupture mode was transgranular. No creep cavitation was observed.

For CCG series CTA and CTS at shorter t_R, grains close to the crack were deformed and transgranular crack propagation were observed in the crack growth zone, see Fig. 7a. At longer t_R, deformation close to the crack was hardly seen, see Fig. 7b, and the crack propagated intergranularly, decorated by rock pattern on the fracture surface, see Fig. 7c. In the final fracture zone, the fracture mode is transgranular, characterised by dimples, see Fig. 7d. This is independent of rupture times.

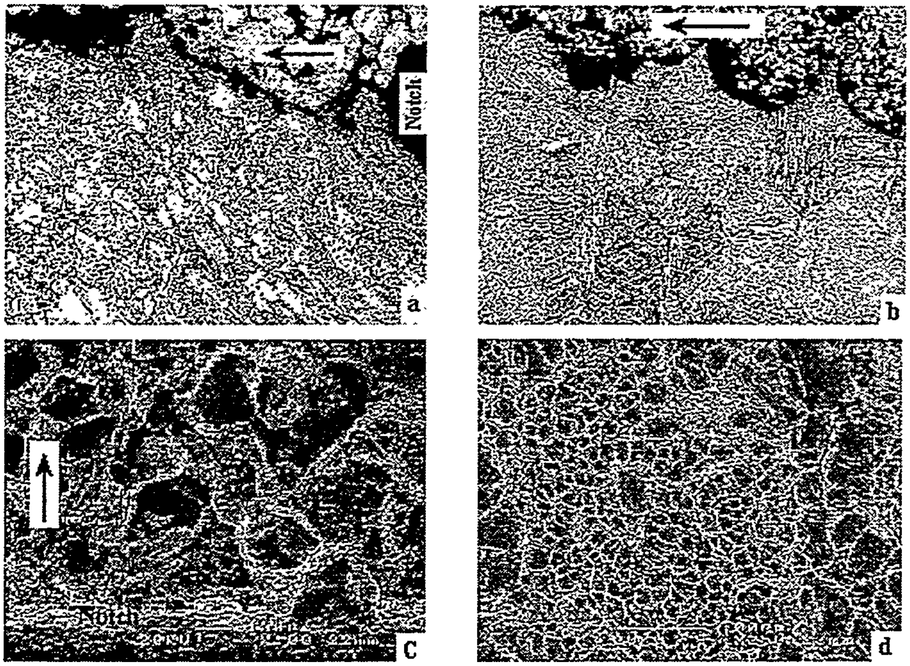

Fig. 7. Post metallography. Arrows indicate the crack propagation direction. a) LOM image from series CTA, 503 MPa/315 hrs. Deformed grains and transgranular crack propagation in the crack growth zone. 200X. b) LOM image from series CTS, 550 MPa/407 hrs. Intergranular crack propagation in the crack growth zone. 50X. c) SEM image from series CTS, 475 MPa/2080 hrs. Intergranular crack propagation in the crack growth zone. 100X. d) SEM image from series CTA, 470 MPa/1211 hrs. Transgranular fracture in the final rupture zone. 250X.

4 DISCUSSION

Bainite-ferrite in the as-received condition changed to tempered martensite after heat treatment simulation. This results in a significant increase in both grain size and hardness. Gooch [6] has showed that the tempered martensite formed by quenching from 1050°C is more crack resistant than the softer ferrite-pearlite. This is ascribed to the fine structure of the martensite and the absence of high energy ferrite-ferrite and ferrite-pearlite boundaries. This agrees with the present studies, in which the tempered martensite gives longer t_R at higher σ_{ref} than the bainite-ferrite microstructure, c.f. series CTS and CTA in Fig. 1. There is a tendency, however, that the bainite-ferrite is more crack resistant than the tempered martensite at lower σ_{ref}. This may be due to the higher austenitizing temperature for tempered martensite which is 1150°C in the present case.

Comparing to the PC results studied previously on a ASTM A508 class2 having ferrite-pearlite microstructure [17], the tempered martensite shows much longer t_R at 360°C. Besides, stress index n in Norton′ law and η value in eqn. (3) for the tempered martensite are about four and 2.4 times higher than those for the ferrite-pearlite in [17] which are 60 and 70, respectively. As a result, t_R is very sensitive to the stress variation, c.f. Fig. 1. As stress is reduced 10 MPa, t_R increases by a factor of more than 17.

Power-law relations between t_R and σ_{ref}, c.f. Fig. 1, between $\dot{a}_s$ and σ_{ref}, c.f. Fig. 5 and between $\dot{a}_s$ and t_R, c.f. Fig. 6 are found for the CCG tests. The power-law t_R-σ relation for the PC has been demonstrated to be valid in many engineering materials and this is also true for CCG tests at given σ_{ref}. The power-law $\dot{a}_s$-σ_{ref} and $\dot{a}_s$-t_R relations for the CCG tests are actually analogous to $\dot{\varepsilon}_{min}$-σ (Norton's law) and $\dot{\varepsilon}_{min}$-t_R (Monkman-Grant) relations for the PC, respectively.

Because the t_R-σ, $\dot{\varepsilon}_{min}$-σ and $\dot{\varepsilon}_{min}$-t_R relations have been successfully used in both creep design and estimation of the remaining lifetime of materials subject to creep, the t_R-σ_{ref}, $\dot{a}_s$-σ_{ref} and $\dot{a}_s$- t_R relations are believed to be useful in the applications where the creep crack growth is a great concern. Although these relations are obtained at accelerated circumstances, the extrapolation to the service condition, thereby an estimation of lifetime, can be made.

For the PC tests no creep cavitation was visible. Transgranular fracture and large plastic deformation close to the fracture were observe, in consistent with a previous study [17]. Hence, failure in the PC tests is controlled by locally excessive plastic deformation leading to plastic collapse. For CCG tests there is an apparent crack growth. At longer t_R the cracks propagate intergranularly, independent of microstructure. The intergranular crack growth in similar materials at similar test conditions has been reported [3, 6]. Gooch [3] stated that for ferrite-pearlite structure the favoured paths for crack growth are along ferrite-ferrite and ferrite-pearlite boundaries. For tempered martensite having larger grains and higher hardness than bainite-ferrite does, it is not surprising that crack propagates intergranularly.

The results from both PC and CCG tests as well as post metallography have demonstrated that creep crack growth, rather than creep cavitation, may be the mechanism limiting the service performance of low alloy reactor pressure vessel steel exposed below the limit temperature subjected to stress. Therefore, understanding the creep behaviour in terms of small crack propagating is essential in both conventional and nuclear power plants.

Although the temperature of 360°C where rupture due to CCG has been observed is slightly higher than the maximum temperature of 320°C at which nuclear reactor vessel operates, the occurrence of creep cracking must be seriously considered as a real possibility.

Data for design with respect to CCG at 320°C is insufficient. However, a design stress at 360°C can be estimated and evaluated.

The yield stress of this steel at as-received condition at 350°C is 415 MPa. The lowest stress causing failure after 9117 hours for as-received material at 360°C is 446 MPa. Assuming that linear extrapolation to lower stresses is applicable, failure stresses for the heat affected zone are found to be 377, 286 and 258 MPa after 10,000, 100,000 and 250,000 hours, respectively. Clearly, if a reactor would be operating 1t 360°C, the static strength of the pressure vessel would be controlled by CCG. Safe design would imply a reduction of the characteristic strength by a factor 415/256 = 1.62 in relation to the criteria based on the yield point. In fact, the failure time against CCG would be less than 5,000 hours if the design was based on the yield stress.

5 CONCLUSIONS

1) The PC and CCG tests on tempered martensite give similar t_R at higher σ/σ_{ref}. At lower σ/σ_{ref}, t_R for the PC tests is considerably longer than that for CCG tests. t_R for the CCG tests having bainite-ferrite is shorter than that for the PC tests, independent of σ/σ_{ref}.

2) For the CCG tests t_R on tempered martensite is longer than that on bainite-ferrite at higher σ_{ref}. This tends to be reversed at lower σ_{ref}.

3) No creep cavitation is observed and transgranular fracture is dominant for the PC tests. For the CCG tests, crack propagates predominantly intergranularly. This is most prominent at longer t_R. Final rapid rupture is transgranular for the CCG tests.

4) The crack growth rates correlate well with C* and the crack growth rates fall in a narrow band for the tests when plotting against C*.

5) There are three stages for the crack growth. After initiation, the crack grows constantly before it accelerates to approach the final rupture. Notable crack growth takes place at later stages of tests.

6) The power-law t_R-σ_{ref}, $\dot{a}_s$-σ_{ref} and $\dot{a}_s$- t_R relations are found on the CCG tests. These findings may have a potential application in the estimation of lifetimes where the creep crack growth dominates.

7) The design stress against CCG has been estimated to be 256 MPa. This is a factor of 1.6 lower than the yield stress on which the design is based. Hence, CCG controls the static strength at 360°C.

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Relaxation cracking in the process industry, an underestimated problem

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Abstract

Austenitic components, operating between 500 and 750°C, can fail within 1 year service while the ordinary mechanical properties after failure are still within the code requirements. The intergranular brittle failures are situated in the welded or cold deformed areas. This type of cracking has many names, showing the uncertainty concerning the mechanism for the (catastrophical) failures. A just finished investigation showed that it is a relaxation crack problem, introduced by manufacturing processes, especially welding and cold rolling. Cracking/failures can be expected after only 0.1- 0.2% relaxation strain. These low strain values can already be generated during relaxation of the welding stresses. Especially coarse grained "age hardening" materials are susceptible. Stabilising and Postweld Heat Treatments are very effective to avoid relaxation crack problems during operation. After these heat treatments the components can withstand more than 2% relaxation strain. At temperatures between 500 and 750°C relaxation cracking is the predominent factor for the safety and lifetime of welded austenitic components.

1 Introduction

In chemical process industries, austenitic materials are often used at temperatures between 500 and 750°C. The pressure containment components typically contain welded joints of varying thickness, resulting in high residual stresses after welding. As such materials are rarely Post Weld Heat Treated, these high residual stresses (up to yield strength of the parent material) can only be relieved by time dependant inelastic deformation. This phenomenon, characterised by a continuously decreasing strain rate, is called relaxation and is a creep mechanism.

Materials that have a high (creep) ductility can easily withstand the inelastic strains due to relaxation. However, when the material exhibits limited (creep) ductility, severe cracking can develop during service leading to catastrophic failure. This type of cracking has many names (relaxation-, stress induced-, stress induced corrosion-, stress assisted grain boundary oxidation cracking etc.) and is in practice an uncontrolled and hardly understood phenomenon, reference 1-12. Practical experience has shown that susceptible materials fail within one or two year service and after weld repair even earlier.

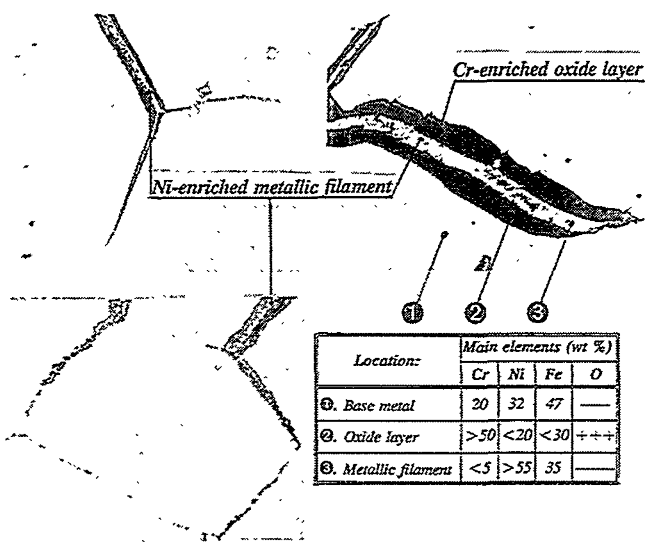
The uncontrollness of the phenomenon "Relaxation Cracking" is illustrated by the fact that the failed components fully meet the requirements of the standard room temperature mechanical tests (tensile, Charpy-V toughness, bending). The same accounts for the "ordinary" high temperature properties (low-cycle fatigue and creep). It appears that the tests required by the material standards do not prevent or predict failures by relaxation cracking.

Because of these uncertainties the designers do not know which austenitic material or material condition they must select to avoid relaxation cracking in installations operating between 500 and 750° C.

2 How to identify relaxation failures

Relaxation failures in austenitic welded joints can be identified by their typical crack appearance:

- The cracks are always located on the grain boundaries, and in front of the cracks small isolated cavities are present;
- Mostly a metallic filament is present on the cracked grain boundaries. This filament is enclosed by a chromium rich oxide layer. The chemical composition of the metallic filament is material depending;
- In Alloy 800H this filament is enriched with nickel and chromium is almost depleted. In the oxide layer chromium is enriched and the iron and nickel contents are low, see Figure 1. However, in some materials (for instance the Ni-base Alloy 617), no clear metallic filament is present.



Location:	Main elements (wt %)			
	Cr	Ni	Fe	O
1. Base metal	20	32	47	—
2. Oxide layer	>50	<20	<30	+++
3. Metallic filament	<5	>55	35	—

Fig. 1. Appearance and chemical composition of relaxation cracks in Alloy 800H.

Another fingerprint is the experience that the cracks are only present at locations where the Vickers hardness is higher than 200 HV10.

When the cracked regions fulfill the above mentioned description, the failure can be classified as a relaxation failure. In the literature the cracks are not always recognised as relaxation cracks, because the appearance seems to be a consequence of a corrosion mechanism. TNO proved that relaxation cracking is a pure mechanical mechanism, the appearance of the cracks can be simulated in the laboratory without any specific environment by using a special developed 3-point bending test rig. An example of a crack obtained in the three point bending equipment is shown in Figure 2. Up till now the 3-point bending relaxation test has been proven to be the only test which can really simulate the relaxation behaviour of (welded) components.

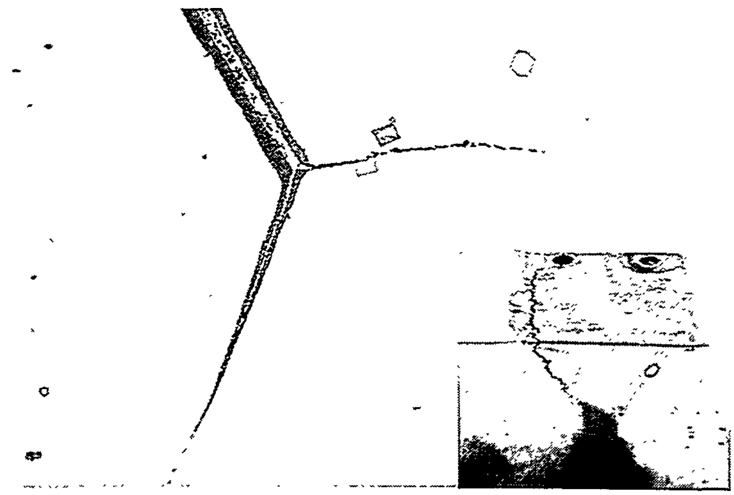


Figure 2. *Relaxation crack in the HAZ of an Alloy 800H weldment after 150h testing at 650° C in the 3-point bending test rig. Cracks have the same appearance (metallic filament) as in-service cracked material.*

Within a just finished multi-client programme, several participants discovered that several of their earlier not well understood failures were relaxation failures.

The most commonly used method for the determination of high temperature ductility is ***long term creep testing***. This method has been proven to be inadequate for the prevention of relaxation cracking. After the test the cracks never show a metallic filament and the creep ductility is always >1%, while the ductility of relaxation failures is almost zero. Moreover, most relaxation failures have been reported within one year service, thus after a short time of the operating lifetime. Low cycle fatigue tests are also unable to recognise a material condition which is susceptible for relaxation cracking. The cycles to failure are comparable with those in the as delivered condition and the cracks never show a metallic filament.

3 Limiting conditions

The major cause of relaxation cracking is "lack of ductility". This is preliminary because many austenitic materials show an age hardening behaviour at temperatures between 500 and 750° C. During age hardening many very fine matrix particles will precipitate within the grains, through which the hardness level will be dramaticaly increased and the deformation capacity reduced. The amount, size and location of the precipitates is not only determined by the operating temperature and chemical composition of the specific heat , but also by the dislocation density. When the dislocation density is high the precipitation processes accelerate. ery small matrix particles will precipitate on the dislocations and will also pin them. As a consequence of this phenomenon the deformation within the grains is blocked.

Figure 3 shows an example of an "age hardened" crack susceptible microstructure in Alloy 800H with a hardness >200 HV3. High hardness values are also present in the Heat Affected Zones (HAZ) and the weld metal (WM) of welded joints, even before service. These high hardness values are the consequence of a high dislocation density generated during welding (or cold rolling etc.).

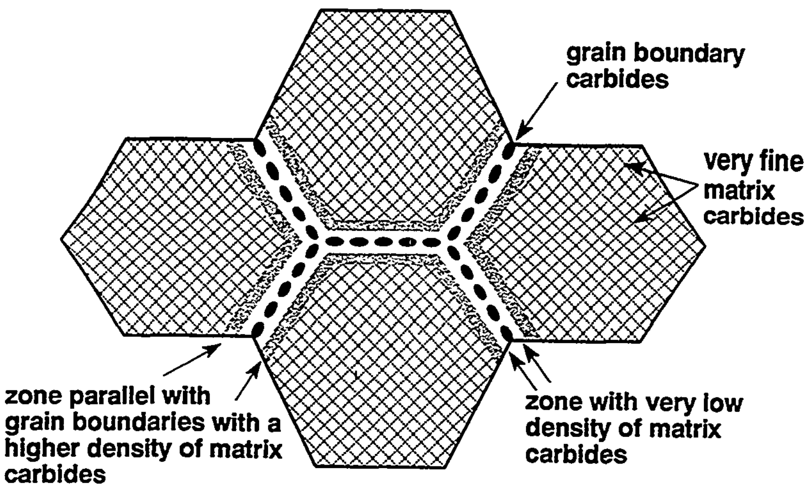


Figure 3. Age hardened, relaxation crack susceptible, microstructure in Alloy 800H after 6000h service at 600° C. Vickers hardness >200 HV10.

During service between 500 and 700° C the hardness values in the welded joints will even further increase, see Figure 4. This figure also shows that the width of the HAZ in austenitic welded joints can be more than 15 mm. Mostly it is believed that the width of the HAZ in austenitic welded joints is always very small (one grain in width). In reality the width of the HAZ is the region where the hardness is higher than the hardness of the base metal.

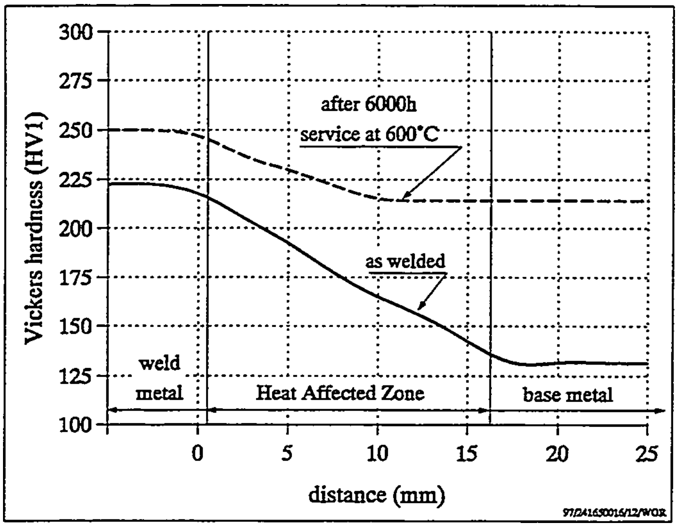


Figure 4. *Hardness in a Alloy 800H welded joint in the as welded condition and after 6000h service at 600° C.*

Figure 5 shows a typical HAZ microstructure with a high dislocation density (hardness >200 HV10) in comparison with that in solution annealed base metal (hardness <160 HV 10) and a low. dislocation density.

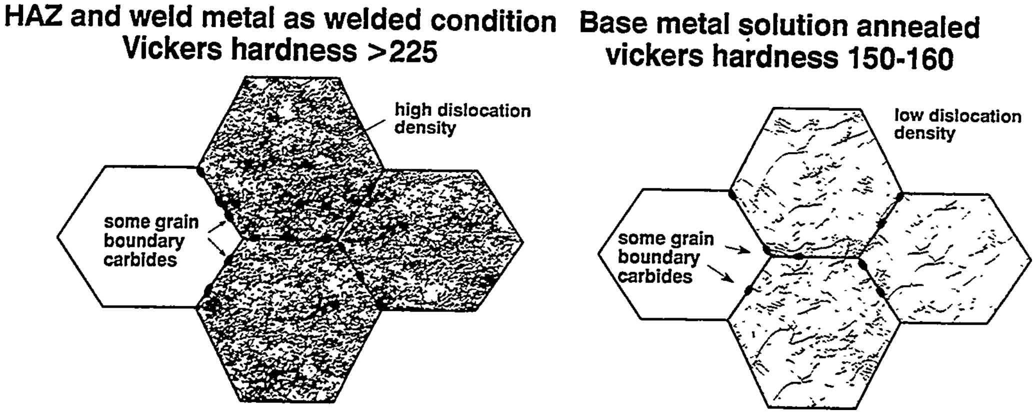


Figure 5. *Typical dislocation structures in HAZ (left) and solution annealed base metal (right).*

The deformation behaviour during relaxation depends on:

- Chemical composition of the material or the specific heat, especially the "age hardening" elements as carbon, titanium, aluminum, niobium;
- Grain size of the heat: coarse grained material are more susceptible;
- Service temperature, critical when the material is operating in the middle of its age hardening range;

- Level of internal stresses (dislocation density) after welding and cold deformation;
- Cyclic deformation and level / direction of system stresses during service.

4 Understanding relaxation failures

4.1 Approach

A joint industry sponsored project was undertaken to clarify the controlling factors concerning relaxation cracking failures in austenitic welded joints. The approach was based on the experiences which were built up by TNO during the failure analysis of 2 catastrophic incidents in the chemical industry. More than 30 companies all over Europe and the United States were involved (steel suppliers, designers, boiler makers, consumable manufactures, endusers, authorities).

The main goals were:

- To identify key treatment conditions and associate microstructures leading to, and indicating potential risk for stress relaxation cracking;
- Develop recommendations for the authorities and codes (Stoomwezen, TÜV and ASME) and also protocols for new equipment design.

The investigation was mainly focused on the effect of welding and cold rolling, because failures were always reported in welded joints and cold deformed material. Pre-and post weld heat treatments were executed to reduce / deminish the susceptibility for relaxation cracking. Both common as well as newer austenitic materials, with quite different creep rupture strengths, were included, see Table 1.

Table 1. Selected parent materials, plate thickness 16-35 mm.

Material	*Chemical composition (main elements, wt. %)*										*ASTM grain size*	*$\sigma 10^5$ /650 °C (MPa)*
	C	*Ni*	*Cr*	*Fe*	*Al*	*Ti*	*Mo*	*Nb*	*Co*	*Ce*		
AISI 304H	.06	10.4	18.3	bal.							2	45
AISI 321H	.044	9.2	17.2	bal.		.42					7	47
AC66	.07	31.4	27.3	bal.				.83		.09	2	92
Alloy 800H	.07 .08	30.6 31.2	20.5 19.2	bal. bal.	.30 .32	.35 .30					0 0	77
Alloy 617	.06 .08	bal. bal.	22.1 22.1	1.9 1.6	1.2 1.1	.39 .29	8.9 9.7		11.5 12.6		1 0.0	125

For Alloy 800H material both Fe base and Ni base consumables were used and for the other materials matching consumables. For Alloy 800H also in-service failed material was in the programme.

4.2 Overview results relaxation tests

Within the programme the effects of welding, cold rolling, pre and postweld (form) heat treatment, service temperature and long term ageing have been investigated. The results are summarized in Table 2.

Table 2. Results of relaxation tests on parent materials and welded joints.

Effect of:	*Material and test temperature:*						
	304H		*AC66*	*800H*		*617*	*321H*
	575 °C	*650 °C*	*650 °C*	*575 °C*	*650 °C*	*650 °C*	*575 °C*
Welding:	cracks	no cracks	no cracks	no cracks	cracks	cracks	no cracks
Postweld heat treatment: (875°C/3h for 304H+800H) (980°C/3h for Alloy 617)	no cracks	no cracks	—	no cracks	no cracks	no cracks	—
Long term ageing: (16,000h / 650°C)	no cracks	—	no cracks	—	cracks	cracks	—
Cold deformation base metal: (from 0 up to 15%)	cracks	—	no cracks	—	cracks	cracks	no cracks
Heat treatment before cold def.: (875°C/3h for 304H) (980°C/3h for 800H)	no cracks	—	—	—	no cracks	—	—
Heat treatment after cold def.: (875°C/3h for 304H) (980°C/3h for 800H)	no cracks	—	—	—	no cracks	—	—
Heat treatment in-service cracked material: (980°C/3h)	—	—	—	—	no cracks	—	—

It revealed that:

- The AC66 and AISI 321 welded joints and cold bent parent materials are not susceptible at operating temperatures between 575 and 650°C;
- AISI 304H, Alloy 800H and Alloy 617 welded joints and cold bent parent materials are susceptible for relaxation cracking:
    - AISI 304H at 575°C and not at 650°C,
    - Alloy 800H at 650°C and not at 575°C,
    - Alloy 617 at 650°C;
- For Alloy 800H no difference in behaviour between Fe base and Ni base welded joints was established, both were susceptible;
- A PWHT at 875°C is effective to avoid relaxation cracking in 304H and 800H welded joints;
- A PWHT at 980°C is effective to avoid cracking in Alloy 617 weldments;
- After 16,000h ageing at 650°C the Alloy 800H and 617 welded joints are still susceptible for relaxation cracking;

• After 16,000h ageing at ***650° C*** the 304H welded joints are not susceptible anymore for relaxation cracking at a temperature of ***575° C*** ;

• After cold bending the 304H, Alloy 800H and Alloy 617 base metal are susceptible for relaxation cracking, but a heat treatment before or after cold bending is effective to avoid relaxation cracking;

• A heat treatment of 980° C/3h of in-service cracked Alloy 800H base metal is effective to avoid relaxation cracking and can be an option for repair.

• The negative effect of manufacturing processes on the relaxation cracking susceptibility is most predominant in the Alloy 617, followed by Alloy 800H and AISI 304H. The AC66 and fine grained 321H do not show such an effect, after manufacturing these materials are still not susceptible for relaxation cracking.

5 Discussion

The programme clearly showed that many austenitic materials, especially the welded joints and cold deformed material, are susceptible for relaxation cracking. After welding or cold deformation relaxation strains <0.2% are sufficient for severe cracking. However, after heat treatment the material can even withstand relaxation strains of >2% without cracking.

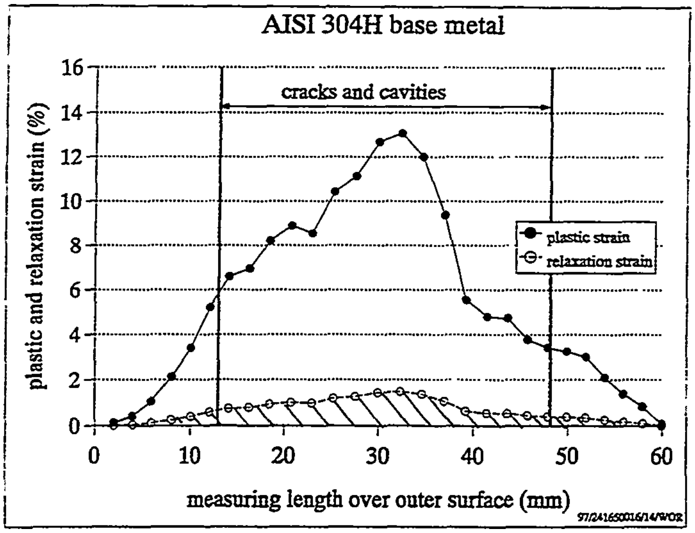


Figure 6. *Presence of relaxation cracks in AISI 304H base material as a function of the measured plastic and calculated relaxation strain, Test performed at 575° C, relaxation time 300 hours.*

The temperature range where the materials are most susceptible is material dependent and cannot be exactly determined at this moment. For several materials the following guideline can be used:

* *AISI 304H, 321H etc. most susceptible between 525 and 600° C;*
* *Alloy 800H, most susceptible between 550 and 650° C;*
* *Alloy 617, most susceptible between 550 and 700° C.*

Even a small amount of cold deformation during manufacturing can make a material susceptible for relaxation cracking: 2-3% cold deformation is enough to create a susceptible material. These low deformations can for instance be expected in cold rolled plate material used in reactor vessels. In most codes deformations of 10-15% are allowed without performing an extra heat treatment. These values seems to be too high regarding the prevention of relaxation cracking. However, it showed that a duplex heat treatment of the material ***before cold deformation*** is effective to avoid relaxation cracks in AISI 304H and Alloy 800H. Such a heat treatment can be executed easily by the steel supplier, but is not allowed yet by the codes.

The AISI 321 welded joint within the programme was not susceptible for relaxation cracking, even not after cold deformation. The grain size of the material was very small (ASTM 7) and the carbon content of the heat was on the lower bound of the specification (0.044%). It is believed that, especially due to the small grain size, the material was not susceptible. A recent failure in AISI 321 showed large grains (ASTM 1). There are strong indications that 304H with a small grain size also is not susceptible for relaxation cracking. This statement will be verified in a new ongoing project.

The positive effect of heat treatments can be roughly explained as follows:

- **Effect Postweld Heat Treatment (PWHT) welded joints:**
  After PWHT the dislocation density (residual stresses) in the HAZ and the weld metal will be dramatically reduced, through which hardly matrix particles can precipitate on the dislocations and age hardening will be reduced. The consequence is a material condition which can withstand relaxation strains > 2% without cracking.

- **Effect duplex heat treatment base metal:**
  An additional (stabilising) heat treatment of the base metal after solution annealing generates coarse particles within the grains and on the grain boundaries. For the formation of these carbides age hardening elements (C, Ti, Al, Nb etc.) are necessary resulting that at operating temperature less elements are available for the formation of fine carbides within the grains. The consequence is again a material condition which can withstand relaxation strains >2%.

The programme also showed that after a duplex heat treatment up to at least 15 % cold deformation is allowed without cracking. The explenation of this fact is that, although cold deformation generates many dislocations, the precipitation density at service temperature is less compared with that in solution annealed material. The age hardening elements have been greatly used for the formation of the coarse precipitates during the second stabilising heat treatment.

An additional advantage for duplex heat treatments is that modifications/repairs in in-service exposed components can be executed easily. The material still has a ductile relaxation behaviour, because the precipitates within the grains are coarse.

In practice the residual service lifetime in age hardened material (only solution annealed) after modification (welding) is very short. The material is not able to withstand the relaxation strains introduced by welding due to the presence of hardly deformable grains.

Although after a duplex heat treatment parent materials show a ductile relaxation behaviour, a PWHT after welding is necessary to avoid relaxation crack problems in the welded region.

6 Conclusions

- When materials are subjected to temperatures where age hardening is the dominant factor, relaxation cracking can be expected at relaxation strains <0.2%. These very low relaxation strains are already be induced during manufacturing processes as welding and cold deforming.

- An extra heat treatment can reduce the negative effect of age hardening. After such a heat treatment the material can withstand >2% relaxation strain, which is sufficient for a safe operating lifetime.

- Welded joints and cold deformed material are more susceptible for relaxation cracking than base meterials because during manufacturing high internal stresses (high dislocation densities) are introduced. This results in an accerelation of the precipitation processes within the grains, thus reducing the capacity to withstand deformation, while exactly at the same locations high relaxation stresses/strains can be expected.

- The susceptibility of in-service cracked Alloy 800H can be dramatically reduced by a stabilising heat treatment. This can be a serious option for weld repair.

7 Still existing uncertainties

To clarify still existing uncertainties a second programme, sponsered by 35 companies, has been started in the Netherlands in 1997.

The main topics are:

* Selection materials intrinsitically not susceptible for relaxation cracking. Additional heat treatments are expensive and not always possible. It is better to avoid them by selection of not susceptible materials;
* Optimizing heat treatments before and after welding. From econimical and practical point of view the second heat treatment temperature has to be as low as possible;
* Effect grain size. Coarse grains seems to be detrimental;
* Determination creep rupture strength after duplex heat treatment in order to establish the (un-)necessarity for stress reduction factors;

* Code acceptance of duplex heat treatments. It is not allowed yet to perform a second heat treatment;
* Development repair weld procudures for relaxation failures. At this moment the residual operating lifetime after weld repair is unsufficient;
* Relaxation and creep behaviour dissimilar welded joints, especially P91-Alloy 8ooH and P91-1.4910 (nitrogen alloyed austenitic material). The new strong martensitic steels can be an option for the chemical industry up to 650°C. However, dissimilar welded joints can not be avoided.

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