HIGH TEMPERATURE ALLOYS FOR THE HTGR GAS TURBINE: REQUIRED PROPERTIES AND DEVELOPMENT NEEDS

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1. INTRODUCTION

Recent advances in the design of turbomachinery, recuperators and magnetic bearings provide the potential for the use of the High Temperature Gas Reactor (HTGR) with a closed cycle gas turbine. The reactor size has been reduced in developing the passively safe module design and the size of industrial gas turbine has increased to accommodate the energy released from a HTGR module. Highly effective compact recuperators have been developed, they are a key requirement for achieving high efficiency. The availability of large magnetic bearings has also eliminated the potential problem of coolant contamination by the oil of lubricated bearings.

National and international R&D programs are under way to explore areas where technical development is needed [1]. Among these programs, the closed-cycle gas turbine concept is investigated in several industrial projects [2]:

- The Pebble Bed Modular reactor (PBMR) in South Africa, with a gross electrical generation of 117 MWe. The project schedule has been established, with a deployment of a first unit in 2006.
- The Gas Turbine Modular Helium Reactor (GT-MHR) developed by an international consortium, with a targeted 286 MWe generation per module, a prototype single unit is scheduled in Russia in 2009.
- Test Reactors are being commissioned in Japan (High Temperature Test Reactor HTTR) and China (HTR10) to evaluate the safety and performance of HTGR. These reactors are designed with an indirect conversion cycle, but they will support R&D activities like electricity generation via the gas turbine and high temperature process heat applications.

A common European approach to the renewal of HTR technology through the direction of a European HTR Technology Network (HTR-TN) has also been established to enable and encourage work-shared structures within this nuclear R&D field.

Among these recent R&D programs, Framatome and CEA are involved in the materials development for the key components of the HTGR. The development of advanced HTGR concepts requires materials data and understanding of materials behaviour under reactor operating conditions and environment. The components for the primary circuit operate at temperatures above 600°C and up to 850°C in order to reach high efficiencies. For these materials and components, considerable data and know-how exists, but industrial and technical feasibility are not well established for the most recent designs. For example, a significant effort is needed for the turbine components, for which the expected working conditions are beyond the today's industrial capabilities. The fundamental technologies required for the design of the turbomachine have been proven for aerospace and industrial gas turbines. However, the HTGR gas turbine requires a design that includes high temperature capability and long term endurance. The required design properties, associated with the large sizes of components, can be seen as a major issue.

In this work, a review with a selection of most relevant materials and processes is presented, for both turbine blades and disks. The focus of this work is to discuss the choice of high temperature materials in accordance with the recent HTGR design specifications. The GT-MHR turbine design is used as a reference for high temperature materials selection. Also an evaluation of recent advances in materials for industrial gas turbine is presented, with a brief overview of associated fabrication processes.

2. HTGR TURBINE DESIGN SPECIFICATIONS

The GT-MHR module consists of a nuclear source of heat (reactor system) and the Power Conversion System. Details of the general design can be found in [2] and [3].

The Power Conversion System (PCS) receives about 600 MW of thermal energy from the reactor system and converts 286 MW of net usable electrical energy, with an overall efficiency of about 47%. The PCS includes the turbomachine, the precooler and intercooler, and connecting pipelines. The turbomachine consists of the turbocompressor, the electrical generator, bearings and seals. The turbocompressor includes the turbine and two compressor sections (low pressure and high pressure compressor).

The helium is received by the PCS from the hot gas duct. The helium then expands trough the gas turbine which is coupled to the electrical generator. From the turbine exhaust, the helium flows trough the hot side of the recuperator, transferring heat to helium returning to the reactor. The helium leaving the hot side of the recuperator is cooled (precooler) before passing trough the low-pressure compressor, intercooler and high-pressure compressor. The helium then passes in the cold side of the recuperator where it is heated for return in the reactor system.

The entire assembly is installed in a vertical orientation and is rotating at 3000 rpm (50Hz). The turbine design is based on the technology available for large industrial engines. Substitution of helium for air in this nuclear gas turbine modifies aerodynamic requirements by removing Mach number limitations. As the rotational speed is fixed (synchronous generator), the size of the turbine is dictated by the choice of blade speed. The highest blade speed is desirable to limit the number of stages, but it is limited by the high temperature stress limits for the blades. In the GT-MHR concept, a 12 stages turbine with very high efficiency was established. With turbine inlet temperature of 850°C, blade and disks cooling are not considered as necessary in the design. Salient features of the GT-MHR turbine are given in table 1.

3. CRITERIA FOR MATERIAL SELECTION

For the material selection, the key points are the first stages turbine disks and blades where the stresses and temperatures are the highest. Table 2 summarizes the thermal and mechanical loads for the turbine disks and blades. The materials for these components should ensure a safe operation for at least 60000 hours. Therefore, a ground rule for the material selection of the most critical parts was proposed as following [5]:

- for the blade alloy $\sigma_{60000h}^{850°C} \geq 225 MPa$
- for the disk alloy $\sigma_{60000h}^{850°C} \geq 180 MPa$

TABLE 1. GT-MHR TURBINE CHARACTERISTICS AT FULL POWER [4]

Power, MW	560
Rotational speed, rpm	3000
number of stages	12
Expansion coefficient	2.67
Adiabatic efficiency, %	93
hub diameter, mm	1400
Inlet parameters	
temperature, °C	848
pressure, MPa	7.0
He mass flow, kg/s	320
pressure losses, MPa	0.007
blade height, mm	170
Outlet parameters	
temperature, °C	510
pressure, MPa	2.62
pressure losses, MPa	0.02
blade height, mm	225

TABLE 2. PRELIMINARY STRESS ANALYSIS FOR THE GT-MHR TURBINE [5]

	Stage 1 (850°C)	**Stage 12 (510°C)**
Blade root section area, mm^2	827	827
blade height, mm	170	225
centrifugal force created by a blade, N	85400	117110
Blade root section stresses, MPa		
Radial stress	92	118
Bend stress	68	82
Total stress	160	200
Stesses in the disk (rotor), MPa		
Annular	150	165
Radial	116	131

The use of high temperature materials for nuclear systems will require an extension of material design rules and codes currently used. From the designer side, increasing the temperatures means a change from time-independent to time-dependent characteristics (creep, creep-fatigue).

Figure 1 illustrates the maximum temperature of metallic components in current and future reactor systems. In addition, figure 1 indicates the maximum temperature considered in the design codes. Although some existing codes use time-dependent properties in design (ASME Code Case N47 now incorporated as subsection NH of section III and RCC-MR), the temperature limits of materials included in the design codes available to day are significantly lower compared to HTGR needs and therefore a significant step forwards is required.

The first criteria being high temperature tensile strength and stress to rupture, other properties as resistance to thermal fatigue must be considered in design. Notch sensitivity is also probably detrimental to the high cycle fatigue of rotating parts of complicated shapes.

Possible corrosion effects of environment should also be considered for the materials' choice as helium impurities can influence the metallic material properties in service via carburisation and oxidation mechanisms. Part 6 will discuss the corrosion performance of several alloys in term of weight gain that can be related to the reduction of effective load bearing thickness.

However, for the complete assessment of structural integrity, the combined effect of different failure modes must be considered and particularly the following:

- creep-fatigue: it is generally considered that the amount of fatigue endurance reduction by creep or relaxation is increased when the material has low creep strength. Creep ductility can also be considered as a limiting parameter in creep-fatigue.
- fatigue and environment effect: initiation of cracks particularly in case of thermal fatigue takes place at the surface of the material and can be influenced by the effects of the environment on the material surface as pointed out at the end of section 6.
- creep-fatigue and environment effect: the effect of environment can be important in creep-fatigue and in thermal fatigue, and experiments have shown that the reduction of fatigue life by hold times in relaxation can be quite different in vacuum from what is observed in air. The corresponding mechanisms are difficult to clarify for a quantitative prediction, the helium effects being suspected to be intermediate between vacuum and air effects.

As long term service is needed, long term stability of material properties must be assessed: this point is discussed in part 7. When the optimum strength is obtained by a heat treatment at temperature lower or nearly equal to the service temperatures, there are some doubts about the stability of the corresponding microstructure.

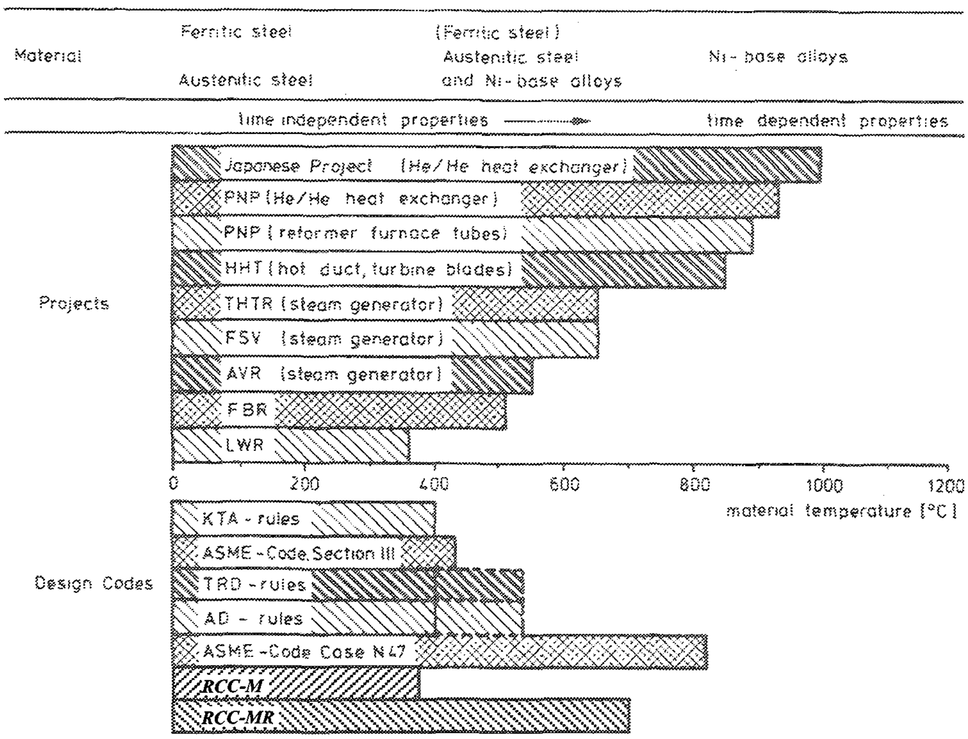

FIG.1. Material temperature and design codes for metallic components in nuclear applications (partly from [6]).

Based on these requirements, the selection of metallic materials for blades and disks is discussed in the next sections. The chemical compositions of alloys that are evaluated is given in appendix 1.

4. MATERIALS FOR THE TURBINE DISKS

At this stage, it remains unclear if alloys containing substantial additions of cobalt or tantalum would be selected for use in the turbine of a HTGR. In some past studies, alloys containing more than residual levels of these elements have often been excluded from the list of reference alloys for the primary circuit, because of potential radioactive contamination. However, many of the high temperature alloys with Cobalt have the highest mechanical properties and they are examined in the case of further acceptability [7,8].

Inconel alloy 718 was selected for the HTGR turbine disks in recent studies [8]. Alloys IN718 is a nickel-based precipitation hardened material. It has the necessary strength, short term creep and corrosion resistance only in the case of active cooling of the disk. With a turbine inlet temperature of 850°C, IN718 will require cooling to lower the temperature of the disks to around 650°C. Alternatively, alloys containing cobalt may be better in terms of high temperature strength (like Udimet 720 with $\sigma_{1000h}^{850°C}$=245MPa).

From the GTMHR design reports issued from OKBM, classical nickel-base superalloys used for industrial gas turbines (IN 718, Waspaloy) do not achieve the long term stress level requirements [5]. For OKBM, the only existing alloy that could be envisaged for a non-cooled first stage disk is the alloy MA 6000. MA 6000 is an Oxide Dispersion Strengthened (ODS) superalloy that offers very high strength and microstructural stability. The creep strength of this grade could reach values higher than 185 MPa for 60000 hours at 850°C. This grade is produced by mechanical alloying of powders and subsequent Hot Isostatic Pressing or hot extrusion [9]. The main difficulties with using ODS grades are that the process route is not mature and that much work is needed to produce large ingots with homogeneous mechanical properties.

Among the cast alloys that could serve as a basis for further grades optimisation, OKBM proposes ZhS6F and VZhL12U grades, VZhL12U chemical composition being very close to that of IN 100 alloy.

In the frame of the Dragon project, Graham has proposed A286 and IN 706 as reference grades for the disk production. These are Fe-Ni-Cr precipitation hardened grades with sufficient forgeability for large disks production but medium high temperature properties. Again, these grades can only be envisaged in the case of cooled turbine disks [7].

In the case of large components as the GT-MHR turbine disks, the manufacturing capability is closely related to the strength of the alloy. In the case of nickel-base superalloys, the two major issues are the following:

- to obtain large ingots (~5-10 tons) without solidification porosities and macro-segregations. For recent superalloys, manufacturing route includes a vacuum induction melting, a vacuum arc remelting and/or electro-slag remelting. The powder metallurgy would allow to produce high quality ingots with highly alloyed grades. In this case, microstructural inhomogeneities would be limited to the size of the powder particle.

- to forge these ingots which usually offer a very low hot-workability. Isothermal forging is used, but with the most recent superalloys (like Udimet 720), the maximum forgeable size is much lower than the GT-MHR disk diameters. Again, elaboration of near-net shapes components by Hot Isostatic Pressing of powders appears promising for these large disks, as hipping furnaces with large diameters are available (~1.4 m).

5. MATERIALS FOR TURBINE BLADES

Materials selection and testing for HTGR turbine blades has been extensively studied. Essentially 2 types of metallic materials were investigated:

- Nickel-base cast superalloys.
- Molybdenum-base grades.

5.1. Ni-base cast superalloys

In several past R&D programs, selected alloys were ranked by their high temperature strength, castability and cobalt content. Most promising alloys for the blades are therefore:

- 713LC [6,7,8,10,11,12,13]
- M21 [7,10,12]
- MAR-M 004 [7,13,12]

Alloy 713 LC is a cast nickel base precipitation hardened alloy that combines superior castability and creep resistance. Alloy 713LC has the advantage of wide industrial experience in conventional gas turbine (turbine housings, case, stator) [8]. Alloy 713 LC neither contains Co or Ta and should therefore not present any contamination problems. In HTGR environment, alloy 713LC can be susceptible to carburisation and sulfidation problems, and coatings have to be envisaged. Alloy 713LC is well suited for the turbine blades required specifications, except for the first row of blades where cooling would be necessary to achieve the required lifetime [8]. Directionally Solidified (DS) or Single Crystal (SC) blades would solve this problem, but alloys commonly used for DS or SC blades contain about 10% cobalt (DS Mar M 247, SC René N4).

Alloy 713LC was used for the fabrication of the turbine blades in the HHV project [11]. During this project held in Germany, a full-scale test turbine driven by HTGR–type helium was built. During the short high temperature lifetime experienced (~325 hours at 850°C), no material problems appeared with the working blades.

Alloy M21 is a low chromium nickel base alloy that combines precipitation hardening and solid solution hardening (~10% tungsten addition). It was selected for its superior corrosion resistance in impure helium.

Alloy MM004 has been developed from alloy 713LC and is claimed to have a better toughness because of Hafnium addition [13].

Among alloys that were also studied for a potential use as HTRG turbine blades, there are:

- IN 100 grade with good corrosion resistance [10]. IN 100 is the reference alloy for PBMR power-turbine cooled blades [1].

- Nimonic 80A with medium creep rupture strength which is envisaged for the last row of blades (lower temperature) [6,13].
- Alloys Nimonic 90, 105 and 115, Udimet 520 et 700, IN 591, IN738, IN 792, René 80, M22, MAR-M 247, Nx 188 were also proposed in various studies [7,13,14]. FIS 145 alloy was developed in Germany for HTGR applications. It combines precipitation and solid solution hardening (~13.5% tungsten) with a high castability [13].

In figure 2, a comparison of several blade alloys properties is shown, for creep rupture performed in both air and helium. Jakobeit pointed out the sharp decrease in creep strength for long times at 850°C, except for the Mo-base alloy. This decrease is less pronounced at lower temperatures, supporting the idea of a design with cooled blades to increase the blade lifetime [13]. L-TZM is the strongest alloy in figure 2, this Mo-base grade is presented in the next section.

Alloys proposed by OKBM in the GT-MHR project include precision investment cast Ni-base alloys (ZhS6K, CNK8M) and single crystal alloys (ChS-120M that is close to CSMX-2 grade) [5].

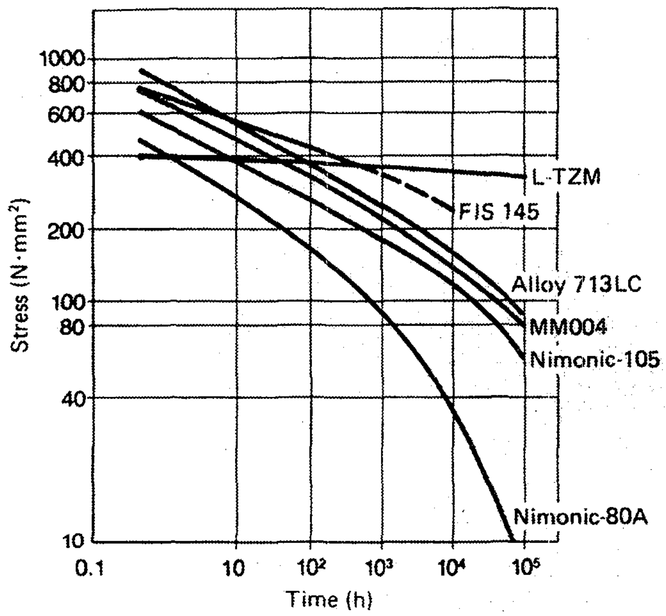

FIG. 2. Creep rupture strength of different turbine blade materials at 850°C [13].

5.2. Molybdenum-base alloys

The molybdenum-base alloy TZM (Mo-0.5Ti-0.08Zr) has not been used in industrial gas turbines because of its poor oxidation resistance in air. However, R&D efforts performed in German HTGR programs have demonstrated a promising application for this alloy for helium turbine blades. As shown in figure 2, Mo-TZM exhibits a completely different creep-resistance behaviour as compared to the nickel-base alloys, mainly because of its high melting point (2607°C) [15]. Almost flat creep curves make a 100 000h life time appear possible with an uncooled blade, as shown in figure 3 [12].

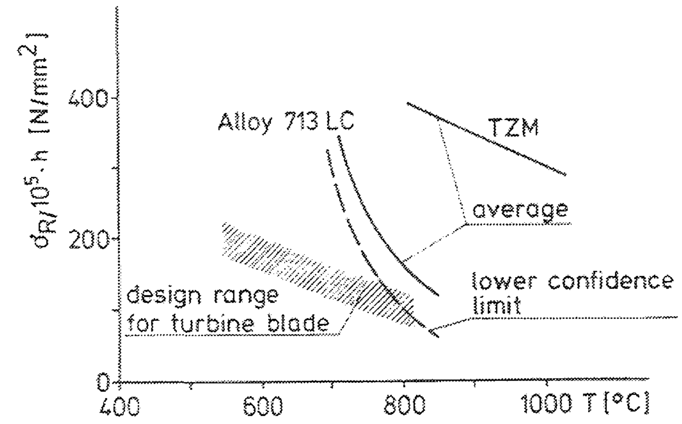

FIG.3. Stress for rupture in 10^5 h versus design temperature for HTGR turbine blade [12].

Precision forged blades were fabricated, starting from vacuum-arc-melted or powder metallurgy ingots. These blades showed a very high corrosion resistance in impure helium, but several fabrication difficulties and inherent drawbacks were encountered, and efforts for further development are almost abandoned today:

- Mo-TZM is brittle at temperatures up to 360-440°C and the notch sensitivity remains high at HTGR service temperature.
- in case of air ingress in the circuit , this alloy will suffer a massive oxidation.
- microstructure is heterogeneous in the blade, as a result of locally non uniform deformation state during hot forging. Low strength areas were found in fatigue and creep, especially in the airfoil/root transition zone [15].

6. EFFECT OF HELIUM ENVIRONMENT

The main corrosion effects of metallic materials in HTGR helium environment have been extensively studied, especially for high temperature materials. Corrosion derives from the presence of low partial pressures of H_2O, CO, and CH_4 in helium. Hydrogen also plays a role in controlling the oxygen potential trough the H_2/H_2O ratio. A recent review has given the following general trends [16]:

- below 850K (577°C), corrosion is limited. Only mild steels can suffer decarburisation. Steels with additions of chromium are slightly oxidized.
- from 850 to 1173K (577-900°C), creep resistant alloys form a chromium rich oxide scale. Internal microstructural changes are observed (precipitate free zones, carburised zones), especially when the surface scale is porous.
- under 1173K, rapid carburisation or decarburisation can occur, the dominant mechanism being controlled by the environment chemistry.

Concerning the high temperature alloys for blades and disks, the mains conclusions are:

- Mo-TZM alloy is almost insensitive to He environment up to 1000°C [7]. Jakobeit has observed a 30 μm thick MO_2C surface scale formed after 36000 hours at 850°C. This surface modification does not influence the creep resistance [13].
- 713 LC alloy and more generally nickel-base superalloys develop an oxide surface scale (Cr_2O_3) with an internal oxidation (Al_2O_3) and carburisation ($Cr_{23}C_6$). The

carburised zone is depleted in γ' precipitates. Creep tests with 713LC specimens performed from 500 to 850°C in HTGR helium and air show virtually no environment effect on rupture time for test durations up to 55 000 hours [13].

The first way of optimisation to deal with corrosion problems is the optimisation of alloy composition, as shown in figure 4. Several chemical ratios were proposed as controlling parameters for the formation of stable protective surface scales:

- Alloys with high Al/Cr ratios (M21, IN591) are much more sensitive to corrosion than alloys with the same Al content and a reduced Cr content (Mar-M004, 713LC). Alloys with low Cr and high Ti develop a stable oxide scale. For this reason, alloys IN 100 and IN738 appear promising for HTGR applications if the constraints on cobalt contents are lowered [7].
- Alloys with a ratio Al/Ti around unity develop more stable surface oxides than alloys with Al/Ti<1 (as 713LC, M21) [10].

The second way to prevent corrosion problems is to apply a coating on the surface. An industrial experience exists for aluminide coatings for alloy 713LC, which then offers a stable continuous Al_2O_3 film [8].

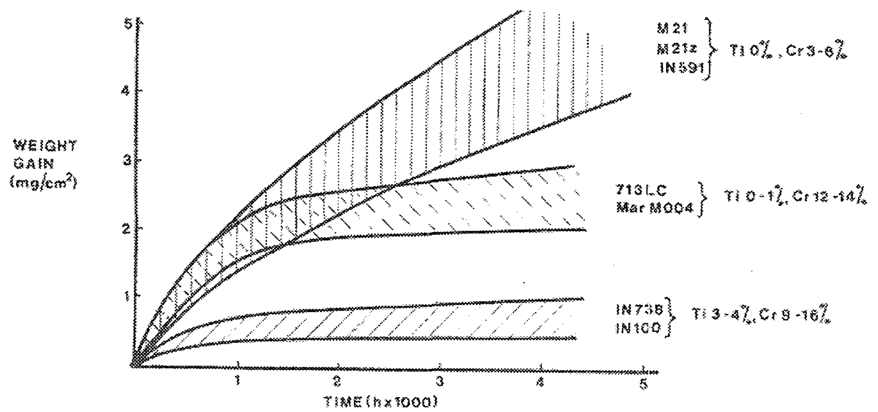

FIG.4. Weight gain of cast Ni-base alloys in HTGR environment at 900°C [Graham76].

The main concern with design of high temperature alloys in impure helium is whether the surface corrosion influences the strength (and lifetime) of the components. From the literature available on creep rupture properties, it appears that degradation of mechanical properties after elevated exposure in helium is similar to degradation experienced in air [8,13]. Therefore the degradation is mainly due and thermally activated structural changes rather than corrosion. However, when dealing with crack propagation properties, a study on cast Ni-base alloys has shown that environment effects are not similar in fatigue and creep crack propagation [14]. Complex mechanisms can occur at the crack tip (oxidation/plasticity interactions) which are difficult to model and predict.

7. LONG TERM MATERIALS PROPERTIES

Most of Ni-base superalloys investigated for turbine blades and disks are heat treated before use for maximum strength, usually with a solution treatment followed by aging treatments. They are strengthened by a very fine dispersion of coherent precipitates (γ' or γ'') with some carbides and borides. They are therefore inherently subjected to structural instabilities in high temperature service. Microstructural changes are of fundamental importance for HTGR material selection as most of the foreseen grades were developed for aeronautical turbines with much shorter lifetimes. For example, precipitation of hard brittle phases must be controlled for component lifetimes greater than 50000 hours.

Figure 5 shows an example of large microstructural changes of 713LC alloy after a creep test at high temperature. For the HTGR turbine, blade and disks alloys will endure thermal aging and there will be a strong need to understand the induced changes in strength, creep ductility and remaining life [17].

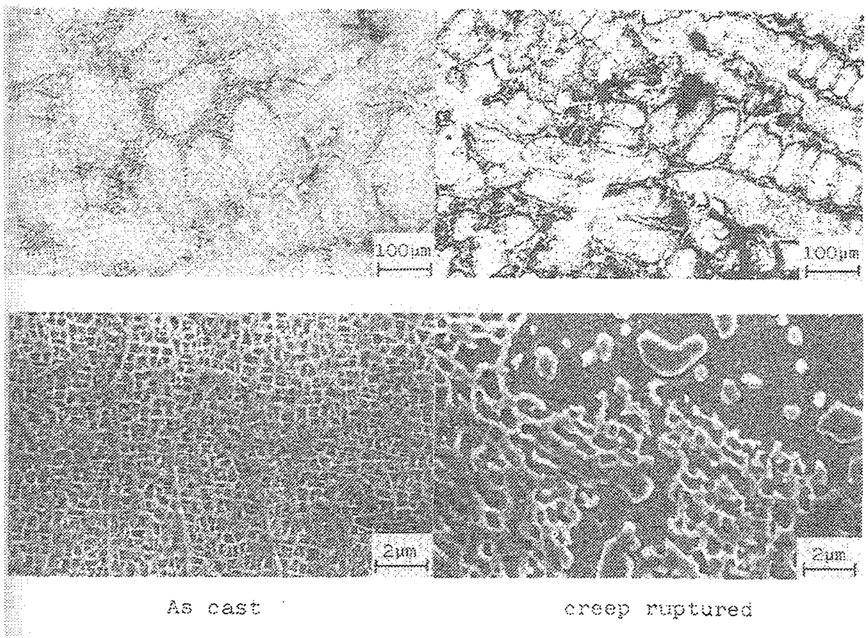

FIG 5. Optical (upper) and scanning electron (lower) micrographs of alloy 713LC before (left) and after (right) a creep test at 1000°C for ~50000 hours [17].

8. POTENTIAL BENEFIT OF RECENT ADVANCES IN GAS TURBINE MATERIALS

8.1 Evolutions in turbine technology

There has been a considerable development in natural gas fired advanced land-based turbines with combined cycles (reaching 60% thermal efficiency). These units are intended for base-load operations, with power continuously increasing: from 60-70 MW in the 70's to 280 MW today and around 500 MW in the next years (GE MS 7001H turbine in 2001). Reviews of recent achievements in turbine technology and associated materials developments can be found in [18,19].

The need to increase engine combustion temperature to increase the efficiency of gas turbines has resulted in a large increase in Turbine Inlet Temperature (TIT), for both land-based and aero turbines. In the last 50 years, the TIT has risen from around 800°C to nearly 1600°C [18,20]. This increase has been accompanied by several changes in the materials for the hottest parts. Recent advances in material processing and strength capability are now presented, as they certainly offer new possibilities to achieve the HTGR requirements.

8.2. Advances in disk materials

This increase in TIT has a significant impact on turbine disks technology. Turbine disks rim temperatures have risen to 680°C and will exceed 700°C in future aero-engines. In the past, Waspaloy has been used extensively, and Alloy 718 and Udimet 720 are now replacing it. However, even U720 approaches its limits. Therefore, major efforts are made to produce disks with temperature capabilities above 700°C [20].

Alloy 718 has a large propensity for segregation during casting. For aero-engines, melting technology advances have allowed to produce the required disk diameters of largest engines.

However, for power generation, turbine disks can be typically 1.5 meters or more in diameter. Such large components require the production of around 10 tons ingots with subsequent forging. This has not been possible with 718 alloy because of low castability, and a new grade with less Mo and Nb was developed (IN 706). This grade allows the production of large disks with modest diminution in mechanical properties. However, melting technology of large 706 ingots remains complex, and the alloy reaches today the limits of its performance. Again, large efforts are put to produce large disks in more resistant 718 grade, and also Udimet 720 for the future [21].

Large segregation during solidification of highly alloyed grades has forced to move to powder metallurgy processing for which segregation is not an issue. Alloys such as Merl 76 (Pratt &Whittney), René 88DT (General Electric) and N18 (Snecma) represent the current state of the art for aero-engines [22].

In the past, hipped powder compacts yielded excellent static properties, however low-life fatigue failure occurred in service. These failures were initiated at defects on powder particle boundaries due to powder contamination. To overcome these problems, atomisation and handling of the powders were improved, and post-HIP isothermal forging used to mitigate the influence of contamination. Today, powder metallurgy offers two interesting perspectives [21]:

- Production of Ni-base superalloy grades that are almost not castable (due to excessive segregation) and alloys with a low forgeability.
- Production of net shape parts with minimum final machining.

Recently, there has also been interest in the development of HTGR ceramic turbine disks in Japan [2]. Achieving a rotor of lightweight and high strength could indeed facilitate the turbine design. With the HTGR helium environment, C/C composite was chosen, and the fabrication of a representative disk was achieved in 1998. Tests showed poor rotating properties, but further fabrication and tests are under way. Many technical problems still need to be resolved for this long-term solution of disk fabrication.

8.3. Advances in blade materials

The rise in TIT has been met by replacing the forged blades by cast blades ($T_{140MPa}^{100000h} \approx 805°C$ and $\sigma_{100000h}^{850°C} \approx 175MPa$ for IN 738 [18,22]), and the subsequent introduction of directionally solidified (DS) and single crystal (SC) blades ($T_{140MPa}^{100000h} \approx 870°C$ [18]). Today peak metal temperatures of over 1100°C are experienced in some turbine parts, with service lives around 10 000 hours achievable [20]. The DS process allows blades to operate at temperatures about 25K higher than conventional blades. An additional temperature increase of about 25K is achieved by using blades made of single crystal materials (no grain boundaries). Thermal barriers coatings are extensively used in aircraft turbines, allowing another temperature increase of about 100K [23].

9. CONCLUSION – FUTURE DEVELOPMENTS

Future developments in materials will be associated with new turbine designs. Multi-structure disks, optimised for low cycle fatigue in the bore and creep resistance in the rim, are today under development [24]. This process route is likely to be more expensive, but it offers the designer to optimise independently the properties of the bore and the rim. This will result in better performance and disk endurance [20].

Oxide Dispersion Strengthened alloys (ODS) like MA6000 are promising for their high temperature strength and stability. These grades are indeed more suited for static components (vane, combustion chambers) than for rotating parts . This is because the strength advantage of ODS occurs at stresses which are lower than the stresses in the blades. ODS alloys only become superior where a large microstructural stability is required, at medium stresses and temperatures higher than the γ' coarsening temperature: $\sigma^{850°C}_{100000h} \approx 250MPa$ for MA 6000, compared to $\sigma^{850°C}_{100000h} \approx 175MPa$ for IN 738[25].

The modelling of production processes will need further development, essentially for cost savings. In fact, typically 70% of the price of semi-finished parts of blades and disks is the input material cost. Then, the final machining doubles the component cost. Therefore, cost savings can only be done by producing net-shape components to reduce the material input weight. This will be done by precise modelling of the production steps: solidification, hot working or Hot Isostatic Pressing [20].

The development of large land-based turbines like in HTGRs also requires progress in material mechanical testing and life modelling [25]. The total lifetime required for the hot components will be greater than in the past: around 100 000 hours instead of 20 000 hours. Low cycle and thermal fatigue will still be life determining failure modes, but high temperature oxidation and creep rupture may become more important. In service degradation of the alloy microstructure will lead to a reduction in the creep rupture strength, and it will be needed to predict accurately the life of "degraded" components. This will be possible by developing experimental tests to quantify and to evaluate the interaction between creep damage mechanisms and microstructural evolutions.

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Appendix 1

CHEMICAL COMPOSITION OF INVESTIGATED ALLOYS

Possible alloys for blades (weight %).

Alloy	process	Ni	Cr	Co	Mo	Al	Ti	W	Nb	others
713LC	C	b	12.0	0.04	4.65	5.82	0.74	-	2.0	0.07C, 0.1 Zr, 0.009B
MAR-M 004	C	b	11.86	-	4.42	5.95	-	-	1.6	1.3Hf, 0.065C, 0.3Ta
IN 738	C	b	16	8.5	1.75	3.4	3.4	2.6	0.9	1.75Ta, 0.11C, 0.04Zr, 0.01B
IN 792	C	b	12.15	9.25	1.8	3.45	4.10	3.78	-	3.75Ta, 0.52Hf, 0.11C, 0.012B, 0.09Zr
René 80	C	b	13.8	9.4	3.9	3.15	5	3.8	-	0.16C, 0.017B, 0.04Zr
M21	C	b	6	-	2	6	-	10.5	1.5	0.1C, 0.02B, 0.1Zr
M21Z	C	b	6	-	2	6	-	10.5	1.5	0.1C, 0.02B, 0.5Zr
IN 591	C	b	3	12	-	5.7	-	19	-	0.1C, 0.03B, 0.37Zr, 3Ta
IN 100	C	b	10	15	3	4.7	3	-	-	0.18C, 0.014B, 0.06Zr, 1V
Udimet 700	C	b	15	18.5	5.2	4.3	3.5	-	-	0.08C
MAR-M 247	C, DS	b	8.5	-	-	5.5	1	10	-	0.15C, 3.0Ta, 1.3Hf
Nx-188	C	b	-	-	18	8	-	-	-	0.04C
Nimonic 80A	F	b	20	0.17	-	1.32	2.45	-	-	0.04C, 1.86Fe, 0.045Zr
Nimonic 90	F	b	19.5	16.5	-	1.4	2.35	-	-	0.09C
Nimonic 105	F	b	15.4	20.25	4.72	4.69	1.00	-	-	0.14C, 0.051Zr
FIS 145	F	b	7.44	9.90	-	5.28	-	13.46	-	0.11C, 0.88Hf
Nimonic 115	F	b	14.2	13.2	3.2	4.8	3.7	-	-	0.16C
Udimet 520	F	b	19	12	6	2	3	1	-	0.05C, 0.005B
René N4	C, SC	b	9	8	2	3.7	4.2	6	0.5	4Ta
Mo-TZM	C, P	-	-	-	b	-	0.45	-	-	0.015C, 0.09Zr

F : wrought or forged, C : as Cast, P : Powder Metallurgy, DS : Directionally Solidified, SC : Single Crystal.

Possible alloys for disks (weight %).

Alloy	process	Ni	Cr	Co	Mo	Al	Ti	W	Nb	others
A 286	F	26	15	-	1.3	0.2	2.0	-		Fe base, 0.05C, 0.015B
IN 706	F	41.5	16	-	0.5	0.2	1.0	-	2.9	Fe base, 0.03C,
Waspaloy	F	b	19.5	13.5	4.3	1.3	3.0	-	-	0.08C, 0.006B, 0.06Zr
Udimet 720 (PER 72)	F, P	b	17.9	14.7	3.0	2.5	5	1.3	-	0.03C, 0.033B, 0.03Zr
Merl 76	P	b	12	18.5	3	5	4	-	1.5	0.02C, 0.5Hf
René 88DT	P	b	16	12.7	4	2.15	3.7	4	0.7	0.05C, 0.05Zr
N18	P	b	11.2	15.6	6.5	4.4	4.4	-		0.13Fe, 0.03Zr, 0.5Hf, 0.015B, 0.018C
IN 718	F	b	19	-	3	0.6	0.8		5.2	19Fe
MA6000	P	b	15	-	2.0	4.5	2.5	4.0	-	2.0Ta, 0.05C, 0.01B, 0.15Zr, 1.1Y2O3
ZhS6F	C	b	5.5	9.4	0.9	5.3	1.0	12.0	1.6	0.11C, 0.9V, 0.9Hf
VZhL12U	C	b	9.5	13.5	3.1	5.4	4.4	1.4	0.75	0.17C, 0.75V

F : Forged, C : as Cast, P : Powder Metallurgy.