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THE EUROPEAN EFFORTS IN DEVELOPMENT OF NEW HIGH TEMPERATURE ROTOR MATERIALS – COST536

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Abstract

Despite the ongoing efforts to increase the amount of available alternative energy sources, fossil fuels such as lignite and hard coal will remain important for the energy mix and sustainability of energy supply. Fossil-fuelled Steam Power Plants (SSP's) or Combined Cycle Power Plants (CCPP's) will also continue to supply a significant portion of our energy needs.

Within the frame of European COST536, a new project was installed with the aim of Alloy development for Critical Components of Environmentally friendly Power planTs (ACCEPT) aiming for material solutions for steam conditions up to 650°C.

Martensitic materials should be used for thick-walled components to maintain high operational flexibility of such large plants. Rotors, casings, bolts, tubes, pipes, and water walls, are the critical components under current investigation. The class of the 9-12%Cr steels offers the highest potential to meet the required property levels for critical components such as rotor forgings. Therefore a significant effort to increase the application temperature of these steels was and is the focus of studies within Europe. Although there are 600°C materials already being successfully utilised in a number of advanced European power plants, further improvement in creep strength is being achieved by the addition of Boron and a well balanced Co content. Full-size prototype components are now being tested.

New ideas to improve the behaviour and increase the application temperatures are under investigation. Results are reported here.

Keywords: COST536, 10Cr steels, high-temperature application, creep strength, material development

1. Introduction

Energy is the source of general well-being and the standard of living in each country. In the coming decades, there will continue to be heavy reliance on fossil fuels, such as coal, oil and natural gas. Power plant utilities are forced to increase the efficiency of their plants for environmental and economic reasons.

This improvement in efficiency of modern steam power plants is related to raising the temperature as well as the pressure of the steam generated in the boiler. New materials are required with improved high-temperature capability. At the same time the material solution has to be cost effective and reliable. Here the steels of the 9 to 12%Cr class have shown highest potential in long-term creep strength and oxidation resistance in steam, along with ease of fabrication for large forgings, castings and pipe sections.

In Europe, the efforts to further improve the available 9-12%CrMoV steels have been concentrated in the COST programmes, COST501 (1986-1997), COST522 (1998-2003) and COST536 (2004-2009) [1-3]. The resulting improved steels are in commercial operation in advanced European power stations and have made it possible to increase the operating steam temperatures from a range of 530-565°C to 580-620°C with a corresponding increase in thermal efficiency. This article describes the work performed in Europe within COST536 to improve the basic knowledge and to develop improved steels for large rotor forgings.

2. Rotor Materials Requirements

For power ranges up to 1,000MW, several basic steam turbine types with the following thermodynamic characteristics are possible:
- High pressure (HP) turbines with high temperature and pressure (≥530°C/ ≥180bar)
- Intermediate pressure (IP) with high temperature and reduced pressure (≥530°C/ ≥30bar)
- Low pressure (LP) turbines (≤ 350°C/10bar)

Combined HP-IP and IP-LP turbines for the smaller power range for Combined Cycle Power Plants (CCPP) complete the solutions for power generation with steam turbines.
Specific design requirements for the single components have to be met by the materials in order to offer a certain flexibility in fulfilling the various customer needs for the power plant.
The property profile of rotors for temperature application T>450°C and the appropriate material properties are given in *Table 1*.

Table 1: Requirements and material properties for steam turbine high-temperature rotors

Requirement in design and service	Material property
Static strength	Tensile strength (UTS) 0.2 Yield Strength (0.2YS)
Long-term strength	Creep Rupture Strength (CRS) Creep elongation limits (CEL)
Toughness - short-term - long-term	 Fracture toughness (K_{IC}) Creep rupture elongation Toughness values after long-term aging
Fatigue strength	Low Cycle Fatigue (LCF) High Cycle Fatigue (HCF) Creep Fatigue Interaction (CFI)
Crack tolerance	Static: Creep Crack Growth behaviour (CCG) Alternating: Fatigue Crack Growth (FCG)
Oxidation resistance	Steam oxidation behaviour
Erosion resistance	Erosion behaviour

As shown, the HP and IP rotor forgings, which can reach diameters of up to 1,200mm, need to be made in carefully selected material in order to meet all property requirements. Creep behaviour plays an important role for areas such as the rotor centre and the blade attachment, whereas the fatigue resistance is mainly considered in the surface regions.
The material class of the 9-12%CrMoV steels meets well all boundary conditions relevant for a flexible design:
- A good through-hardenability up to larger diameters >1,000mm
- Balance between strength and toughness (short and long term)
- Physical property profile
- Weldability
- Potential for high oxidation resistance
- Lower cost than Austenites and Ni-base alloys and ease of fabrication

The development aim for new high class materials in Europe was defined as follows:

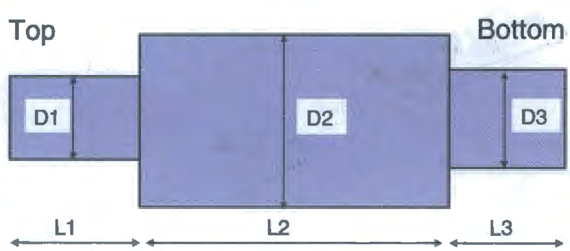
- 100,000 h creep rupture strength at target temperature (≤650°C) of about 100 MPa
- Good creep rupture ductility (>10% elongation), and no notch sensitivity
- Through-hardening up to at least 1,200 mm diameter
- Minimum 0.2-yield strength of 700 MPa
- Other properties such as toughness and susceptibility to embrittlement should not be worse than with conventional 12%CrMoV and 1%CrMoV rotor steels

Details about the achievements in COST536 are described in the following chapters.

3. Materials Development in Europe

3.1. Rotor Material Qualification for 620°C

The outcome of the previous round, COST522, was the demonstration of the manufacturability of large rotor forgings in the alloy with the highest potential for 620°C application which is a 9Cr-1Mo-1Co-100ppm Boron type material named FB2.
Three trial rotor forgings have been manufactured in Europe. The forgemasters Boehler Kapfenberg/Austria, Saarschmiede/Germany and Societa delle Fucine, Terni/Italy, started with the same material specification but have followed different steelmaking routes [3, 4]. Boehler/Austria has used a 29to ingot made by Boehler-BEST process, a pouring process with special measures to improve the homogeneity of the ingot.
SdF Terni/Italy has applied the steelmaking process VCD with an ingot weight of 53to.
Saarschmiede/Germany has used their wide experience in ESR melting by making an ingot of 56to weight.
A summary of the main prototype rotor dimensions are given in *Figure 1*.
The largest diameter D2 with 1,100mm to 1,200mm is comparable for all three rotor forgings. Heat treatment parameters have been chosen to fulfil strength requirements of 0.2YS(RT) >700MPa. The heat treatment conditions used for final quality heat treatment are given below. The double-tempering applied previously for the 600°C alloys of the COST material family was again chosen to ensure a fully tempered martensitic microstructure, *Table 2*.



Forge-master	Process	D1 mm	D2 mm	D3 mm	L1 mm	L2 mm	L3 mm
Boehler/A	BEST	770	1180	865	1350	930	1110
Terni/I	EAF+ ASEA	925	1110	790	800	2750	830
Saarschm/ D	ESR	800	1215	1050	1085	2130	800

Fig. 1: Dimensions of the COST trial rotor forgings in FB2 composition made in Europe

Table 2: Quality heat treatment conditions for COST FB2 trial rotor forgings

	Austenitizing 1,100°C	**1st tempering 570-590°C**	**2nd tempering 700°C**
Boehler / Austria	10h/ water-air spraying	22h/ air	22h/ air
SdF Terni / Italy	17h/ oil	24h/ air	24h/ air
Saarschmiede / D	16h/ water spraying	22h/ air	22h/ air

The NDT results show a minimum detectable flaw size of 1.5-2.0mm for the rotor body location. The quality of the rotor forgings was inspected by determining the basic strength and toughness values at different positions showing the homogeneity in different former ingot locations (top, middle, bottom of ingot) and from surface to centre [4].
The long-term creep strength determination of the trial rotor forgings is ongoing. Maximum testing times achieved so far are 55,000 h. The results show that all three rotor forgings confirm the behaviour of the 500kg trial melt, as in *Figure 2*.
For comparison, reference lines are given for the 600°C materials COST Rotor-E (10Cr-1Mo-1W) and COST Rotor-F (10Cr-1.5Mo) together with the line of material B2. Alloy B2 of COST501 containing 0.18C-1.5Mo-100ppm Boron was the benchmark for further improvements of European 9-10%Cr steels. The results show that the FB2 rotor forging data are well above the reference lines offering therefore improved creep rupture strength values for the high temperature design. The rupture ductility is maintained on a high level which means that notch weakening effects can be excluded. The homogeneity of the long-term properties resulting from the different steelmaking processes is still under investigation.

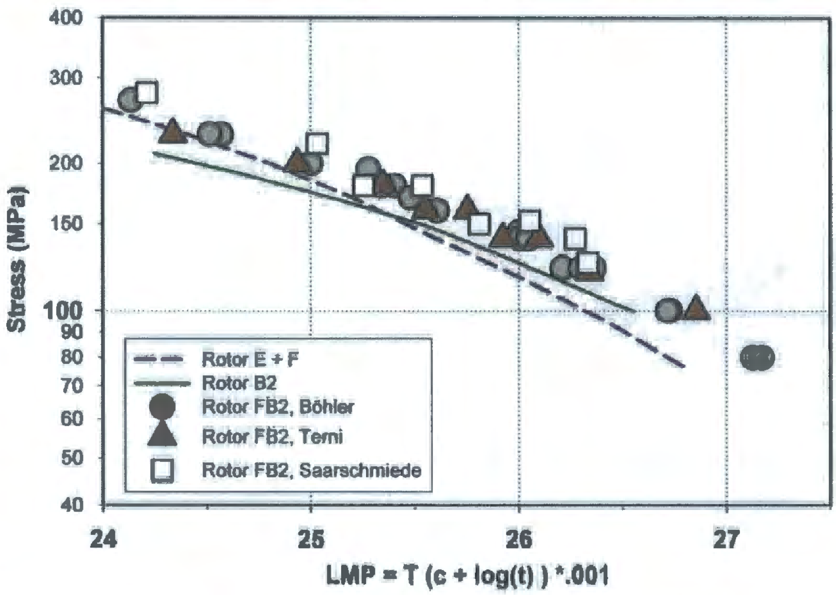


Fig. 2: COST trial rotor forgings FB2, lon- term creep strength in Larson-Miller plot, position middle of ingot, surface

Other properties like high temperature strength, toughness, low cycle fatigue strength, and fracture toughness, are not so different from the known range of 9-12%Cr steels. Furthermore the weldability of FB2 is improved compared to rotor B2. No changes in design rules have to be made by applying this material.
To summarize, it can be stated that with the chosen balance in chemical composition and the applied manufacturing processes the requirements for high-temperature rotor forgings up to 620°C application are well fulfilled.
Currently there are new USC Steam Power Plants under construction in Europe which apply the FB2 rotor material in the high-temperature area.

3.2. Material Development for Application Temperatures above 620°C

Additional improvement of the ferritic-martensitic grades is necessary with respect to creep strength. Experience has shown that steels with higher microstructure stability also show higher long-term creep strength. The development work so far was based on the knowledge acquired under the COST501 and COST522 programmes, especially the intensive microstructure investigations, the commercially available computing tools such as ThermoCalc and Dictra, the newly developed calculation methods of the equilibrium transformation temperature, and the diffusion parameters of potential candidate test materials.
On the basis of the promising composition FB2, different strategies have been developed to follow in the further work packages.
The first block is dealing with experiments to replace Niobium by Tantalum.

3.2.1. Replacement of Niobium by Tantalum

The idea was to investigate the role of Niobium and Tantalum in the long-term creep stability. It originated in a German basic research project (DFG) in which around 80 different model steels were investigated with Cr contents of 11% to 13% and additional variations of the alloying elements W, Mo, Cu, V, Nb, Ta, N and B [5, 6]. Based on this, three different 50kg melts have been produced.
The Cr-content was fixed for two alloys FN6-Ta and FN7-Ta at about 11% to ensure sufficient oxidation resistance. In order to generate a ferritic-martensitic microstructure with precipitates of M23(C,B)6, MX and Laves phase, the different choices of alloying elements were made as in *Table 3*.

Table 3: Chemical composition and heat treatment of the Ta trial melts

Melt	C	Cr	Mo	Co	W	V	Nb	B	N	Ta	B/N	QHT °C	0.2YS at RT MPa
FB2	0.13	9.4	1.50	1.0	-	0.21	0.070	0.010	0.020	-	0.50	1100 710	714
FB2-3 Ta	0.12	8.9	1.49	1.0	-	0.20	0.003	0.013	0.009	0.08	1.44	1150 700	680
FN6-Ta*)	0.19	10.9	0.53	1.0	2.0	0.28	0.006	0.023	0.014	0.08	1.64	1150 765	636
FN7-Ta*)	0.19	11.0	0.48	1.0	2.0	0.27	0.006	0.012	0.009	0.08	1.33	1150 765	597

*) FN6-Ta: 0.71%Cu, FN7-Ta: 0.73%Cu

The rationale can be summarized as follows:

- balanced amounts of Co, Mn, C and Cu to obtain a ferritic-martensitic matrix
- Cr, W, B and C for strengthening by M23C6 precipitates
- W for strengthening by Laves phase
- Cu to promote a fine distribution of Laves phase by nucleation at Cu-precipitates
- V and Nb or Ta for strengthening by MX precipitates

Trial melt FB2-3Ta is based on FB2 composition with higher Si content for steam oxidation resistance, a changed B/N ratio, lowest Ni content, and replacement of Nb by Ta.

On the basis of calculations with the software ThermoCalc the heat treatment was specified as Austenitizing at 1,150°C and tempering at 700°C or 765°C to dissolute Boron and carbides of different type and to stabilize the microstructure. The results are shown in *Figure 3.*
The results for the trial melt FB2-3Ta suggest that Tantalum in the chosen alloy composition at 650°C creep rupture testing would not be more effective than Niobium for a replacement ratio Ta/Nb = 1.14 compared to FB2. At the same time, the effect of lower creep strength is also affected by a lower Nitrogen content (only 50% of FB2) causing possibly a deficit in strengthening MX particles.
Compared to FB2 the melts FN6-Ta and FN7-Ta contain a higher percentage of C, Cr of about 11%, less Mo, 2%W, and different amounts of Boron and Nitrogen. But even FN6-Ta with the highest Boron content of 230ppm does not exceed the reference line for COST rotor B2 with 100ppm Boron meaning that there is no advantage observed. Therefore the tests will be interrupted. The reason for the low creep strength is not fully understood yet. Different aspects can play a role if the chemistry is compared to FB2, such as a possible effect of missing MX (lower N content), higher Cr content (11%), replacement of Mo by W, replacement of Nb by Ta. The COST group will deal with these aspects in the near future.

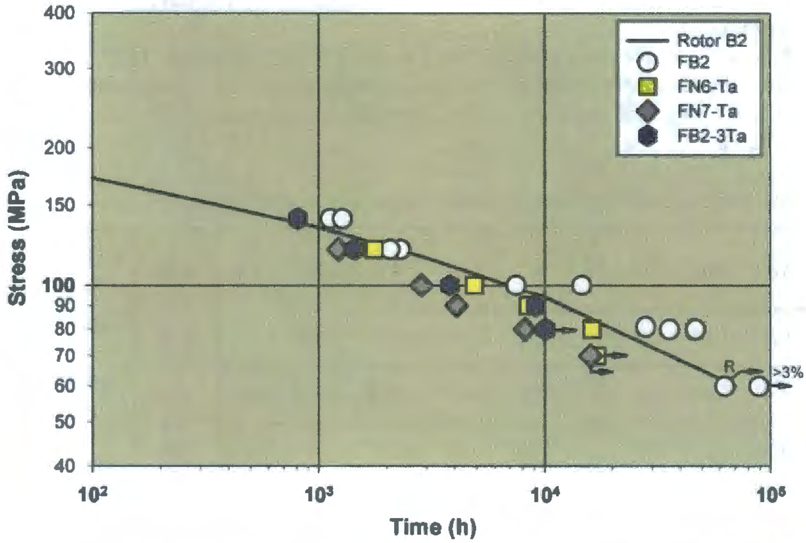


Fig. 3: Creep rupture strength of the COST trial melts with Tantalum at 650°C

3.2.2. The Role of Niobium, Boron, Nitrogen and Heat Treatment

A second work package deals with modifications made in the C-, Cr-, B-, N- and Nb-contents, and by the addition of W in one case.

The melts FB2-3, FB2-5 und FB2-6 are based on FB2 but reflect different ideas: the Nb is reduced, the B/N ration is increased up to B/N=3.5, the QHT was changed once in Austenitising temperature to 1150°C, and the first tempering temperature was increased to T1=700°C with the aim of improving the microstructure stability, *Table 4*.

The test data up to 10,000h show that the alloy FB2-6 with the highest B-content is not clearly improved compared to FB2-3. The B/N ratio is twice that of FB2-3 but a large effect has not been observed yet, as in *Figure 4*.

Melt FB2-5 with the lowest N content but about the same B/N ratio as FB2-6 seems to behave better. It is note worthy that FB2-5 had a modified Austenitizing temperature of 1,150°C. Further tests have to clarify which effect this change will have in the long term.

The melt FB3-1 was made by replacing the 1.50% Mo of FB2 by W and reducing the N content to 1/3 of FB2. At the same B content like FB2, the B/N ratio is therefore increased to B/N=1.14 compared to 0.5 for FB2. The first annealing temperature was also increased to T1=700°C for microstructure reasons. There are no disadvantages in creep observed up to 10,000h.

Further tests have to show which concept can offer further advantages compared to FB2.

Table 4: Chemical composition and heat treatment of the trial melts with different B/N ratios

Melt	C	Mn	Cr	Mo	Co	W	Nb	B	N	B/N	QHT °C	0.2YS at RT MPa
B2	0.16	0.06	9.3	1.60	-	-	0.060	0.010	0.015	0.67	1100 570/700	650
FB2	0.13	0.90	9.0	1.50	0.96	-	0.065	0.010	0.020	0.50	1100 570/710	714
FB2-3	0.15	0.35	9.4	1.60	1.10	-	0.035	0.017	0.010	1.70	1100 700/700	660
FB2-5	0.13	0.15	9.0	1.54	1.00	-	0.034	0.021	0.006	3.50	1150 700/700	665
FB2-6	0.15	0.35	9.4	1.60	1.10	-	0.035	0.032	0.010	3.20	1100 700/700	691
FB3-1	0.14	0.79	9.2	0.20	1.00	2.47	0.051	0.008	0.007	1.14	1100/ 700/700	691

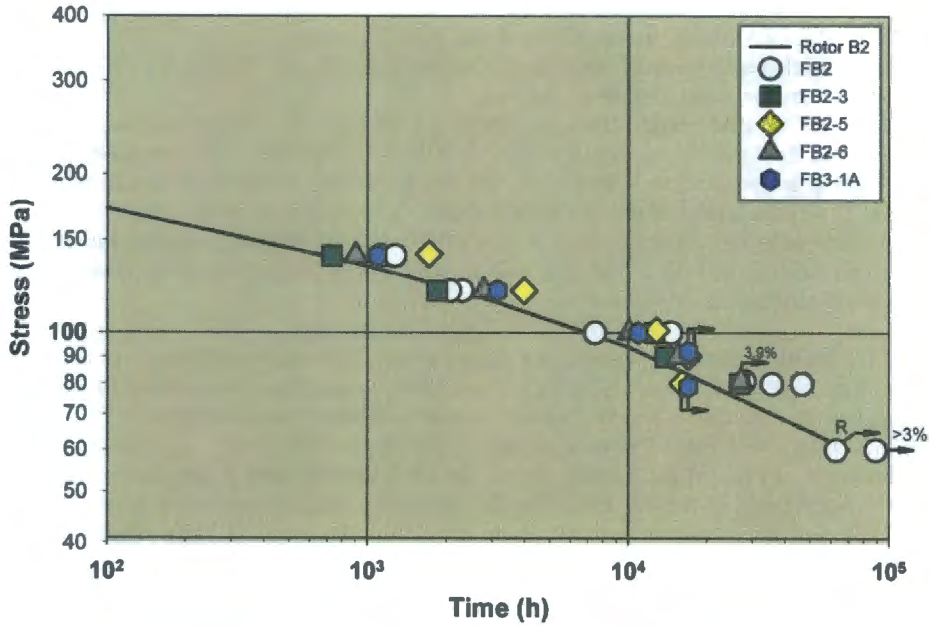


Fig. 4: Creep rupture strength of the COST trial melts with different B/N ratios at 650°C

3.2.3. The Role of B-N Ratio and Heat Treatment

Further work has been started to investigate the role of the Boron to Nitrogen ratio in FB2 basic chemistry and to further understand the influence of heat treatment.

For this the content of C and B has been increased, and the N level reduced to 110ppm. Two heat treatment versions have been applied for the same mother melt to enable a direct quantification in creep, *Table 5.*

Table 5: Chemical composition and heat treatment of the trial melts with low Nitrogen

Melt	C	Mn	Cr	Mo	Co	Nb	B	N	B/N	QHT °C	0.2YS at RT MPa
B2	0.16	0.06	9.3	1.60	-	0.060	0.010	0.015	0.67	1100 570/700	650
FB2	0.13	0.90	9.0	1.50	0.96	0.065	0.010	0.020	0.50	1100 570/710	714
FB2-2 LNP-A	0.16	0.31	8.8	1.41	0.97	0.045	0.015	0.011	1.36	1100 700/700	696
FB2-2 LNP-M3										1100 570/700	710

It is too early to draw any conclusions. Up to now no negative influence is observed for testing times of 10,000h, *Figure 5.* The results are still comparable to the FB2 trial melt. Longer testing is required and will become a part of the next COST action.

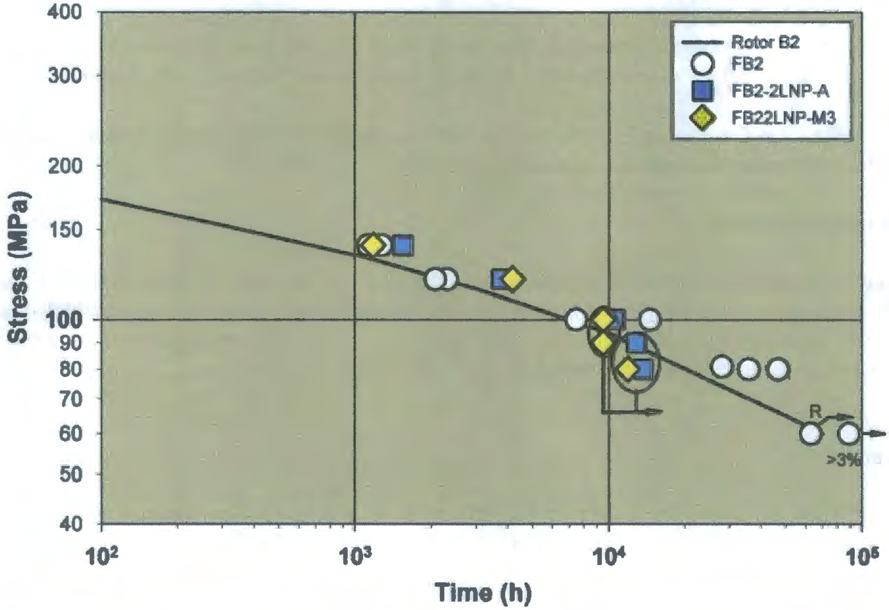


Fig. 5: Creep rupture strength of the COST trial melts with low Nitrogen at 650°C

The knowledge and experience gained with the new alloy types underlines the findings that the further increase of the application temperature above 620°C for ferritic-martensitic steels has become problematic, thus making it clear that the limit could be near.

4. Future work

The next COST round is already under preparation. It has been agreed that the described work packages will be continued up to the start of the next round.
Intensive microstructure investigations are planned to accompany the ongoing tests to further sharpen the modeling tools. The influence of heat treatment parameters is included in the work packages and will remain in focus.
The manufacturing of full size 20to rotor forgings is under preparation. The influence of preliminary heat treatment on the results of NDT, such as detectable flaw size and sound attenuation, and the influence on creep behavior are going to be investigated.

5. Summary and Conclusions

- After identifying a potential alloy composition for 620°C application, three full-size prototype rotor forgings with different steelmaking routes have been manufactured in Europe. The creep results with currently 55,000h show that the transformation from the trial melt to the rotor forgings was performed successfully. The material is currently being manufactured commercially for new power plant projects in Europe and USA.

- A series of new trial melt compositions was designed with different directions of the development strategy. Microstructure investigations and modern modelling tools have formed the basis for the definition of the chemical analysis and heat treatment. The testing times for the Niobium containing test melts are still too short for conclusions. The expected tendency of improved creep strength by replacing Niobium with Tantalum was not confirmed.
- The next COST round will focus on the role of chemical composition, heat treatment, surface protection by coatings, modelling, and trial rotor production.

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