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9-10% Cr steel forgings for USC turbines – experiences in manufacturing and development status of MARBN steels

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ABSTRACT

Sufficient energy availability in combination with lowest environmental pollution is a basic necessity for a high living standard in each country. To guarantee power supply for future generations, improved technologies to achieve higher efficiency combined with reduced environmental impact are needed. This challenge is not only aimed to the power station manufacturers, but also to the producers of special steel forgings, who have to handle with more and more advanced materials and complex processes.

Bohler Special Steel is a premium supplier of forged high quality components for the power generation industry. This paper reports about experiences in the fabrication of forged components for steam turbines for ultra-supercritical application - from basic properties up to ultrasonic detectability results. The materials used so far are the highly creep-resistant martensitic 9-10% Cr steel class for operating temperatures up to 625°C developed in the frame of the European Cost research program.

Additionally our research activities on the latest generation of high temperature resistant steels for operating temperatures up to 650 degree Celsius – the boron containing 9% Cr martensitic steels (MARBN) - are discussed. In order to improve the creep behavior, MARBN steels with different heat treatments and microstructures were investigated using optical microscopy, SEM and EBSD. Furthermore, short term creep rupture tests at 650 degree Celsius were performed, followed by systematic microstructural investigations. As a result it can be concluded, that advanced microstructures can increase the time to rupture of the selected MARBN steels by more than 10 percent.

INTRODUCTION

Energy is a basic necessity for a high standard of living in each country. To preserve the environment for future generations and to protect health of humanity and other living beings, energy production itself is faced with the introduction of stringent emission regulations.
Figure 1 shows linear growth rates of population, CO_2 emissions, traded goods, GDP and energy production [1]. Assuming constant growth rates, it will take about 55 years to double the population, 40 and 38 years doubling CO_2 emissions and energy production. The average CO_2 emissions and energy consumption grow at much higher rate than population.

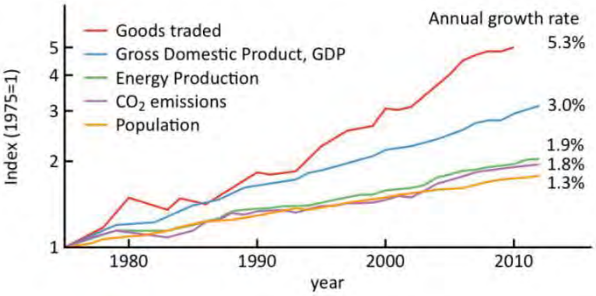


Figure 1: Growth in population, CO_2 emissions, energy production, GDP and traded goods over the past 40 years [1].

The continuous trend towards more economic electricity production parallel to reduced environmental pollution can only be sustained by improving the thermal efficiency of power generation plants. The efficiency is increased by raising the temperature as well as the pressure of the steam, which finally results in the need for improved high-temperature materials.

For many years, Bohler Edelstahl GmbH & Co KG is a premium supplier of forged components for the power generation industry, e.g. discs, centre shafts, turbine shafts, shaft components and accessories for gas and steam turbines. A complete range of special steelmaking equipment, a special melting shop with vacuum and remelting facilities, a 52 MN hydraulic forging press and the R&D support of FEM modelling are a good basis for high-quality forgings.

From a material point of view, all the typical steels introduced in energy engines application are manufactured so far, but more or less focussed on higher alloyed steels. These are specifically the 9-10% Cr class, developed in the frame of the European COST research program, where Bohler Edelstahl participated since 1987. Today Bohler is also active in the current KMM-VIN action, the continuation of COST.

One of the latest developments for service temperatures up to 650°C are the so-called MARBN steels (martensitic 9% Cr steels containing boron and nitrogen), developed at the end of the COST program.

Graz University of Technology (TUG), Institute of Materials Science and Welding (IWS), in cooperation with Bohler Edelstahl open die forging and the R&D department, investigated the microstructure and creep behavior of such 9% Cr Boron containing martensitic steels, named FB2-2LN and NPM1. Comparative investigations of heat treatments led to the development of a quench- and partitioning (Q&P) heat treatment, which is based on an idea of Edmonds et al. [2], but for low alloyed steels. The heat treatment offers the possibility to transform the austenite into ferrite and precipitates [3] and can be viewed in a video from in-situ investigations with a laser scanning confocal microscope on a classic power plant steel [4].

1. Development of martensitic 9-12%Cr steels for USC application – a brief review

12% Cr-steels, alloyed with Mo and V, have been used in power plants since the middle of the 20th century. The German alloy X21CrMoV12 1, strengthened by solid solution and precipitation of $M_{23}C_6$ and a small amount of V(C, N), was first used for blades, forgings and castings in the 1950's. At the end of the 1950's, two 12% CrMoV rotor steels were also developed in the United States for HP and IP rotors. One of them is alloyed with 1% tungsten and the other with additions of niobium and nitrogen (Figure 2) [5].

Steel	Source	C	Si	Mn	Cr	Mo	Ni	W	V	Nb	N	Creep Rupture Strength at 600°C/10^5 h [MPa]
						[Weight %]						
12%CrMoV	SEW 555	0.22	0.25	0.50	12.0	1.0	0.50	-	0.30	-	-	59
13%CrMoWV	USA	0.22	0.40	0.80	13.0	1.0	0.75	1.0	0.25	-	-	
11%CrMoVNbN	USA	0.18	0.25	0.70	10.5	1.0	0.70	-	0.20	0.08	0.06	85

Figure 2: Standard and developed 10-12% Cr steels for HP and IP Steam Turbine Rotors.

At the same time, development work has been going on in Japan, led by Prof. T. Fujita at Tokyo University. Based on the highly creep-resistant 12% Cr steels, developed in Europe and the United States, Fujita started to improve the creep strength for 600°C application by alloying and balancing the steel composition with Nb, N and W. In the middle of the 1980's this led to new alloys for turbine rotor forgings TR 1100, 1150 and 1200 (593, 621 and 648°C) (Figure 3) [5].

Steel	Source	C	Si	Mn	Cr	Mo	Ni	W	V	Nb	N	Creep Rupture Strength at 600°C/10^5 h [MPa]
						[Weight %]						
TR1100 (TMK1)	Japan	0.14	0.05	0.50	10.3	1.50	0.60	-	0.17	0.05	0.04	90
TR1150 (TMK2)	Japan	0.14	0.05	0.50	10.3	0.50	0.70	1.80	0.17	0.05	0.04	90
TR1200	Japan	0.12	0.05	0.50	11.3	0.30	0.80	1.80	0.20	0.05	0.06	125

Figure 3: Newer developed 10-12% Cr Steam Turbine Rotor steels in Japan.

The steel TMK 1 or TR 1100 was then selected for the first big forging for industrial use for the HP rotor of the 50 MW demonstration plant at Wakamatsu [5, 6]. The rotor weighted 28 metric tons with a Barrel diameter of 980 mm.

The developments in the United States and Japan have been followed up in Europe in the COST (COST = **Co**-operation in **s**cience and **t**echnology) programs. In these programs, new ferritic creep- resistant 9-12%CrMoV steels for turbine forgings, castings and pipework were developed and characterised, carried out under the frame of the European community.
It started in the 1980's and targeted a creep strength of 100MPa for 100,000 hours at 600°C.
The most promising candidate alloys B2, E and F have been selected out of five grades of steel (called A to E) for the manufacture of trial rotor forgings (Figure 4) [7].

Steel	C	Si	Mn	Cr	Mo	Ni	W	V	Nb	N	B	Creep Rupture Strength at 600°C/10^5 h [MPa]
						[Weight %]						
Cost B2	0.17	0.07	0.06	9.3	1.55	0.12	-	0.27	0.06	0.015	0.010	122
Cost E	0.12	0.10	0.45	10.3	1.05	0.75	0.90	0.18	0.05	0.05	-	95
Cost F	0.12	0.10	0.50	10.3	1.50	0.60	-	0.18	0.05	0.05	-	95

Figure 4: Within COST developed 10-12% Cr steels for Steam Turbine Rotors.

The trend to even higher steam conditions was the subject of the COST 522 program, which explored the possibilities of stabilising the microstructure through addition of boron. From all variants only one alloy showed the best behavior and led to a new modified steel called "FB2", first produced as a trial melt followed with the manufacture of a trial rotor (Figure 5) [8].

Steel	C	Si	Mn	Cr	Mo	W	Ni	Co	V	Nb	N	B
FB2 test melt	0.13	0.05	0.82	9.32	1.47	-	0.16	0.96	0.20	0.050	0.019	0.0085
FB2 trial rotor	0.13	0.09	0.33	9.08	1.43	-	0.16	1.26	0.22	0.054	0.022	0.0076

Figure 5: Chemical compositions of steel FB2 [Weight %].

These newly developed material grades are highly creep resistant martensitic materials for the use of up to 625°C and steam pressures above 300 bar. Figure 6 shows the steps in the development of materials for USC-power plants with respect to increasing steam temperatures.

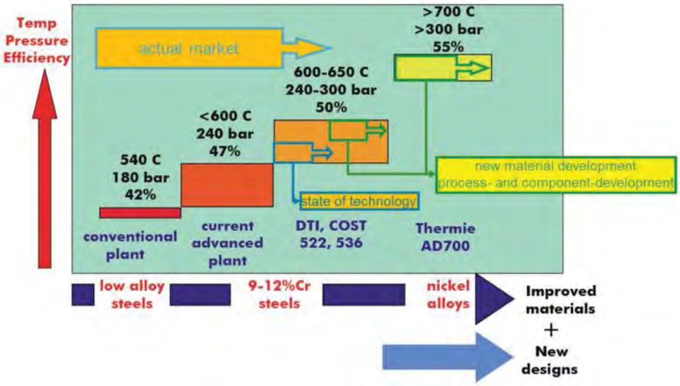


Figure 6: Steps in the development of the materials for USC's [9].

1.1. Cost E and Cost F for 600°C; experiences in manufacturing and properties

In the early 1990's, industrial production of these newly developed 9-10% Cr steels became ongoing in Europe and in Japan.

To date, many rotor forgings in different sizes and weights have been manufactured by Bohler Edelstahl Open Die Forge. The applied melting routes used so far were EAF (electric arc furnace) for small shafts, the PESR (protective gas electro slag remelting) process for shaft parts for welded rotor constructions up to 14 metric tons delivery weight and the BEST (Bohler electro slag toping) process for larger rotors with ingot weights up to approximately 45 metric tons. The principles of the melting processes have already been reported [8, 10].

After heating the ingots to forging temperature, they are forged on a forging press mainly by multiple upsetting operations followed by cogging and forging to the final shape. When forged, the rotors are preliminary heat treated (PHT) - which can be carried out in different ways. Meanwhile pearlitic phase transformation has become a common procedure [8, 11]. After pre-machining, the quality heat treatment (QHT) to adjust a yield strength ≥ 700 N/mm^2 is performed, followed by final machining to delivery contour and testing including heat stability test prior to shipment. The quality heat treatment consists of austenitizing and double tempering; first tempering to complete the martensitic transformation and second tempering to adjust the desired properties (Figure 7).

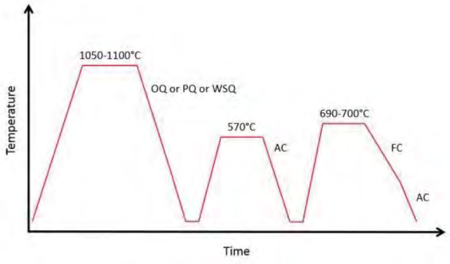


Figure 7: Quality HT cycle (schematic).

Beside the mechanical properties, the ultrasonic detectability including sound attenuation is an important criterion for the quality of rotor forgings (Figure 8).

Steel	Melting Process	Body [mm]	Q-Heat Treatment	Periphery, tangential, body end						Core of journal, radial, body end side						MDDS Body PHT [mm]	MDDS Body QHT [mm]	Sound Attenuation 2 / 4 / 5 MHz [dB/m]
		Ingot weight [kg]		UTS [MPa]	0.2%YS [MPa]	EL [%]	RA [%]	Charpy [J]	FATT [°C]	UTS [MPa]	0.2%YS [MPa]	EL [%]	RA [%]	Charpy [J]	FATT [°C]			
E	BEST	1020 44,000	1080°C/Oil + 570°C + 705°C	842	718	19	63	87		867	740	19	63	45	+37	2.0	1.0	0.5 / 2.0 / 4.0
E	ESR	1300 n/a	n/a	866	744	18	59	49		878	743	18	56	52	+34		1.2	1.9 / 3.5 / 5.0
E	ESR	1240 154,000	n/a	862	736	18	60	87		854	730	15	60	80	+18		1.0	1.3 / 4.4 / 4.5
E	ESHT-J	1280 69,500	1090°C/Oil + 570°C + 685°C	896	780	20	60	37	+30	903	782	16	47	34	+27		0.9	0.4 / n/a / 4.6
F	ESR	1410 115,000	1090°C/Oil + 570°C + 690°C	875	740	18	56		+17							3.4	1.4	0.4 / n/a / n/a
F	ESR	1370 115,000	1090°C/Oil + 570°C + 690°C	873	741	18	59		+22							3.4	1.4	0.8 / n/a / n/a

MDDS ... Minimal Detectable Defect Size PHT ... Preliminary Heat Treatment (= pearlitic transformation) QHT ... Quality Heat Treatment

Figure 8: Basic data and mechanical properties at RT of COST rotors E and F from different suppliers [8, 11].

To date, these new steels have been introduced in high efficient USC power plants with a total capacity of about 187 GW worldwide [IEA WEO 2013]. COST E and F are meanwhile specified in the German standard SEW 555 with the steel numbers 1.4906 (grade E) and 1.4902 (grade F). Bohler manufactured more than 490 rotor forgings out of COST steels type E and F (Figure 9).

Figure 9: HP-rotor at final forging, COST steel E.

1.2. Cost FB2 for up to 620°C

After the successful development of COST type E, F and B2 material within COST 501 (1983-1997), the subsequent COST 522 action (1998-2003) followed the trend to develop materials for even higher steam temperatures (Figure 10).

Trial Rotor	0.2%YS [MPa]	Max. testing time [h]	CRS at 600°C/10^5 h [MPa]
B2	> 600	131,000	122
E	> 700	106,000	95
F	> 700	115,000	95
FB2	> 700	60,000	125

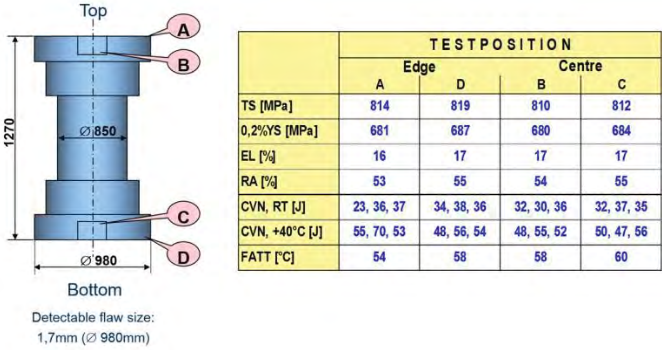
Figure 10: 100,000 h creep rupture strength (CRS) of COST type E, F, B2 and FB2 steels.

Based on B2 steel, which showed the highest creep resistance of the three steels [12], a new modified steel called “FB2”, with the addition of Co has been developed and first produced as a 3.5 metric tons trial melt by Bohler Edelstahl. The very promising properties of this FB2 test material led to an upscale in industrial heat and the manufacture of a full-size trial rotor forging with a final weight of 17,000 kg, again manufactured by Bohler [8]. Then forgings from Società delle Fucine Terni and Saarschmiede followed [13].

The excellent creep resistance of FB2 and the successful transformation of trial melt behavior to large components led to the start of industrial production for new USC power plant projects in Germany, USA and Asia, beginning in 2007.
Again, as already described in the previous chapter for the 600°C materials COST type E and F, the melting route for FB2 steel is also ranging from conventional ingot casting over BEST process [8, 10, 14] or equivalent ESHT (electro slag hot toping) [15] up to electro slag remelting [16]. Therefore, the melting/remelting know-how in combination with the specific steelmaking equipment is of great importance to fabricate a highly homogeneous and uniform ingot with a good boron distribution – which is a basic necessity to gain the excellent creep rupture strength properties for the forging. During the last years Bohler manufactured rotor components with delivery weights from 7 to 9.2 metric tons and diameters up to 1100 mm. Hereby the basic manufacturing steps for FB2 rotor forgings are quite similar to that for type E or F forgings and have already been reported [9, 14, 17].
It has to be pointed out that, especially for large forgings, the PHT as a pearlitic transformation, similar to that applied on the 600°C class 10% Cr rotor forgings, have meanwhile become evident. It is reported [15-16], that by applying (isothermal) pearlitic transformation the grain transformation process results in a significant improvement of the minimum detectable defect size of 1.1-1.3mm for a rotor barrel diameter of 1200mm.

After forging, PHT and pre-machining, the quality heat treatment has to be carried out by austenitizing at 1090-1110°C / rapid cooling (oil or polymer or spray quenching, depending on the facilities) and double tempering to the target 0.2 % yield strength of ≥ 650 N/mm². Double annealing has to be performed to ensure a complete annealed martensitic microstructure.

All turbine rotors are subjected to mechanical technological testing to ensure their suitability for use. Usually the properties are checked at different test positions, depending on the shape of the rotor forging. Typical test results of basic strength and toughness properties are summarised in Figure 11.



	TESTPOSITION			
	Edge		Centre	
	A	D	B	C
TS [MPa]	814	819	810	812
0,2%YS [MPa]	681	687	680	684
EL [%]	16	17	17	17
RA [%]	53	55	54	55
CVN, RT [J]	23, 36, 37	34, 38, 36	32, 30, 36	32, 37, 35
CVN, +40°C [J]	55, 70, 53	48, 56, 54	48, 55, 52	50, 47, 56
FATT [°C]	54	58	58	60

Detectable flaw size:
1,7mm (Ø 980mm)

Figure 11: Mechanical properties of a FB2 rotor forging.

It has to be taken into consideration that boron has to be in solid solution to stabilise the $M_{23}C_6$ carbides and, in addition, nitrogen is necessary for the formation of the MX precipitates (Nb,V–carbo-nitrides), both to get a high level of creep resistance. If there are too many boron nitrides (BN) in the microstructure, especially clusters, the creep properties will not achieve the expected level due to a lack of B and N in the matrix. B and N therefore have to be balanced very carefully (Figure 12).
All results in Figure 12 have been achieved on industrial melts based on 9-12% Cr steels.

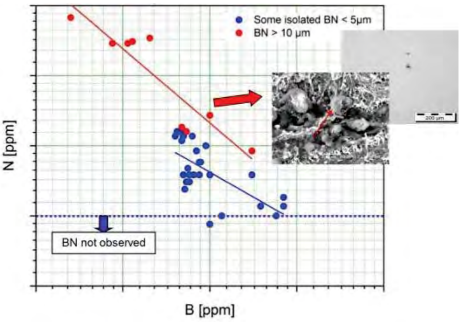


Figure 12: Influence of boron and nitrogen on BN generation.

Great efforts have been made to increase the thermal efficiency by increasing the operating temperature of steam power engines to currently 620°C and now, FB2 is going to be the material for the next turbine generation.

2. Present material development for temperatures above 620°C

Figure 1 gives a schematic overview of the past 50 years of steel development. The maximum achievable steam conditions could be improved from subcritical 180 bar and 540°C to ultra-supercritical values of 300 bar and 600-620°C, now being introduced worldwide with unit sizes of up to 1100 MW. In comparison to the X21 material, the creep rupture strength of the last generation of 9-10% Cr steels nearly doubled [12] with the currently best and most stable alloy for rotor forgings, the FB2 material.

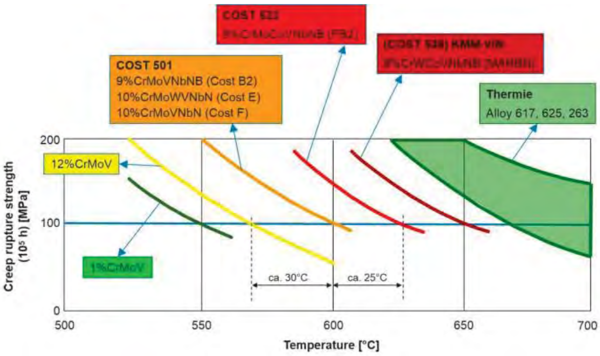


Figure 13: Overview of 100,000 h creep rupture strength of the newly developed European steels.

Within the last COST Action, COST 536 (2004-2009), all attempts to make a more creep-resistant 9-12% Cr steel led to breakdowns in long-term creep strength properties [13, 18]. However, the achievement of a better understanding of microstructural stability, especially the effect of B and N on long-term creep properties, led to the determination of a balanced B to N relationship to avoid the formation of boron nitrides [19]. The effect of soluble B at the grain-boundaries to increase the hardenability by shifting the ferrite nose to longer times is well known [20] and the reason, why the fine-grained heat affected zone (FGHAZ) turns into non-uniform FGHAZ upon welding. Understanding this is the basis for a series of new stronger 9% Cr test alloys for predicted improved creep strength, developed at the end of the COST program and now being investigated and optimized in the working group 2 of the current KMM-VIN action, the continuation of the COST program. In comparison to the FB2-2 material (Figure 14) these new low carbon martensitic steels, alloyed with boron and nitrogen – so-called MARBN-steels, are one of the preferred material group with a big potential for further increase in creep resistance and having good chances to reach the target of 650°C.

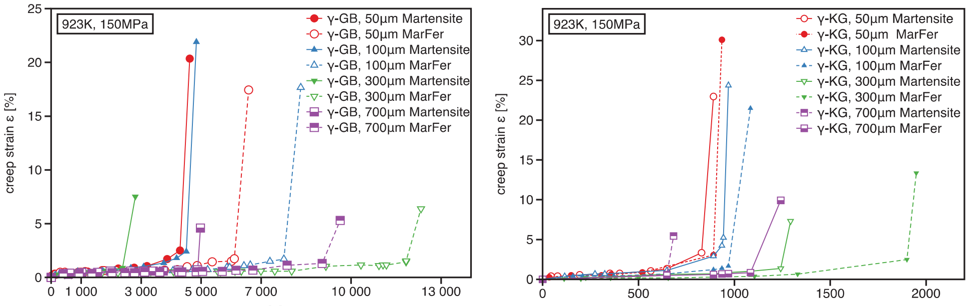
Steel	Bohler	C	Mn	Cr	Mo	Co	W	V	Nb	N	B
Cost FB2-2LN	T570	0.16	0.3	8.8	1.4	1.0	-	0.2	0.04	0.01	0.015
Cost NPM1	T516	0.07	0.5	9.0	-	2.9	2.9	0.2	0.05	0.01	0.010

Figure 14: Chemical compositions of the investigated alloys [Weight %].

Two test alloys with 3.5 metric tons each, FB2-2LN and NPM1, have been manufactured by EAF and PESR process at Bohler Edelstahl, forged to square 250mm and preliminary heat treated. These alloys are now in the phase of investigation and optimization. Running research activities have the goal to create improved microstructures, influencing the mechanical properties at high temperatures. First a specific prior austenite grain size has to be adjusted by selecting an optimized hardening temperature. The second step is to cool from hardening temperature to a temperature between M_s and M_f to get about 75% martensite and 25% austenite. Finally a re-heat to annealing temperature is necessary for the isothermal transformation of the austenite into ferrite and precipitates. The resulting microstructure is called MarFer [21-22].

2.1. Investigation of FB2-LN and NPM1

The conducted heat treatment for the comparative creep tests is illustrated in Figure 15 and Figure 16 [3]. Both steels were compared with martensitic and 75/25% MarFer microstructure and different PAGS (prior austenite grain size) from 50µm to 700µm (test specimen diameter 7,07mm). Comparing the NPM1 material with the FB2-2, NPM1 shows six times longer creep rupture times. For each PAGS the MarFer, compared to the martensitic microstructure, shows longer creep rupture times. For both materials the longest creep rupture time could be achieved with PAGS of 300µm and MarFer microstructure.

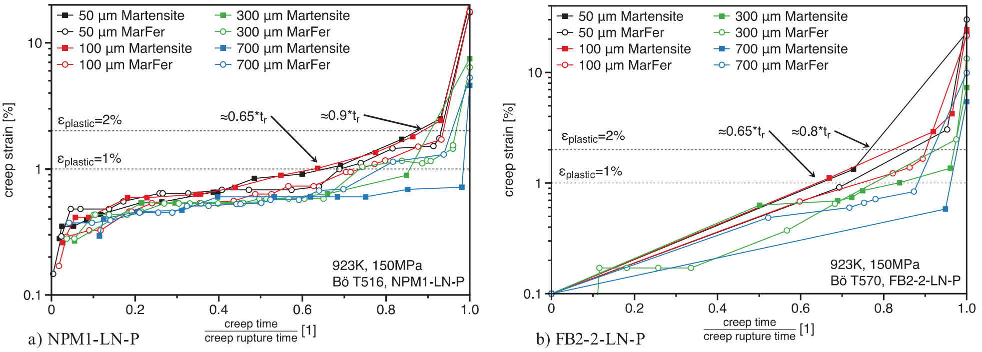


a) NPM1

b) FB2-2

Figure 15: Comparison of creep graphs of NPM1 (a) and FB2-2 (b) with variations of the PAGS and heat treatment.

With an increasing creep rupture time, the plastic limits are also shifted to longer creep rupture times, which are indicated as horizontal 1% and 2% lines for both steels in Figure 16 a) and b). The selection and consideration of an appropriate PAGS and plastic limits as inspection limits is important to avoid sudden brittle fracture. The results are showing that, depending on the PAGS, the 2% plastic strain limit will be achieved after reaching 80-90% of the total creep rupture time. For both materials the largest PAGS (700 µm) showed the lowest creep rupture ductility.



a) NPM1-LN-P b) FB2-2-LN-P

Figure 16: Comparison of creep strain graphs versus normalized creep rupture time for NPM1 (a) and FB2-2 (b).

The reason for the decreasing creep rupture ductility with increasing PAGS is, that creep voids and the subsequent formation of creep cracks grow predominantly at the PAGB. The PAGB is generally weaker due to segregating elements, such as S or P. Therefore, the creep rupture ductility changes about with the inverse square root of the PAGS [23].

The stereo-micrographs in Figure a-d for the FB2-2 specimen show the fracture surface to illustrate the transition from ductile fracture a-b (50/100µm grain size) to inter-granular, brittle fracture with almost no reduction of area and visible prior austenite grains in 17c-d (300/700µm).

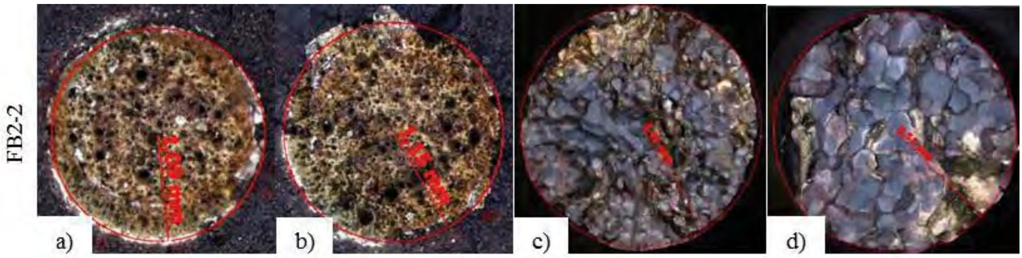


Figure 17: Stereo micrographs of the FB2-2 creep fracture surface.

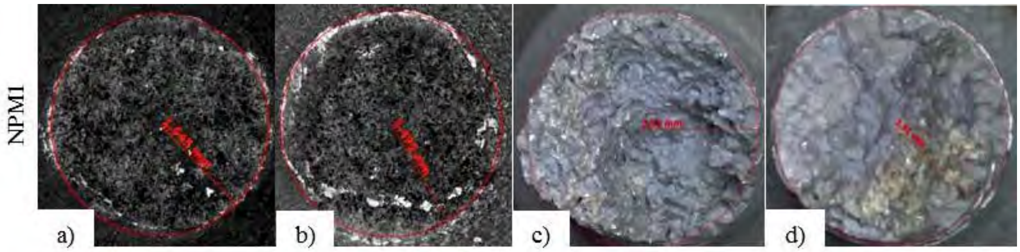


Figure 18: Stereo micrographs of the NPM1 creep fracture surface.

Transmission electron microscopy (TEM) investigations were carried out for the FB2-2 and NPM1 material to investigate precipitates and their chemical composition. Figure a) show energy-filtered TEM (EF-TEM) images for the NPM1 material to illustrate Laves Phase, $M_{23}X_6$ and MX precipitates after the heat treatment and before creep exposure. The total investigated area was about 50 µm with no boron nitrides found. EF-TEM images of FB2-2 (in Figure b)) show $M_{23}X_6$ precipitates at a comparative scale as to a). The difference within the $M_{23}X_6$ precipitates and Laves Phase is Mo. $M_{23}X_6$ precipitates in FB2-2 contain about 5% of Mo, instead of tungsten in NPM1. With electron energy loss spectroscopy (EELS) a varying relationship of min. 8:1 to max. 2.5:1 between C and B have been detected within the $M_{23}X_6$ precipitates of the creep exposed FB2-2 specimen.

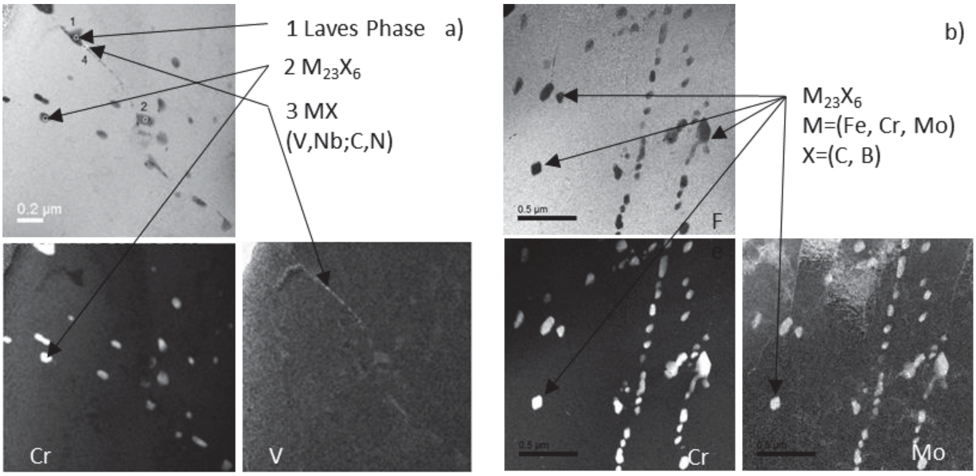


Figure 19: Energy-filtered transmission electron microscopy images to illustrate $M_{23}X_6$, Laves Phase and MX in as-heat treated condition for NPM1(a) and FB2-2 (b).

An illustrative way to investigate coarsening of the precipitates is energy dispersive X-ray maps inside a scanning electron microscope (SEM-EDX). The SEM-EDX mappings of the specimen NPM1 with a PAGS of 300 µm are investigated after the heat treatment (Figure a)) and after creep rupture (~12,000 h) (Figure b)) to illustrate coarsening of $M_{23}X_6$ (Cr mapping) and Laves Phase (W-mapping).

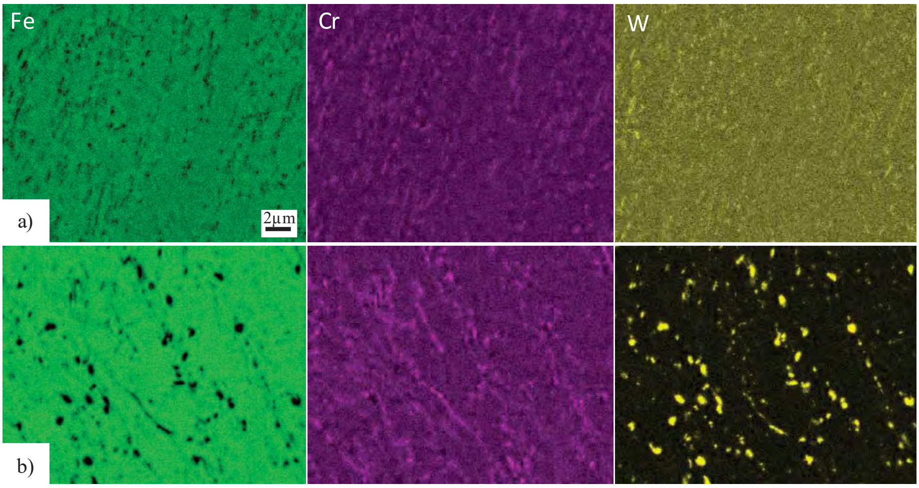


Figure 20: EDX mapping for the elements Fe, Cr and Tungsten (W) of NPM1 a) after heat treatment and b) after 12,000 h of creep exposure.

A comparison of creep strength at 650°C among different grades as E911, P92 (NIMS), P93 (Save12AD) [24], FB2-2 and NPM1 is shown in Figure 21 - not including the improvements achieved in the different heat treatments. It is clearly to see, that the MARBN steels NPM1 and FB2-2LN (Bohler T516 and T570, conventional and PESR) are more than competitive to present steels on the market. NPM1 specimen at 130 MPa load are still in progress.

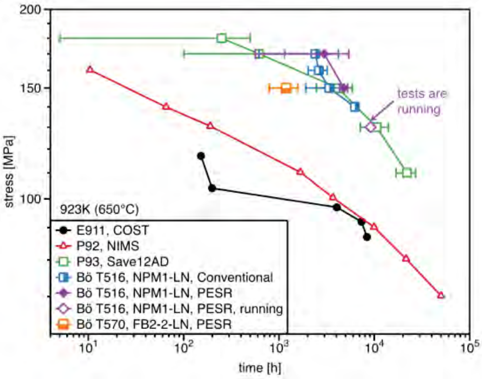


Figure 21: Comparison of creep strength at 650°C between E911, P92 (NIMS datasheet), P93 (Save12AD) [34], FB2-2 (Bö T570), NPM1 (Bö T516, PESR and EAF).

3. CONCLUSIONS

The improvement in efficiency of modern steam power engines can only be achieved by raising temperature and pressure of the steam.

During the last four decades, enormous efforts, especially in development of new materials, were made to establish the technology for the new USC power plants. These improved steels have become well established and qualified and are now in commercial operation in advanced fossil-fired power stations. Manufacturing aspects and attainable properties are shown. They have made it possible to increase the operating steam temperatures from the supercritical plant with 540°C steam temperature and 250 bar steam pressure to the first generation of ultra-supercritical with 580°C/270 bar and finally to the second generation of USC plants with 600°C–620°C and 300 bar steam pressure.

A further increase of the steam parameters up to the aim of 325 bar and 650°C needs to double the creep strength of the currently best martensitic Cr steel FB2. The new MARBN-steels, low-carbon martensitic steels, alloyed with boron and nitrogen, are showing a big potential for further increase in creep resistance.

NPM1 and FB2-2 steel, produced by Bohler Edelstahl, were subjected to different heat treatments, creep-loaded at 650°C and 150 MPa and investigated with TEM and SEM-EDX. The best creep resistance was performed by the MarFer microstructure with a grain size of 300µm.

REFERENCE

[1] M. F. Ashby, *“Materials and Sustainable Development”,* Elsevier, 2016.

[2] D. V. Edmonds, K. He, F. C. Rizzo, B. C. De Cooman, D. K. Matlock, and J. G. Speer, *“Quenching and partitioning martensite - a novel steel heat treatment”,* Mater. Sci. Eng. A, vol. 438–440, pp. 25–34, Nov. 2006.

[3] E. Plesiutschnig, C. Beal, C. Sommitsch, S. Paul, and G. Zeiler, *“Ferritic phase transformation to improve creep properties of martensitic high Cr steels”,* Scr. Mater., vol. 122, pp. 98–101, Sep. 2016.

[4] E. Plesiutschnig, S. Paul, S. Schider, and E. Gamsjäger, *“Martensitic / Ferritic phase transformation of modern power plant steels”,* Austria: https://youtu.be/aKM_EsZBLl8, 2014.

[5] C. Berger, R. W. Vanstone; *“Development of high strength 9-12% CrMoV steels for high temperature rotor forgings – a collaborative European effort in COST 501/II”,* 3rd Int. Conference on Improved Coal-Fired Power Plants, EPRI-Meeting, San Francisco, USA, April 2-4, 1991.

[6] K. Furuja, A. Hizume, Y. Takeda, Y. Takano, H. Yokota, A. Suzuki, S. Kinoshita, M. Kohno and T. Tsuchiyama; *“Advanced 12Cr Steel Rotors developed for EPDC Wakamatsu’s Ultra High*

Temperature Turbine Project", 2nd Int. Conference on Improved Coal-Fired Power Plants, Palo Alto, California, Nov. 2-4, 1988.

[7] C. Berger, K.H. Mayer, R.B. Scarlin, D. Thornton; *"New ferritic 10% CrMo(W)V(B)NbN rotor Steels for advanced power plants"*, Int. Joint Power Generation Conference, Atlanta, Georgia, October 18-22, 1992.

[8] G. Zeiler, W. Meyer, K. Spiradek-Hahn, J. Wosik: *"Experiences in Manufacturing and Long-Term Mechanical & Microstructural Testing on 9-12% Chromium Steel Forgings for Power Generation Plants"*; 4th International EPRI Conference, Conference CD, page 222-236, Hilton Head Island, South Carolina, USA, October 25–28, 2004.

[9] C. Lochbichler, F. Füreder Kitzmüller, G. Zeiler, S. Paul, J. Klarner, T. Vogl, S. Baumgartner, R. Schnitzer, R. Hanus, M. Schmitz Niederau, D. Kreuzer Zagar, S. Schramhauser, U. Trenkmann, M. Schuler, N. Enzinger; *"Know How and Process Development for Components used in (A) USC Power Plants"*, 10th Liege COST Conf. on Materials for Advanced Power Engineering, Sep. 14– 17, 2014, Liege, Belgium.

[10] W. Meyer, G. Zeiler, R. Bauer; *„Recent Developments on 9 to 12% Chromium Steel Open Die Forgings for Steam and Gas Turbine Applications at Bohler",* 14th International Forgemasters Meeting, 03-08. September 2000, Wiesbaden, Germany, Proc. p. 290-294.

[11] N. Blaes, D. Bokelmann, P. Braun, B. Donth, G. Weides, Y. Hirakawa, Y. Kadoya, R. Magoshi, M. Tanaka; *„Largest Turbine Rotors ever manufactured from 10%Cr Steels"*, 16th Forgemasters Meeting, Conf. Proc. p. 383-391, Sheffield, UK, Oct. 15–19, 2006.

[12] J. Hald; *"Development Status and future Possibilities for Martensitic Creep resistant Steels"*, 9th Liege COST Conference on Materials for Advanced Power Engineering, 18-20. Sep. 2010, Liege, Belgium.

[13] T. U. Kern, M. Staubli, K.H. Mayer, B. Donth, G. Zeiler, A. Di Gianfrancesco; *"The European Effort in Development of new High Temperature Rotor Materials – COST 536"*, 8th Liege COST Conference, 18-20. Sep. 2006, Liege, Belgium.

[14] G. Zeiler, A. Putschoegl: *"Experiences in Manufacturing of Forgings for Power Generation Application"*; 18th International Forgemasters Meeting, Conference Proceedings, p. 199 - 205, Pittsburgh, PA, USA, September 12-15, 2011.

[15] K. Kawano, T. Miyata, T. Satoh, T. Nakano, S. Nishimoto, A. Matsuo, Y. Kadoya, Y. Hirakawa: *"Manufacturing of Advanced 12%Cr Steel Forgings for Steam Turbines"*; 18th International Forgemasters Meeting, Conference Proceedings, p. 239 - 243, Pittsburgh, PA, USA, September 12-15, 2011.

[16] V. Vicario, T. Brambilla, M. Colnaghi: *"Large COST FB2 Rotors produced from ESR Ingots: Manufacturing and Characterization"*; 19th International Forgemasters Meeting, Conference Proceedings, p. 328 - 332, Tokyo, Japan, September 29 – October 03, 2014.

[17] G. Zeiler, A. Putschoegl: *"Gas and Steam Turbine Forgings for high efficient Fossile Power Plants*"; 7th International EPRI Conference, Conference Proceedings, p. 281 – 292, Waikoloa, Hawaii, USA, October 22-25, 2013.

[18] J. Lecomte-Beckers, Q. Contrepois, and F. Kuhn, "*Materials for advanced power engineering 2010",* Proceedings of the 9th Liège conference, Forschungszentrum Jülich, 1994.

[19] F. Abe, *"Precipitate design for creep strengthening of 9% Cr tempered martensitic steel for USC - power plants",* Sci. Technol. Adv. Mater., vol. 9, no. 1, p. 013002, Jan. 2008.

[20] E. Houdremont, *„Handbuch der Sonderstahlkunde"*, 2nd ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 1956.

[21] S. Paul, G. Zeiler, A. Putschögl, and E. Plesiutschnig, "*Turbine Components of High Creep Resistant MARBN Steels for Modern High Efficient Fossil-Fired Power Plants",* in Power-Gen Europe, 2014, p. 14.

[22] E. Plesiutschnig, C. Beal, S. Paul, G. Zeiler, S. Mitsche, and C. Sommitsch, "*Advanced Microstructures for Increased Creep rupture strength of MARBN Steels",* Mater. Sci. Forum, vol. 783–786, pp. 1867–1871, May 2014.

[23] E. Plesiutschnig, C. Beal, S. Paul, G. Zeiler, and C. Sommitsch, *"Optimized microstructure for increased creep rupture strength of MarBN steels", Mater High Temp.*, vol. 32, no. 3, pp. 318–322, May 2015.

[24] F. Masuyama, *"Introduction to New Miracle Steel P93",* in Flexible Operation & Preservation of Power Plants - Design Materials", Operation & Cost Issues, 2015.