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REVIEW OF THE EUROPEAN DEVELOPMENTS OF MARBN STEEL FOR USC POWER PLANTS

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ABSTRACT

Current demands of the power generation market require components with improved materials properties. The focus is not only on the higher operation temperatures and pressures but also more frequent cycling to accommodate the energy produced from renewable sources. Following the successful developments of steels within the COST 501, 522 and 536 programmes, further advances are being researched. As nickel superalloys remain an expensive option for coal power plants, there is a significant drive for improvements of 9-12% Cr steels to meet new demands. The most promising of the potential candidates identified for 650°C application is MarBN steel (9Cr-3Co-3W-V-Nb).

This paper reviews the current state of European developments on MarBN steel. Work on this alloy has been carried out for the last 5 years. Initial projects focused on development of the cast components. UK IMPACT and following INMAP projects successfully demonstrated manufacturing capabilities of large casting components. More recent collaborations aim to develop full-size boiler components and large rotor forgings as well as further examine the properties in the operating conditions (i.e. corrosion and oxidation resistance, creep-fatigue behaviour). Additionally significant focus is placed on modelling the behaviour of MarBN components, in terms of both microstructural changes and the resulting properties.

Keywords: 9Cr steel, material development, high-temperature application,

INTRODUCTION

Fossil fuel power plants remain a significant source of produced energy. Due to environmental and economic factors there is a demand for higher efficiencies and flexible operation of the newly designed plants. Current Ultra-Supercritical (USC) power plants use the materials developed through joint European programmes (COST 501, 522 and 536). These projects focused on development of new 9-12%Cr steels. The steels like 9CrMoCoVNbNB (FB2, CB2) have been successfully developed and have already found commercial applications in the new USC power plants with operation conditions up to 620°C. These steels have found applications in both large castings and rotor forgings. Additionally P92 steel is used as a boiler pipe material. The next step is to develop steels for 650°C application. Further increase in the operating temperature will improve the efficiency of new power plants and reduce carbon emission. It is estimated that new operating conditions will allow efficiencies up to 50% in comparison with 46%

in today's USC power plants [1]. Additionally development of renewable energy sources requires power plant to operate in flexible conditions. With the increase of power created from the alternative sources, conventional power stations have to adjust their output to balance the demand. Most of the current power plants were designed to operate at constant load. The changes to operating conditions tend to decrease the lifetime of the components due to creep-fatigue and thermo-mechanical fatigue (TMF). The long start-up times create further costs for power plant operators. Therefore there is a demand for materials that could provide better flexibility in operation.

MarBN steel was identified as a candidate material for new applications. It is a 9Cr martensitic steel strengthened by boron and nitrogen. The relationship between these two elements and its effect on creep strength has been first discovered by Abe [2-3]. It was shown that creep properties were critically dependant on both the absolute level of these two elements and the ratio between them. Studies showed that both elements are most effective in solid solution. With excessive amount of either element, boron nitrides tend to form during solidification and cannot be fully dissolved during heat treatment (Fig. 1). They tend to be detrimental to the creep properties. Therefore there is a fine balance between both elements, which requires tight control during the manufacturing process [4].

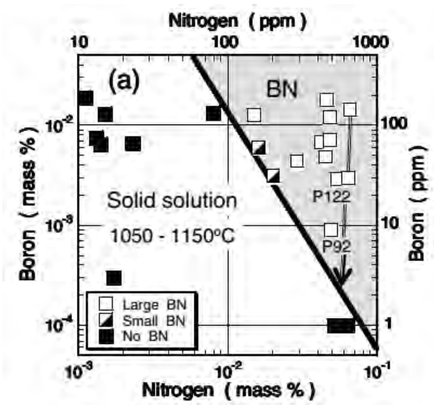

Figure 1: Boron and Nitrogen solubility in 9Cr steels [2]

MATERIAL DEVELOPMENT

The IMPACT project, part-funded by the UK government, was launched in 2010 aiming to develop MarBN steel with excellent creep strength properties as well as ability to be manufactured using commercial processes. Trace elements often cause reduced creep strength due to inclusions and undesirable particles. At the same time the stringent component limits that are obtainable in the laboratory melts cannot always be achieved during manufacturing of commercial products. Therefore the focus of the project was to develop such a chemistry limits and heat treatment that will result in consistent creep properties throughout large components. The efforts of this project resulted in manufacture of 8 tonne bonnet casting (Fig. 2).

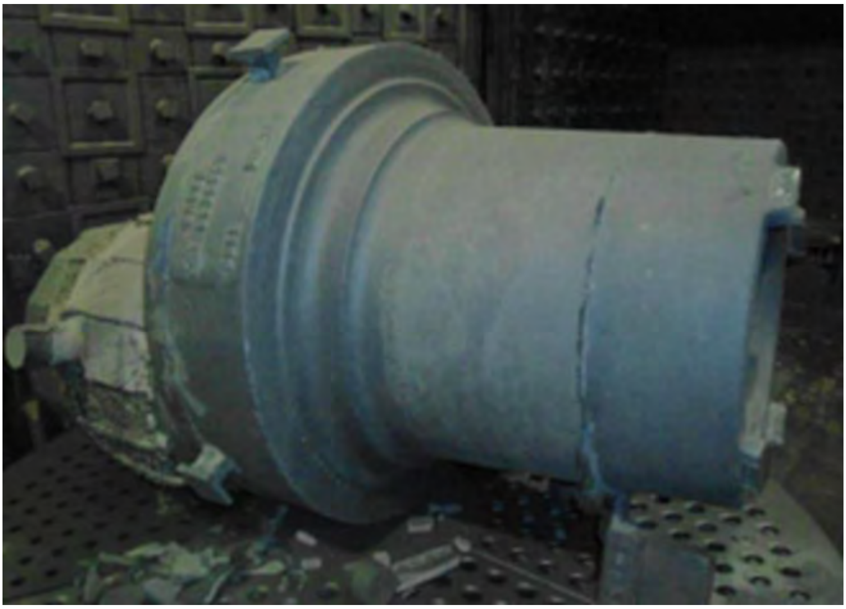

Figure 2: MarBN 8 tonne bonnet casting

CASTING

In fossil fuel power plants large castings find applications usually in the inner casing of turbines and valve chests. To prove the casting technology of the developed MarBN steel, the INMAP project, also part-funded by the UK government, was launched in 2014. The aim of the project was to demonstrate a full-scale component from this steel. A complex geometry and the requirement of a stable chemistry throughout the whole component created additional challenges as a solidification process could produce unwanted defects. For this project a typical valve chest design for USC applications was chosen. The casting was manufactured by electric arc furnace (EAF) followed by Argon Oxygen Decarburisation (AOD) secondary refining to enhance steel quality. Further controls for strengthening elements were introduced to avoid unwanted pickup of elements from atmosphere. Chemistry checks were performed on the component and are presented in Table 1.

Table 1: Detailed composition of valve chest (wt%)

	C	Si	Mn	Cr	Co	W	V	N	Nb	B
Valve chest	0.11	0.31	0.58	8.85	3.19	2.71	0.22	0.015	0.06	0.010

No significant cracking was observed after solidification. The heat-treatment, which was previously optimised during materials development, was applied for this casting as well. The valve chest was normalised at 1200°C followed by tempering at 735°C. One of the issues encountered during the heat-treatment was the significant oxidation during normalising. Nonetheless dimensional requirements were achieved. The machined product (Fig. 3) showed excellent quality. The NDE inspection revealed minimum requirement for repair, which is similar to other 9Cr castings. As currently no matching weld electrode is commercially available, CB2 electrode was chosen to perform the trial weld repair. The produced casting is known to be the first full size turbine component produced from MarBN steel.

Figure 3: INMAP project MarBN valve chest

Both parent material and the weldments are being tested for creep strength. As seen previously MarBN steel shows improvement of about 20-25°C in comparison to current state-of-the-art CB2 steel [5]. Figure 4 shows the comparison between these two steels. The MarBN data set includes results both from the initial 8 tonne bonnet casting produced during material development and from valve chest. The results from the two sources of material are similar.

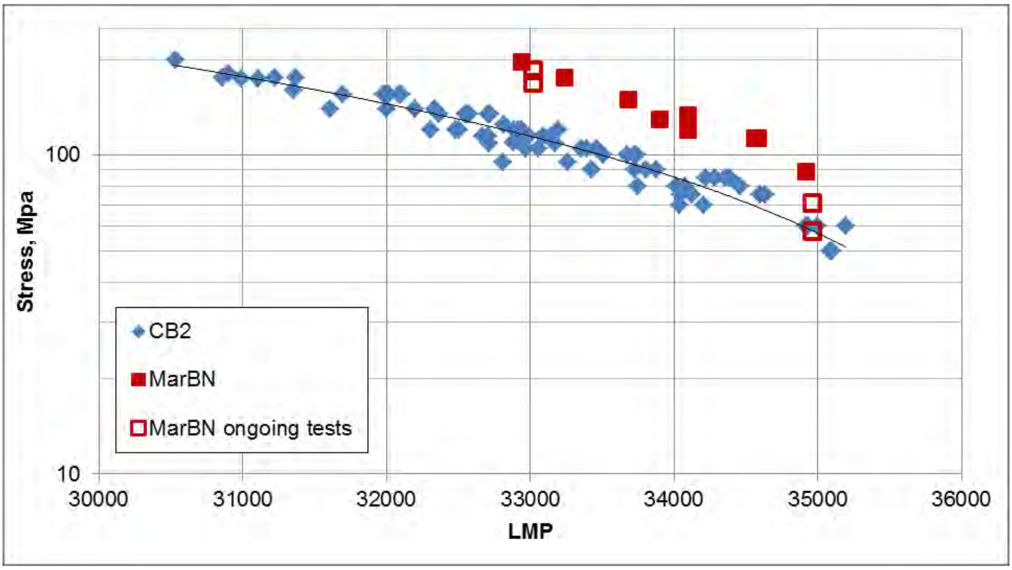

Figure 4: Comparison in creep strength between CB2 and MarBN cast steel

PIPEWORK

Additionally to chemistry and heat treatment optimisation during the material development project (IMPACT) several tubes were produced from forged bar (Fig. 5). These tubes were installed in a coal power plant to test the material behaviour in operating conditions [6]. Two of these tubes were installed in summer 2014 and are operating at approximately 600°C. Third tube was installed in summer 2015. The plan is to run these tubes for 2 and 4 years. Following the operating period, the tubes will be removed and analysed during the recently started project IMPULSE to assess oxidation resistance and microstructural evolution.

Figure 5: MarBN tubes from forged bar [6]

In May 2016 the consortium of manufactures (ingot, piping and weld consumables), boilermakers and Universities launched a project aiming to develop pipework from the MarBN steel. The IMPULSE project is also partially funded by the UK government. Following successful development of material (IMPACT project) and casting technology (INMAP project) the next step is to develop other product forms from the material with similar chemistry. The aim of the project is to produce two full-size boiler pipes. The pipes will be manufactured by extrusion from ingot – process used for these types of pipes with current P91 and P92 steels. Modelling work of the manufacturing process is included in the scope of the project to minimise the risk during extrusion. In order for the pipework to have commercial application, the welding solution has to be developed as well. In parallel, work is planned to develop matching welding electrodes. Following the manufacturing of pipe components and weldments, these products will be characterised to predict their behaviour in operating conditions under static and cyclic load. As pipe and weldment cracking is a serious issue in current power plants, these tests are planned to prevent such occurrences in the future for the new material.

FORGINGS

Large rotor forgings are the next type of product that is currently being developed from MarBN steel. Some work has been done both in the IMPACT project – tubes presented above were machined from forged bars, and at University of Graz - development of NPM1 and consequent testing of welded connections with Nickel filler metal [7]. These efforts focused mainly on small forgings. The large forgings used in rotors for power plants create additional issues such as homogeneity of microstructure at rim and core, the properties resulting from heat treatment and the crack detectability in large component due to signal loss during UT inspection. To address these issues a consortium of forgemaster, power generation equipment OEMs and research institutes was established. HOWEFLEX project (abbreviation from German: New High temperature material for rotor in flexible load power plants) is planned to be partially funded by the German government and aims to produce a full-scale rotor forging. The scope of the work includes modelling of the manufacturing process (forging and heat treatment), NDE testing, characterisation of the material both at rim and core. Additionally lifing models will be developed based on the test results. These types of steels are usually manufactured as disks and then welded to shaft ends from other steels. Therefore the work during this project will also focus on testing the weldability of this material and its resistance to cracking during manufacturing.

MODELLING

The modelling of materials behaviour is beneficial during component design. With the demand for the higher frequency of start-ups and shutdowns, cyclic behaviour at operating temperature is a significant materials property. Product developers have to understand the material behaviour under these conditions and apply models to confidently predict component lifetime. Modelling work on MarBN steel has been carried out for the last few years at NUI Galway. Barrett has previously reported work on the cyclic behaviour of cast MarBN at 600°C [8]. Good agreement was shown between test results and the developed model (Fig. 6). Further work is being carried out to test this material at higher temperature (650°C) and to show that the model works equally well at different temperatures and strain levels.

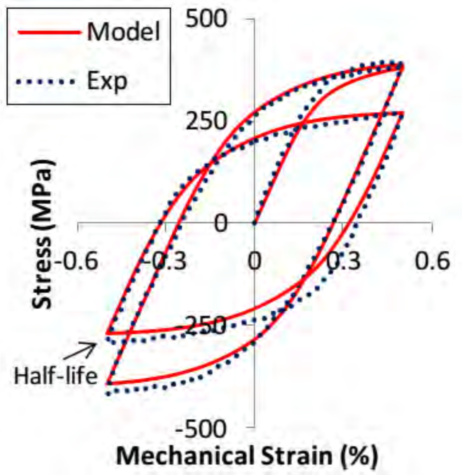

Figure 6: Example of comparison between measured and predicted stress-strain response for cast MarBN at 600°C [8]

Recently the consortium of NUI Galway and University of Limerick has received a support from Science Foundation Ireland (SFI) to develop a lifing model for welded connections based on the microstructure design. The Multi-scale through-process characterisation for innovative manufacture of next-generation welded connections (MECHANNICS) project was launched last year aiming to fully characterise and predict the material behaviour in the weldment. During the project the interaction between microstructure, environment factors and materials properties are being studied in order to improve the prediction models. MarBN was chosen as one of the materials for welded connections in the power plants.

FUTURE WORK

For the casting technology the remaining issue is the weld repair. Several options are being investigated and in the near future it is expected that an optimised solution will be found and qualified for commercial purpose. As the projects on pipework and large forgings are in the early stage, the development work on these products will continue for the next few years.

Collaboration between the projects described in this paper is being facilitated by the KMM-VIN (Knowledge-based Multi-functional Materials Virtual Institute) Energy Materials Working Group (WG2) [1], one of which main objective is the development of MarBN steels.

SUMMARY AND CONCLUSIONS

- The last 5 years have seen significant efforts in the development of MarBN steel for power generation components

- Early focus on the cast component has resulted in manufacture of a full-scale valve chest
- Test results show improvement in the creep strength that will allow MarBN steel to operate up to 650°C
- Casting development reached the status where commercial products could be available in the near future
- The work on pipework and large rotor forgings is in the early stages but work is ongoing and will result in the development of other components from MarBN steel
- Modelling work brings additional benefits for product developers to improve lifing of the new products and prevent premature failures that are often seen in power plants due to increased flexible operation

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