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Effect of normalizing temperature on the strength of 9Cr–3W–3Co martensitic heat resistant steel

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ABSTRACT

Microstructure and room temperature strength of 9Cr–3W–3Co martensitic heat resistant steel after normalizing at 900–1200 °C for 1 h and then tempering at 750 °C for 1 h have been experimentally investigated using optical microscope (OM), field emission scanning electron microscope (FESEM), electron back-scattered diffraction (EBSD), field emission transmission electron microscope (FETEM) and tensile tests. The results show that with increasing normalizing temperature, the strength of the 9Cr–3W–3Co steel increases from 900 °C to 1000 °C, then keeps almost the same from 1000 °C to 1100 °C and finally increases again from 1100 °C to 1200 °C. The change in the room temperature strength can mainly be attributed to the change in precipitation strengthening. The size and the amount of particles after tempering are mainly due to the re-dissolution of particles during normalization. The higher the normalizing temperature is, the more the coarse particles formed during manufacturing will be re-dissolved, and then the larger the amount of fine particles precipitated during tempering is.

1. Introduction

In modern steam power plants, 9–12% Cr martensitic steels are widely used for critical components, because of their good creep and oxidation resistance up to 600–625 °C, together with their good thermal properties and low cost relative to austenitic steels and Ni-based super-alloys [1–6]. As the present temperature range of 625 °C in maximum was expanded up to 650 °C or higher, the traditional martensitic heat resistant steels such as P92, E911 and P122 could not meet the more demanding service conditions [7–10]. Therefore, the development of new 9–12% Cr martensitic steels is highly desirable. In recent years, attention has been paid on 9Cr–3W–3Co steels which were first developed in Japan by NIMS [3]. This new kind of steel with good creep properties is expected to be used in USC power plants for up to 650 °C. Lots of work has been done on 9Cr–3W–3Co steels, such as alloy design [11–14], microstructural stabilization during aging and creep [15–18], effect of tempering temperature on the toughness [19] and so on.

However, in martensitic heat resistant steels, besides good creep and oxidation resistance properties, strength of the steel at room temperature is also sometimes required for commercial use. There have been many literatures reported on the relationship between microstructure and strength of the steels. Some researchers [20–23] reported that the increased amount of alloying elements such Cr and C in the matrix by the dissolution of the carbides could cause an increase in the carbon super-saturation and lattice distortion of martensite, resulting in the increase of the strength. Andres et al. [24] indicated that the presence of retained austenite would result in the decrease in strength. Some others [25–29] also reported that the strength decreased on increasing the prior austenite grain (PAG) size, the width of the packets and the blocks. The larger the grain size was, the weaker the effect of strengthening and plastic deformation resistance would be. The early work by Wang et al. [30] indicated that the precipitated particle could obviously induce the enhancement of yield strength as well as the refinement of martensitic lath. Das et al. [31] reported that with increasing normalizing temperature the strength increases to its maximum and then begins to decrease because of dissolution of carbon and grain growth. Therefore, there are still plenty of controversies about the structure of martensite dominating the strength.

Since martensitic heat resistant steel is newly developed, the effect of microstructure on room temperature strength of 9Cr–3W–3Co steel still lacks research. Martensitic steels are usually used after normalizing and tempering treatment, and it is acknowledged that PAGs, packets, blocks and precipitates can all be affected by normalizing temperature. How the microstructure evolves during the normalizing process followed by tempering can have an important effect on the strength. Therefore, the purpose of

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the present study is to investigate the effect of normalizing temperature on the strength of 9Cr–3W–3Co steel. The strength and the corresponding microstructural characterization were carried out after normalizing at different temperatures and tempering at 750 °C. Furthermore, mechanisms of normalizing temperature on strength of 9Cr–3W–3Co steel were clarified.

2. Experimental details

The test steel used in this study is named G115 steel and it was melted by a vacuum induction furnace and then casted into an ingot at Bao-Shan Iron and Steel Company (BaoSteel). The main chemical composition of the steel is given in Table 1. The ingot was then forged and hot extruded into a pipe with an outside diameter of 254 mm, an inside diameter of 204 mm, and a length of 3.5 m.

Tensile specimens were cut from the pipe along longitudinal axial direction. They were normalized at 900–1200 °C for 1 h, followed by tempering at 750 °C for 1 h. After heat treatments, the blanks were machined into standard tensile test specimens of 5 mm in gage diameter and 25 mm in gage length. Tensile tests based on standard of ISO 6892-1: 2009 [32] were carried out at room temperature using INSTRON 5582 tensile testing machine. The yield strength was determined by the 0.2% offset flow stress. All results were repeated for three times and the average values were taken to describe the strength of the test steel.

PAGs of the test steel were observed by using LeicaMEF4M optical microscope (OM) and the specimens were prepared after being polished and etched with picric acid for 10 min. Particles in the as-treated samples were characterized by TESCAN MIRA 3 LMH field emission scanning electron microscope (FESEM) as well as on thin foils using TECNAI $G^2$20 field emission transmission electron microscope (FETEM) at 200 kV. Thin foils were prepared using conventional double-jet electro-polishing in solution of 150 ml $HClO_4$+850 ml CH_3CH_2OH at a temperature of −25 °C and a potential of 30 V. The chemical composition of the particles was measured using energy dispersive spectrometry (EDS) in the FETEM. Martensitic blocks can be characterized with the assistance of electron back-scattered diffraction (EBSD) technique. The EBSD bulk specimens were mechanically polished and then electro-polished in solution of 100 ml $HClO_4$+900 ml CH_3CH_2OH at a potential of 20 V for 10 s. Dislocation density was obtained by using XRD [18,19]. The radiation was Co Kα, and the voltage was 30 kV.

Table 1
Main chemical composition of G115 steel (wt%).

C	Cr	W	Co	V	Nb	N	B	Fe
0.076	8.83	3.11	2.99	0.19	0.042	0.014	0.013	Bal.

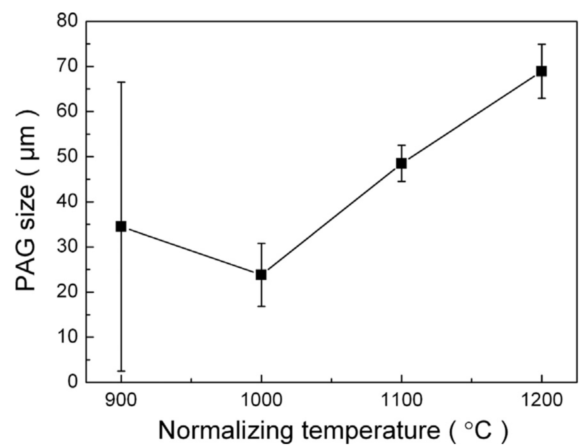

Fig. 2. Average values of PAG size in G115 steel after normalizing at different temperatures.

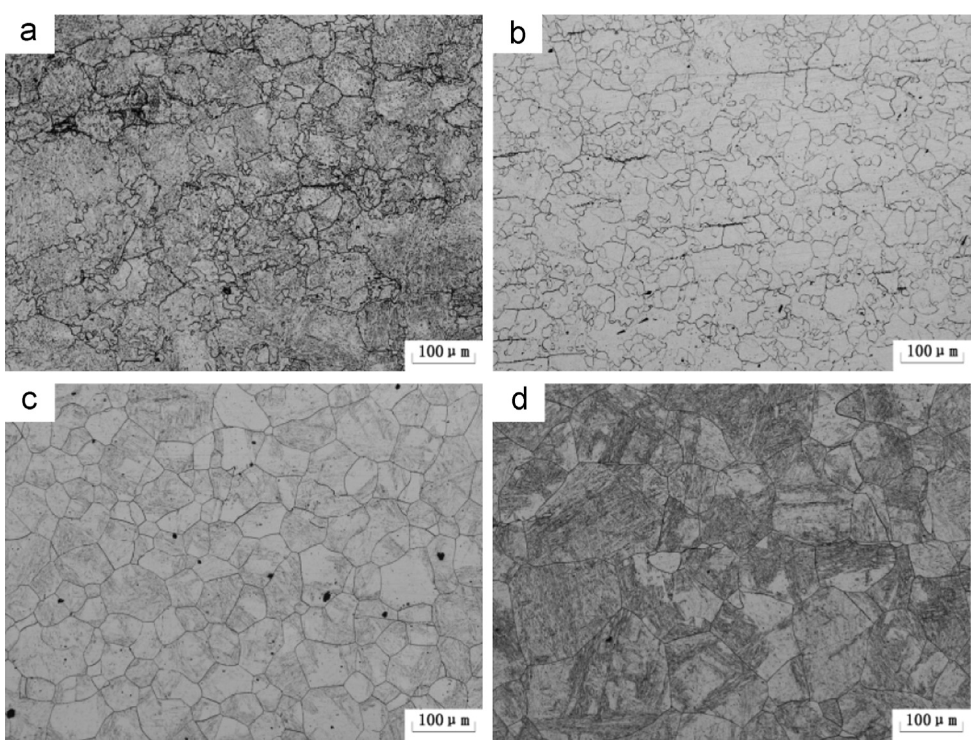

Fig. 1. Prior austenite grains of G115 martensitic steel normalized at temperatures of (a) 900 °C, (b) 1000 °C, (c) 1100 °C and (d) 1200 °C and tempered at 750 °C observed by OM.