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Effects of tantalum content on the microstructure and mechanical properties of low-carbon RAFM steel

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A B S T R A C T

In order to explore the influence of tantalum content on the microstructure and mechanical properties of low carbon RAFM (reduced activation ferritic/martensitic) steels, three low carbon RAFM steels with different tantalum contents (0%, 0.027%, 0.073%) were designed. The precipitation behavior and effect of precipitates on the mechanical properties of the Low-C RAFM steel were investigated. The results indicate that increase of tantalum content causes decrease of the prior austenite grain size and the amount of $M_{23}C_6$ carbides precipitated along prior austenite grain boundaries and packet boundaries as well as increase of the amount of MX nano-sized particles within intragranular regions. The impact properties of low carbon RAFM steels are excellent regardless of the tantalum content. The impact properties and hardness are obviously improved by increasing tantalum content, which may be related to increase of the number of MX and decrease of $M_{23}C_6$. Furthermore, the tensile properties at elevated temperature below 600 °C are hardly changed with increase of tantalum content, yet those at 800 °C are improved with increasing tantalum content. This implies that MX carbides would be more important for tensile properties at higher temperature.

1. Introduction

The reduced activation ferritic/martensitic (RAFM) steels are considered to be the preferred candidate for the structural material in the fusion reactors because of their excellent thermo-physical properties and optimum application temperature [1]. It is generally accepted that the RAFM steel is produced by the modification of the traditional heat resistant steel. The long-lived transmutation elements like Mo, Nb, Cu, Co were replaced by relatively short-lived transmutation elements like Ta, W, and V. Different types of RAFM steels have been developed in many countries for the past decades, such as F82H steel in Japan [2,3], EUROFER 97 steel in Europe [3,4], 9Cr2WVTa steel in USA [5,6]. Owing to the harsh working condition for RAFM steels, continuous efforts are in progress to develop RAFM steels with better mechanical properties by modifying the content of alloy element and processes of heat treatment.

It is well known that there is a close relationship between precipitate phases and mechanical properties. Sub-boundaries decorated with $M_{23}C_6$ carbides and intragranular regions containing MX carbonitrides are considered as primary precipitates during heat treatment, affecting the mechanical properties of the RAFM steel [7–9]. The uppermost effect of precipitation in tempering restrains recovery by pinning the dislocations against the annihilation process, which would enhance the chronic microstructural stability [10]. In general, with the increase of temperature and strain, the coarsening of $M_{23}C_6$ carbides below 900 °C would be accelerated, deteriorating creep and other mechanical properties. However, coarsening of MX particles is inconspicuous, the MX precipitate is of great benefit to creep properties in RAFM steels [11–15]. Carbon and tantalum content is vital to controlling the precipitation behavior of carbides and mechanical properties of RAFM steels. Strength of quenched martensite approximately exhibits a linearly relationship with the content of carbon [16]. Besides, the density of dislocation in martensite is linearly dependent on the carbon content, and the volume of the retained austenite also depends on the carbon content [17]. The steel with 0.012% carbon content has not only the higher strength but also the higher impact toughness and grain coarsening temperature [18]. Tantalum has been reported to be beneficial to refine prior-austenite grains and to improve toughness [19]. Within this context, we adjust the content of tantalum in the condition of low carbon, to investigate the effect of precipitation behavior on

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mechanical properties of Low-C RAFM steels.

This work aims to research the effect of tantalum content on microstructures and mechanical properties of Low-C RAFM steels. The low carbon RAFM steels were designed with different tantalum contents such as 0%, 0.027%, 0.073%. Tensile, Charpy impact and hardness tests were conducted to evaluate the mechanical performance of the Low-C RAFM steels with different tantalum contents. The microstructures of specimens were examined by optical microscopy (OM), scanning electron microscope (SEM) and transmission electron microscopy (TEM) respectively. The correlation between the microstructures especially as distribution of MX particles and mechanical properties of the Low-C RAFM steels with different tantalum contents was also discussed.

2. Materials and experimental methods

The designed RAFM steels were cast in a vacuum induction furnace into an ingot of a weight of 25 kg, then the steels were remelted three times to ensure a high degree of homogeneity, followed by hot-rolled into cylinder bars, with a size of 120 mm in height and 60 mm in diameter. The chemical compositions of the melted steels are shown in Table 1. For all RAFM steels, Fig. 1 shows the processes of heat treatment of RAFM steel, which includes austenitizing at 1050 °C for 0.5 h followed by air cooling to room temperature, and then a tempering at 750 °C for 1.5 h.

The microstructures of Low-C RAFM steel were analyzed through optical microscopy (OM), scanning electron microscope (SEM) and transmission electron microscopy (TEM). OM investigations were carried out to measure the prior austenitic grain size of the steels. SEM and TEM were used to study the microstructure and precipitate phases of the steels. Identification of the type of carbides was carried out by electron diffraction pattern analysis. The samples for OM and SEM were ground, mechanically polished and etched by a mixed solution of hydrochloric acid and ferric chloride. In TEM samples preparation, mechanical polishing was followed by twin-jet-polishing with a solution of 5 vol% perchloric acid in ethanol.

Tensile, Charpy impact and hardness tests have been conducted, the size of gauge section for the tensile specimen is Φ3 × 24 mm, and the size of Charpy-V-notch sample is 10 × 10 × 55 mm^3, containing a 2 mm 45° V-notch with a root radius of 0.25 mm. The tensile specimens were performed at room temperature, 200 °C, 400 °C, 600 °C and 800 °C. RAFM steel is considered not suitable for use at temperatures below ~350 °C and above ~500 °C. Since we tried to improve the high temperature performance by reducing the content of carbon, we researched the tensile strength above ~550 °C. Three samples were used in each condition for tensile and impact test. For high temperature tensile test, the specimens were heated to tensile temperature at a heating rate of 10 °C/min, and then maintained at that temperature for 20 min before tensile. Impact tests and hardness tests were conducted at room temperature. The hardness of each sample was measured using 10 points with a 100 g load and 20 s dwell, from which the average value of hardness was calculated.

Table 1
Chemical composition of the Low-C RAFM steel in wt%.

	C	Cr	W	Mn	Si	V	Ta	Fe
1#	0.06	8.91	1.73	0.37	0.05	0.22	0	Bal
2#	0.05	8.92	1.66	0.31	0.03	0.23	0.027	Bal
3#	0.04	8.93	1.71	0.44	0.04	0.22	0.073	Bal

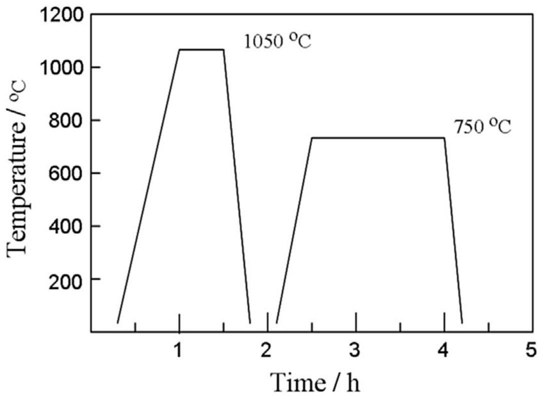

Fig. 1. Schematic diagram of the normalizing and tempering treatment.

3. Result and discussion

3.1. Microstructure observed by OM, SEM and TEM

Fig. 2 shows the OM micrographs of the specimens after normalizing & tempering heat treatment, which show the typical tempered martensitic microstructure with a small amount of δ-ferrite. It is observed that the size of grain decreases with increase in tantalum content, which results in a finer grain size in the specimen with higher tantalum content. The grain size of 1#, 2# and 3# specimens is ~33 μm, ~22 μm and ~17 μm, respectively. The linear intercept method was used to measure grain size [20]. In general, the undissolved carbides are well effective in controlling the grain growth during austenitization by pinning the grain boundaries [21,22]. The number of undissolved carbides increases with the increase of tantalum content, which leads to the prior austenite grain size (PAGS) decreases with tantalum content [23]. This would help to improve the toughness of Low-C RAFM steel.

The $M_{23}C_6$ type carbides play an important role on the microstructure stability. Fig. 3 exhibits the SEM micrographs of the three specimens with different tantalum contents, which displays the distribution of precipitates in the Low-C RAFM steel, in which the large $M_{23}C_6$ carbides precipitate along prior austenite grain boundaries and packet boundaries. Additionally, the amount of $M_{23}C_6$ carbides evidently decreases with the increase of tantalum content. In order to more clearly observe the microstructural characteristics and the variation of $M_{23}C_6$ carbides in the vicinity of martensitic lath, TEM analysis of the thin foil of the normalized and tempered Low-C RAFM steels was carried out, as is seen in Fig. 4 (a), (b) and (c). A lath structure decorated by precipitate phases and with high density of dislocations can be observed in all specimens. The martensitic laths width is similar in the three specimens. It was reported that the lath width is mainly dominated by tungsten rather than tantalum [23]. There is no obvious change about the lath width with addition of tantalum content in 1 W–0.14 Ta steel [24]. In this case, the width of tempered martensitic laths of specimens is in the range of 200–700 nm. The number of $M_{23}C_6$ carbides in 3# specimens is much less than that of in 1# and 2# specimens. Moreover, there are two types of $M_{23}C_6$ carbides, rod-shaped and globular particles. The size of $M_{23}C_6$ is in the range of 80–150 nm. Rod-shaped $M_{23}C_6$ carbides distribute along the martensitic lath boundaries. While within the grain, the growth rate of $M_{23}C_6$ carbides almost same in all directions, so globular $M_{23}C_6$ carbides can be observed in grain. It is more clearly observed that the quantity of $M_{23}C_6$ carbides precipitated along packet boundaries obviously reduce accompanying with the increase of tantalum. Fig. 4 (d) reveals the electron diffraction patterns of