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Microstructure, mechanical properties and strengthening mechanisms of 5Cr5MoV modified by aluminum

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ABSTRACT

The influence of aluminum on the microstructure and tensile properties of 5Cr5MoV was systematically investigated for improving the mechanical properties at room temperature. Microstructure was characterized by optical microscope (OM), scanning electron microscopy (SEM), field-emission transmission electron microscopy (FE-TEM), and additionally the uniaxial tensile tests were performed on a MTS-810 testing system. Tensile strength as a function of aluminum concentration exhibits an obvious two-stage characteristic. In stage I, 5Cr5MoV is continuously strengthened with the increase of aluminum, mainly owing to the refinement of lath martensite, the precipitation of small carbides and the presence of fine twins in martensite. The maximum tensile strength is 1303 MPa at the aluminum concentration of 1.63 wt.%. In stage II, the tensile strength rapidly drops down with the excessive addition of aluminum due to both the presence of large carbides at the boundaries between ferrite and martensite and the excessive ductile phase of irregular ferrites. As a result, the appropriate addition of aluminum can improve the mechanical properties of 5Cr5MoV by introducing the cryptocrystalline martensite as well as the dispersive polygonal ferrite in the microstructure.

1. Introduction

Cold work dies are commonly used to manufacture large-scale cover panels and ultra high strength steel sheets, so high strength, good toughness and abrasion resistance are necessary to deal with the bad working conditions. As a result, medium carbon alloy steel (MCAS) containing 5.0 wt.% Cr, which has got much attention due to their excellent combination of toughness and hardness, is an ideal material for the new-generation large size tool castings. On the one hand, it exhibits higher toughness than the high carbon alloy steel owing to its lower carbon content as well as the other alloy elements; on the other hand, it shows higher hardness and better abrasion resistance than the low carbon alloy steel because of its higher alloy elements [1].

The mechanical properties of martensitic steels generally depend on the chemical composition and the microstructure. Solid solution strengthening, dislocation hardening, precipitate hardening and grain boundary strengthening are the main strengthening mechanisms in martensitic steels [2–5]. As is well known, carbon significantly influences the microstructures and mechanical properties of martensitic steels. Hutchinson et al. reported that the hardness of the as-quenched martensite increased with the increase of carbon content, which was caused by the segregation of carbon at defects behaving similar to carbon in the true solid solution [3]. Moreover, the strength of the secondary hardening martensitic steel is closely related to the carbide precipitation. Michaud et al. showed that the volume fraction of small carbides could significantly affect the yield strength of 5.0 wt.% Cr martensitic steels [4]. For the volume fraction values below 0.6%, a strong correlation occurred with a large increment in the yield strength, as the curvatures of dislocations crossing the particles increased and the stress necessary to bypass the particles increased as well. However, for the volume fraction values above 0.6%, the yield strength reached saturation, because of presence of Orowan islands inducing the progressive saturation of the number density of particles definitively contributing to the pining of dislocations when the volume fraction increased. Nevertheless, the associated loss of impact toughness would occur with the increase of the volume fraction of small carbides. In addition, grain boundary strengthening is also a common strengthening method. Kim et al. investigated the grain size effect in 0.5–0.6 wt.% C martensitic steels, the results of which showed that the yield strength was inversely proportional to the lath width of martensite. It has been confirmed that in spite of the low misorientation angle between the lath boundaries, high density of initial

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dislocation and a large number of lath boundaries still played a remarkable strengthening role in steel [2].

Although the medium carbon alloy cast steel with 5.0 wt.% Cr possesses good toughness and high hardness, its mechanical properties are still inferior to that of the forging die steel. In order to expand its application in the mold industry, its mechanical properties still need to be largely improved. Alloying is an effective way to modify the microstructure and improve the mechanical properties of this kind of die steel [6–8]. Recently, the beneficial roles of aluminum in steels have drawn the researchers' attention [9–13]. The effects of aluminum in TWIP steels were extensively studied, which indicated that the yield strength of the Al-bearing TWIP steels increased partly due to the solid solution of aluminum and higher carbon concentration in the austenite matrix caused by suppressing the precipitation of cementite [9–11]. The reason was that the addition of aluminum decreased both the activity and diffusivity of carbon in austenite. In TRIP steel, aluminum used to replace part of silicon could enhance the formation of ferrite from austenite during intercritical annealing, and thus alter the phase constituents [14,15]. In addition, the addition of aluminum to the ultrahigh carbon steel facilitated the formation of fine lamellar pearlite in as-cast structure, so it could simplify the annealing process [16,17]. Based on the above results, aluminum is one of the effective alloying elements which can significantly improve the mechanical properties of steel. However, the role of aluminum in medium carbon alloy steel was rarely reported in the past decades.

In this paper, the influence of aluminum on the microstructure and mechanical properties of 5Cr5MoV steel was investigated systematically by adjusting the aluminum concentration, and finally the mechanisms in the evolution of mechanical properties were discussed and analyzed meticulously in order to gain a better understanding of the role of aluminum in MCAS.

2. Materials and methods

2.1. Materials and heat treatment

5Cr5MoV ingots with five different aluminum concentrations were smelted at 1600 °C in a medium induction furnace and subsequently cast into a Y-shaped sand mold cooling to the room temperature. Each ingot is approximately 5 kg, the chemical composition of which is listed in Table 1. It is well known that the cooling rate definitively affects the microstructure of castings. For comparison purposes, blanks for the heat treatment experiments were cut from the ingots at the same position where is about 5 mm from the bottom of the Y-block ingots.

The heat treatment process of 5Cr5MoV–*x*Al could be divided into three steps, including isothermal spheroidizing, austenitizing and tempering, which was carried out using an electric furnace. First, blanks were heated to 860 °C in the furnace and held for 120 min. Secondly, they were cooled to 760 °C at a cooling rate of 10 °C/min, and held for 360 min. Thirdly, they were cooled to 500 °C at a cooling rate of 0.1 °C/min. After annealing, the blanks were austenitized for 30 min (holding time) at 1040 °C, followed by quenching in the oil. Finally, the blanks were tempered for 120 min at temperatures in the range of 480–600 °C, and then cooled to room temperature in air.

2.2. Microstructure observation

The microstructures of the steels after heat treatment were observed using optical microscopy (OM; Carl Zeiss-Axio Imager A2m, Germany), scanning electron microscopy (SEM; ZEISS EVO18, Germany) equipped with energy dispersive spectrometer (EDS) analyzer (INCA-X-MAX, England) and field-emission transmission electron microscopy (TEM; JEM-2100F, Japan).

Specimens for OM and SEM were ground up to 2000 grit SiC emery papers, polished with a nylon cloth using 0.5 μm diamond paste, chemically etched in 5% nital for 2 min and finally cleaned with alcohol followed by drying in the cool flowing air. Thin-foil samples for TEM were prepared by ~0.5 mm slices. Each slice was first mechanically thinned to ~100 μm using 2000 grit SiC emery paper, and then thinned to ~60 μm using 5000 grit SiC emery paper, and secondly thinned to ~30 μm using 7000 grit SiC emery paper. Thirdly, the slices were ion-milled using a precision ion polishing system (Leica, EMRES101) and studied by using TEM at an acceleration voltage of 200 kV. The elemental distributions of Al, Cr, Mo and V in steels were quantitatively determined by EDS.

2.3. Tensile test and hardness test

Specimens were directly cut from the blanks at the same position where is approximately 5 mm above the bottom of the blanks subjected to temper for 120 min at 520 °C. The gauge part was 2 mm thick, 5 mm width and 15 mm long. Uniaxial tensile tests were conducted at a constant strain rate of $1 \times 10^{-4}\ \mathrm{s}^{-1}$ using an MTS 810 testing machine at room temperature. Rockwell hardness measurements were performed using a load of 150 kg. Five readings were taken for each condition. The highest and lowest values were removed, and the remaining three were used to obtain the mean and the standard deviation.

3. Results and discussions

3.1. Effect of aluminum on the microstructure of 5Cr5MoV steel

The optical micrographs of 5Cr5MoV–*x*Al steels after quenching and tempering at 520 °C for 120 min are shown in Fig. 1. If the aluminum concentration is in the range of 0.01–0.7 wt.%, the matrix microstructures of 5Cr5MoV–*x*Al steels are lath martensite as shown in Fig. 1(a)–(c). It seems that the lath martensite with a high level of alloying elements (C, Cr, etc.) looks bright, while the dark one contains a relatively low level of those elements. The difference is mainly caused by the elements segregation at the prior austenite grain boundary during solidification and solid state phase transformation. Moreover, no retained austenite can be observed from the XRD diffraction patterns (Fig. 1(f)). It should be noted that the ferrite phase appears in the microstructure of 5Cr5MoV–*x*Al steels containing more than 1.6 wt.% aluminum as shown in Fig. 1(d) and (e). That is to say, the microstructures of

Table 1
Chemical composition (wt.%) of the investigated 5Cr5MoV–*x*Al steels.

Steel	Fe	C	Si	Mn	Cr	Mo	V	N	S	P	Al
5Cr5MoV–0Al	Bal	0.55	1.15	0.85	5.36	0.77	0.78	0.00369	0.01	0.03	0.01
5Cr5MoV–0.5Al	Bal	0.56	1.10	0.86	5.22	0.78	0.78	0.00420	0.01	0.03	0.498
5Cr5MoV–0.7Al	Bal	0.56	1.10	0.86	5.20	0.78	0.77	0.00356	0.01	0.03	0.702
5Cr5MoV–1.6Al	Bal	0.53	1.19	0.87	5.13	0.76	0.76	0.00387	0.01	0.03	1.626
5Cr5MoV–2.2Al	Bal	0.55	1.10	0.86	5.12	0.75	0.78	0.00411	0.01	0.03	2.190