



Austenite layer and precipitation in high Co–Ni maraging steel

Chenchong Wang, Chi Zhang*, Zhigang Yang

Key Laboratory of Advanced Materials of Ministry of Education, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

In high Co–Ni maraging steel, austenite has a great effect on the fracture toughness of the steel and the precipitated carbides are the main strengthening phase. In this study, both austenite layers and precipitation were observed and their formation theory was analyzed by Thermo-Calc simulation and several reported results. TEM and HRTEM observation results showed that the thickness of the austenite layers was about 5–10 nm and the length of the needle-like precipitated carbides was less than 10 nm. The carbides maintained coherent or semi-coherent relation with the matrix.

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1. Introduction

Ultrahigh strength steels have been receiving significant attention for a long time (Guler et al., 2010; Hu and Wu, 2003). Before the development of high Co–Ni maraging steels, the experimental investigation on the ultrahigh strength steels mainly focused on increasing their strength (Wang et al., 2005). But now, high performance applications require steels with both ultrahigh strength and excellent fracture toughness (Hu et al., 2001). Therefore, more attention has been paid to the toughness improvement in high Co–Ni maraging steels as AF1410 and AerMet 100 (Handerhan et al., 1993).

In 1970s, Rice and Johnson (1970) suggested that reducing the size of precipitates in the steel could reduce the growth rate of crack effectively and increase the fracture toughness of the steel. Therefore, in the design of AF1410, great attention was paid to the fine dispersion of coherent carbides (MC and M₂C) which were precipitated during aging process (Olson, 1987). Then, in order to further enhance the fracture toughness and hydrogen embrittlement (HE) resistance of maraging steel, the austenite layers at martensite lath boundaries in AerMet100 were of concern (Figueroa and Robinson, 2007, 2010). However, few studies reported the details of the austenite layers and their specific effect on fracture toughness except for the bright-field image TEM observations (Yoo et al., 1996; Ayer and Machmeier, 1993).

Recently, QuesTek Innovations LLC (Olson, 2013) developed an ultrahigh strength maraging steel, named M54, which has similar strength and fracture toughness, but better HE resistance ability than AerMet100. As this steel was just developed in 2012, few studies reported its microstructure. In this study, the microstructure of this steel, especially the austenite layers, was observed and analyzed.

2. Materials and methods

The chemical composition of the steel in this study is listed in Table 1. Specimens were austenitized at 1060 °C for 1.5 h and quenched in oil to room temperature. Then immediately transferred to a cryogenic bath held at –73 °C for 2 h, and finally aged at 515 °C for 8 h.

The SEM samples were observed by JSM-7001F field emission scanning electron microscope. Thin foils for TEM were cut from the specimens and ground to a thickness of about 50 μm. The thin foils were electropolished in a perchloric acid–ethanol solution at –30 to –40 °C. All the TEM samples were observed by JEOL JEM2011 (Japan Electron Optics Ltd., Tokyo) at 200 kV. The phases in the steel were also analyzed by D/max 2500 V X-ray diffraction (XRD) and the samples were subjected to Cu–K radiation with a scanning speed of 2°/min.

3. Results and discussion

3.1. Microstructure simulation

The equilibrium phase diagram of the steel was calculated by Thermo-Calc software as Fig. 1. The calculation results showed that

* Corresponding author. Tel.: +86 010 862797603.

E-mail addresses: chizhang@tsinghua.edu.cn, liuxiaoming20000@126.com (C. Zhang).

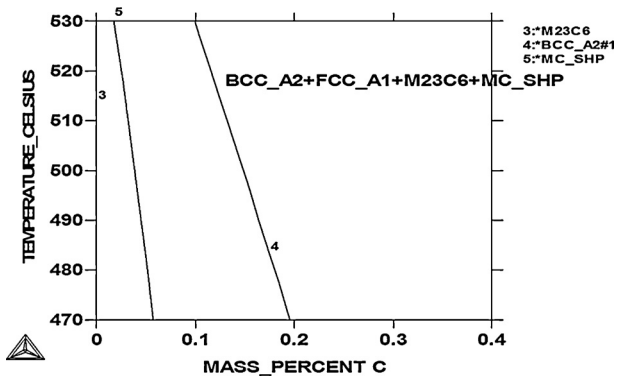


Fig. 1. Equilibrium phase diagram of the steel.

Table 1
Chemical composition of steel (wt.%).

C	Ni	Co	Mo	Cr	W	V	Fe
0.3	10.07	7.31	2.31	1.17	1.3	0.11	77.73

the equilibrium phases of the steel included BCC phase (ferrite), FCC phase (austenite) and carbides ($M_{23}C_6$ and MC) at 515 °C.

As quenching and tempering were both kinetic processes, the actual phases of the steel should not be the same with equilibrium simulation. After quenching and holding in cryogenic bath at -73 °C, the whole steel became martensite, and then a small amount of austenite and carbides would formed during aging process (Ayer and Machmeier, 1993). However, the amount of austenite would not be very large because of the function of W, Mo, Cr, which could inhibit austenitizing (Wang et al., 2000). Also, Olson (Olson, 1987) made the equilibrium simulation and TEM observation of the carbides precipitated during aging in AF1410. His studies reported that although $M_{23}C_6$ should exist after aging as the equilibrium simulation, but in actual, M_2C instead of $M_{23}C_6$ formed after aging in AF1410 because M_2C has higher driving force than $M_{23}C_6$.

In summary, according to the equilibrium simulation results and the reported results in other studies, the probable microstructure of the steel after tempering included martensite (BCC phase) and small amount of austenite (FCC phase) and carbides (M_2C and MC).

3.2. XRD results

Fig. 2 shows the XRD profiles of martensite. $\{011\}$, $\{002\}$ and $\{112\}$ crystal planes of martensite in the steel were obtained. However, we could not find the peak of austenite or carbides in the

steel by XRD results. Similar problems also appeared in the former studies of AerMet100 (Ayer and Machmeier, 1993; Wang et al., 2000). In the former studies of AerMet 100, austenite and carbides (M_2C), whose sizes were only 5–10 nm, could be observed by TEM observation (Ayer and Machmeier, 1993), but the peak of austenite or carbides could not be obtained in XRD profiles because their content was less than 5 wt.% (the test limit of XRD) (Wang et al., 2000). The peak movement of $M\{011\}$ was observed as Fig. 2(b). The peak of $M\{011\}$ in aged sample was 0.3° larger than that in quenched sample (without aging process). It means the carbon in the martensite was consumed by the formation of carbides during aging process (Wang et al., 2000). This result could prove that the formation of carbides does exist during aging process in this steel. However, without the actual peak of the carbides, the type of the carbides (MC, M_2C or $M_{23}C_6$) formed in this steel could not be identified.

3.3. TEM observation

Fig. 3 shows the morphology images of martensite on the quenched sample (without aging process). No austenite layers or carbides were found in the quenched martensite. Magnetic domains were observed in the quenched samples, suggesting that the sample may have been strongly magnetic.

Fig. 4 shows the morphology images of martensite on the aged samples. As the matrix of the steel, martensite could be easily observed by TEM. The width of martensite lath measured in Fig. 4 was not uniform (from 50 to 250 nm).

A large number of austenite layers were observed at the interfaces between martensite laths on the aged samples as Fig. 5 shown. Their thickness (5–10 nm) was a bit larger than the similar microstructure observed in AerMet 100 steel (about 3 nm) (Ayer and Machmeier, 1993). Because austenite has better corrosion resistance ability than martensite, its corrosion rate was smaller than martensite during the electropolishing process. Therefore, we could find some austenite layers which extended out of the matrix as Fig. 5(c). Similar observation results were also reported in AerMet 100 steel after overaging (Ayer and Machmeier, 1993).

Because no austenite layers were observed on quenched samples, these austenite layers in Fig. 5 were probably reverted austenite. When martensite is heated to the temperature above A_{c1} , austenite formation will occur. This austenite is called reverted austenite. Two basic types of reverted austenite are acicular or lath-like austenite and globular austenite. Acicular or lathlike austenite nucleation is almost exclusively confined to the boundaries of the martensite laths (Kimmins and Gooch, 1983). For different types of reverted austenite, the austenite formation mechanisms are not

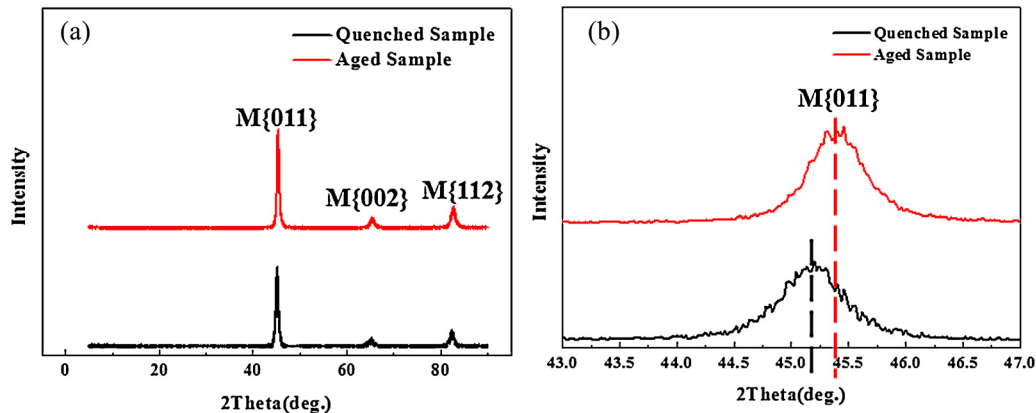


Fig. 2. XRD results. (a) XRD profiles of martensite; (b) peak movement of $M\{011\}$.

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