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Characterization of the microstructures and mechanical properties of 25CrMo48V martensitic steel tempered at different times

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ABSTRACT

The microstructures of 25CrMo48V martensitic steel quenched (*Q*) at 900 °C and tempered (*T*) at 650 °C for 5–105 min were characterized by transmission electron microscope (TEM). The tensile and impact properties were evaluated from the *Q–T* treated samples. The results indicate that the precipitate size is increased with the prolonged soaking time and the dependence of volume fraction of precipitated particles on the tempering time follows the classical Johnson–Mehl–Avrami (JMA) model. The refinement precipitated particle could induce the enhancement of yield strength. The dependence of the yield strength of 25CrMo48V martensitic steel tempered at 650 °C for different times on the lath width and the precipitated particle size can be described as $\sigma_y = 645 + 145w^{-1} + 1.27 \times 10^{-17} D_p^{-13}$.

1. Introduction

The material of ultra-high strength oil casing requires an excellent impact toughness for the safe application in ultra-deep oil well. In order to avoid the brittle fracture, the transverse impact energy higher than 100 J at 0 °C in a seamless steel tube with the yield strength of 1000 MPa grade and wall thickness higher than 25.4 mm should be obtained. The quenching (*Q*) and tempering (*T*) treatment is a normal routine to obtain the required strength and toughness combination in a lath martensitic steel. However, the improvement of toughness in a *Q–T* treated martensitic steel is often at the expense of strength and restricted by the tempering induced embrittlement. Therefore, the development of such a specific product needs a reasonable design of *Q–T* scheme.

A large amount of researches have been carried out to deal with the relationship between the martensitic microstructures and the mechanical properties of fully martensitic [1–5] and martensitc–bainitic [6,7] steels. The early work by Smith and Hehemann [6] and Naylor [7] indicated that the strength is increased with the refinement of the martensitic lath. And in recent works by Hsu et al. [8,9], they attributed the ultra-high strength of 2000 MPa to the refinement of the martensitic lath to a nanometer scale. However, Norstrom revealed that the lath width makes little effect on the change in strength [10]. On the other side, the secondary hardening was presented by Irvine et al. [11] and Janovec et al. [12] in tempered Cr–Mo–V steels, and they attributed the hardening to the precipitation of M_2C (M=Cr, Mo, V, Fe) alloy carbide. Similar behavior was also found in the heat-affected zone of Cr–Mo–V steel during the post weld heat treatment [13,14]. According to these investigations, the precipitation of alloy carbide could make a considerable contribution to the high strength with an excellent toughness after a high temperature tempering.

Therefore, there still exist plenty of controversies about the microstructures of lath martensite dominating the mechanical properties. The microstructures and the mechanical properties varied with the tempering time of a as-quenched and tempered 25CrMo48V martensitic steel were investigated in the present work. The purpose is to provide evidence to further understanding the microstructure-strength relationship in lath martensitic steel and provide a basis for developing a tough seamless steel tube with ultra-high strength for the ultra-deep oil well service.

2. Experimental material and procedures

The 25CrMo48V martensitic steel used in this work was prepared by sequential processes of melting in an electric furnace, continuous casting with argon shielding, and then hot piecing–rolling–stretching

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into a seamless steel tube. Its chemical composition is listed in Table 1.

The steel rods of $12 \times 12 \times 100$ mm, which were cut from the steel tube, were quenched at 900 °C for 35 min, followed by tempering at 650 °C for 5–105 min. The samples which were subject to different tempering time were further mechanically grinded to 30 μm in thickness and chemically thinned in a dual submerged jet polisher using a solution of 465 ml CH_3COOH and 35 ml perchloric acid electrolyte. The thin foils were examined in a JEM-2010 high-resolution transmission electron microscope (TEM) to observe the martensitic lath and the precipitated particles. The lath width and the particle size were measured by the linear intercept method and the area method on TEM image, respectively. The microstructure size was measured statistically by averaging at least 100 laths and 1000 particles from the images of TEM. The mechanical properties of *Q–T* treated 25CrMo48V martensitic steel were evaluated by the Vickers hardness measurement under the load of 10 kg (HV_{10}), tensile test at the room temperature and transverse Charpy-V-Notch (CVN) impact test at 0 °C, and the fractographs of the broken CVN impact specimens were observed in a KYKY-2800 SEM. The yield strength was determined by the 0.2% offset flow stress.

3. Experiment results

3.1. Estimations of mechanical properties

The HV_{10} of 25CrMo48V martensitic steel varied with the tempering time is shown in Fig. 1(a). It is indicated that the HV_{10} exhibits a complicated change with the tempering time. The tempering process at 650 °C could be divided into four stages according to the curve of HV_{10} plotted against the soaking time. At the initial stage, the HV_{10} is decreased with the prolonged soaking time sharply in the range of less than 30 min. In the second stage, a step of the HV_{10} appears in the period from 30 to 45 min indicating a hardening behavior. In the third stage, the HV_{10} reduces as the soaking time is further increased from 45 to 75 min. When the soaking time exceeds 75 min, the second step of HV_{10} appears, indicating a secondary hardening.

Table 1
Chemical compositions of 25CrMo48V martensitic steel (wt%).

C	Si	Mn	P	S	Cr+Mo+V	Al	Ni
0.25	0.26	0.50	≤0.010	≤0.003	1.83	0.03	0.04

The yield strength ($R_{p0.2}$) at the room temperature and the transverse CVN impact energy at 0 °C of 25CrMo48V martensitic steel tempered at 650 °C for different times are shown in Fig. 1(b). It is indicated that the yield strength is decreased from 1134 MPa to 1024 MPa and the impact energy is significantly increased from 75 J to 130 J with the tempering time prolonged from 30 min to 75 min, and in the tempering time period of 75–105 min, the yield strength and the impact energy change little. And the martensitic steel tempered at 650 °C for 60 min has typical plastic dimple fracture surface as shown in Fig. 1(c). The required yield strength and toughness could be obtained when the experimental steel tempered at 650 °C for 60–105 min.

3.2. Microstructure observations

The TEM precipitated particles tempered at 650 ºC for 30 and 90 min are shown in Fig. 2 and Fig. 3, respectively. There is a large quantity of rod-like particles distributed in the martensitic lath or around the boundaries. As revealed by the selected area diffraction pattern (SADP) in Fig. 2(c), the majority of particles in long rod shape are ε-carbide and the short rod-like particles are mainly Mo_2C alloy carbides after tempering for 30 min. Due to the precipitation of Mo_2C particles, a hardening phenomenon occurs as shown in Fig. 1(a). And after tempering for 90 min, the alloy carbides of $Cr_{23}C_6$ coexist with the ε-carbide according to the SADP. The $Cr_{23}C_6$ particles are also mostly in rod-like shape, but in a bigger size than that of Mo_2C particles as shown in Fig. 3. The $Cr_{23}C_6$ particles could cause a hardening behavior, and keep the

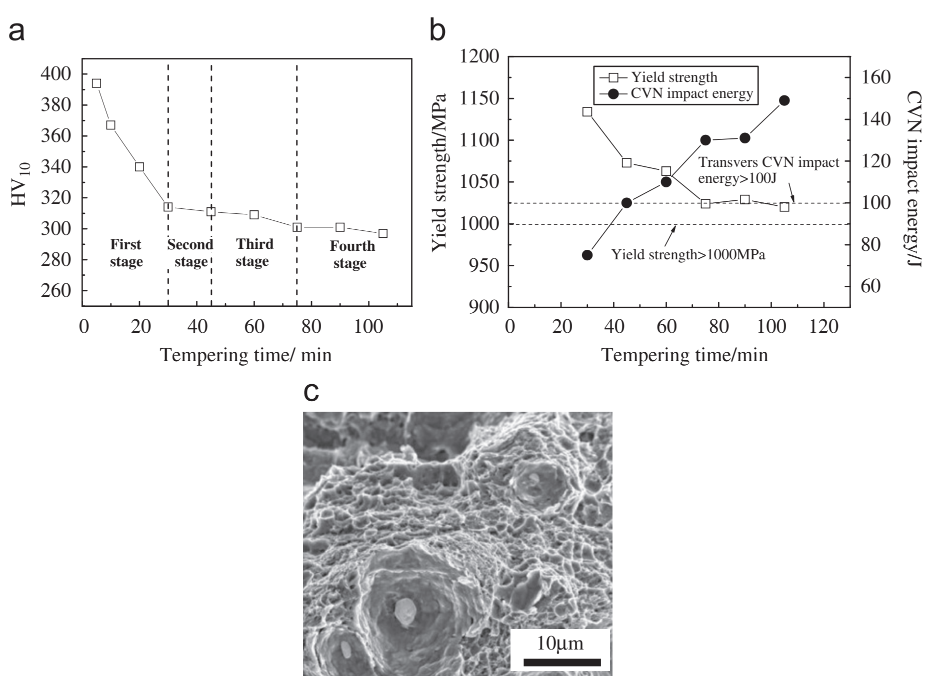

Fig.1. (a) HV_{10}, (b) yield strength, and CVN impact energy of 25CrMo48V martensitic steel as a function of tempering time, and (c) SEM fractographs of 25CrMo48V martensitic steel tempered at 650 °C for 60 min.