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Influence of Direct Quenching on Microstructure and Mechanical Properties of Steel Plate for Large Oil Storage Tanks

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The influence of direct quenching on microstructure and mechanical properties of high performance steel plates for large oil storage tanks was studied. The direct quenched and tempered (DQ&T) steel plates were rolled at different finish rolling temperatures (1113 and 1173 K), and their microstructures and mechanical properties were compared with those of reheat quenched and tempered (RQ&T) steel plate. The optical microscopy of the DQ steel shows deformed grains elongated along the rolling direction, while complete equiaxed grains are visible in RQ steel. Transmission electron microscopy (TEM) of the DQ steel shows refined lath martensite with high density of dislocations, which acts as preferred precipitation sites for NbC or Nb(C,N) particles during tempering. In all the plates, strength decreases with increasing tempering temperature. The strength of RQ steel increased significantly compared with that of DQ steel at the higher tempering temperature, which leads to better tempering resistance in DQ steels. The optimum combination of strength and toughness (yield strength (YS) reaches 585 MPa, tensile strength (TS) 667 MPa, and Charpy impact energy at 253 K of 291 J) in the DQ steels is achieved by quenching at 1113 K and tempering at 923 K.

Keywords direct quenching, mechanical properties, microstructure, reheat quenching

1. Introduction

The 610 MPa grade high-strength steel has been applied for large oil storage tank with volume up to 15000 m^3 (Ref 1). High strength, good impact toughness, and easy weldability are the major criteria for the steel. The process of on-line direct quenching and tempering (DQ&T) has been developed as a part of thermo-mechanically controlled process (TMCP), and has been used to produce high-strength steels in order to replace the traditional quench-and-temper process (Fig. 1) (Ref 2-5). The DQ&T process has several advantages over the traditional off-line reheat quenching and tempering (RQ&T) process. First, it reduces the production cost by eliminating the reheating and quenching steps. Second, the strength-toughness balance can be optimized without affecting weldability due to the microstructure and the precipitation behavior upon heat treatment. Third, it could save costly alloying elements by satisfying the mechanical properties and weldability requirements through control of alloy chemistry (Ref 6-11). In a typical DQ&T process, the repeated recrystallization of austenite brings about the grain refinement by setting the finishing rolling temperature (FRT) at the austenite region, and therefore making a fine quenched structure and introducing a large number of dislocations in it. To make the quenched structure much finer, deformation bands are formed inside austenite grains before quenching by rolling in non-recrystallization austenite region (Ref 12-19).

In this study, the DQ&T process was applied to high-strength steel for large oil storage tanks. In order to understand the mechanism of direct quenching, the correlations between microstructure and mechanical properties of DQ&T and RQ&T conditions were investigated.

2. Experimental

The steel used in this study is a high-strength steel for large oil storage tank with a minimum tensile strength of 610 MPa. The chemical compositions of the steel plate are shown in Table 1. The steel was melted in a vacuum induction furnace and forged to 100 mm thick plate. The forged plate was heated in the box-type resistance furnace, maintained at 1423 K for 2 h. After reheating, the plate was rolled to a final thickness of about 14 mm in a laboratory scale two-high rolling mill. The rolling ratio was in the range of 13-25% at each pass. Rolling ratio in the non-recrystallized austenite region was about 60%, and the finish rolling temperature was 1113 and 1173 K. After finish rolling, the plate was direct quenched in water with approximate cooling rate of 30-50 K/s .The quench cooling rate can be adjusted by ultrafast cooling control system. In comparison, in the RQ&T process, the plate was air cooled from finish rolling temperature to room temperature after rolling, then austenitized again at 1103 K for 40 min, and

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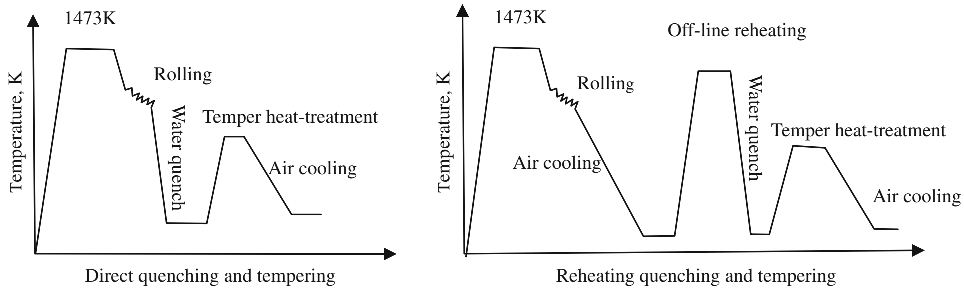

Fig. 1 Different heat-treatment process

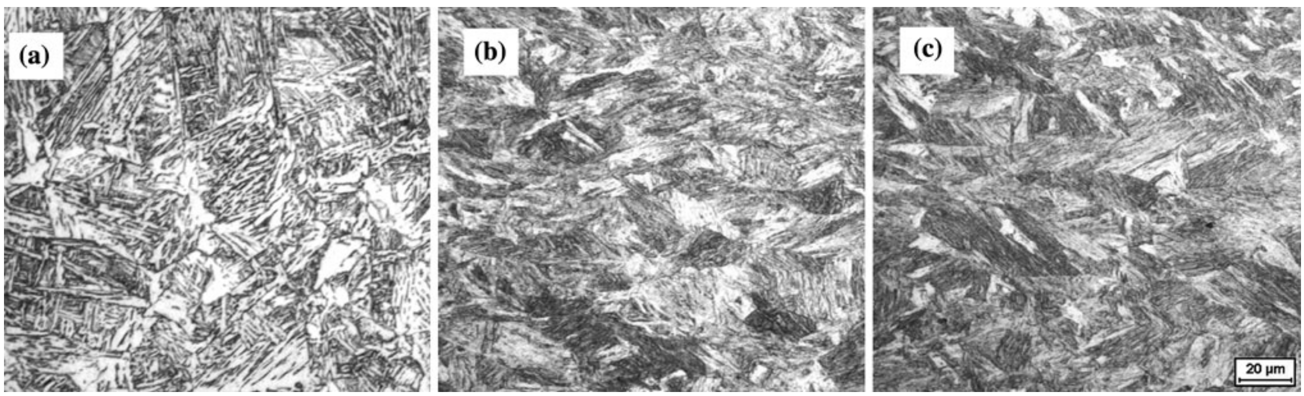

Fig. 2 Optical micrographs of as-quenched (a) RQ, (b) DQ-1113K and (c) DQ-1173K plates

Table 1 Chemical compositions of steel plate, wt.%

C	Si	Mn	P	S	Ni	Mo	V	Ti	Nb
0.07-0.09	0.20-0.40	1.30-1.50	<0.015	<0.01	0.10-0.30	0.10-0.30	0.03-0.05	0.01-0.02	0.02-0.04

quenched. The specimens were tempered for 1 h at 873 and 923 K, respectively.

The tensile test of all the specimens was carried out on the INSTRON machine at room temperature at a constant cross-head speed of 1 mm/min. Charpy V-notch impact testing of the specimens was conducted at 253 K. The average of three consistent test results was recorded as the value for the corresponding specimens. The tempered martensite structure including precipitates and carbides was observed by a transmission electron microscope (TEM).

3. Results and Discussion

3.1 Optical Microscopy

The optical photomicrographs of the reheat quenched and the direct quenched (DQ-1113K and DQ-1173K) steel are depicted in Fig. 2(a)-(c), respectively. DQ steels have finer and irregularly spaced laths (Fig. 2b, c) compared with RQ steel (Fig. 2a). Figure 3(a)-(c) shows the optical micrographs of the prior austenite grains. In DQ steels, prior-austenite grains elongated along the rolling direction within which a large amount of deformation exists (Fig. 3b, c), whereas many equiaxed grains are observed in RQ steel (Fig. 3a). The prior austenite grain size of the DQ-1113K steel is found to be slightly finer by 3-5 μm compared with the DQ-1173K steel. In contrast to DQ steels rolled at 1113 and 1173 K, the RQ steel exhibits equiaxed prior austenite grains slightly bigger in size (~19 μm) with no evidence of a deformed structure.

3.2 Transmission Electron Microscopy

Martensite laths and the fine precipitates distributed throughout the matrix are observed by TEM (Fig. 4 and 5). The martensite laths of DQ steel (Fig. 4a, b) are shorter in length, wavy, and crossing each other as compared with the straight and long martensite laths observed in RQ steel (Fig. 4c) in the same tempering condition. The lath spacing (0.23 μm) of DQ-1173K steel tempered at 873 K is less as compared with the RQ steel (0.4 μm). The TEM microstructure of DQ-1113K steel shows an almost similar structure to that of the DQ-1173K steel with an average lath spacing of 0.21 μm.

The precipitation and growth behavior of NbC particles vary with the fabrication process of DQ&T and RQ&T steels. Figure 5 shows that precipitates of DQ&T steel are much smaller than those of RQ&T steel at the tempering temperature

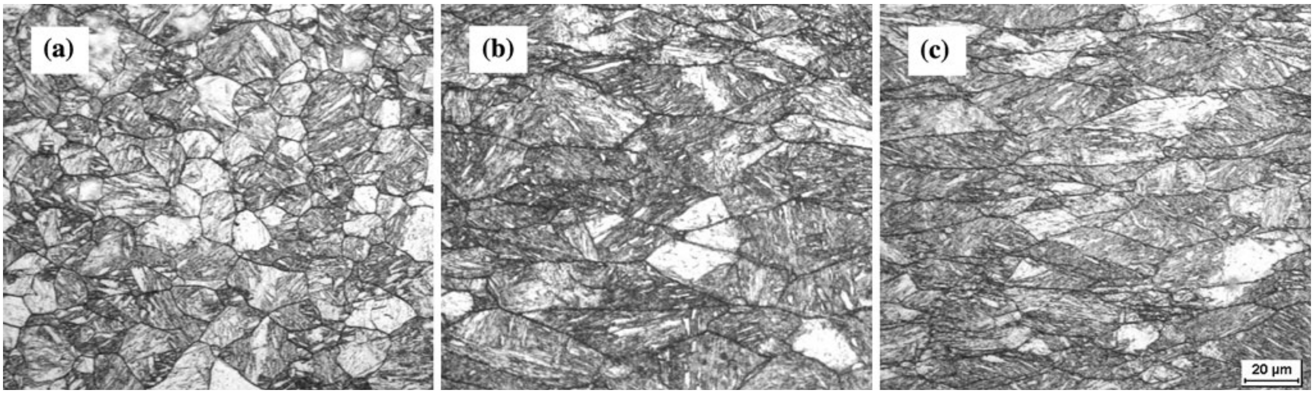

Fig. 3 Prior austenite grains of as-quenched (a) RQ, (b) DQ-1113K and (c) DQ-1173K plates

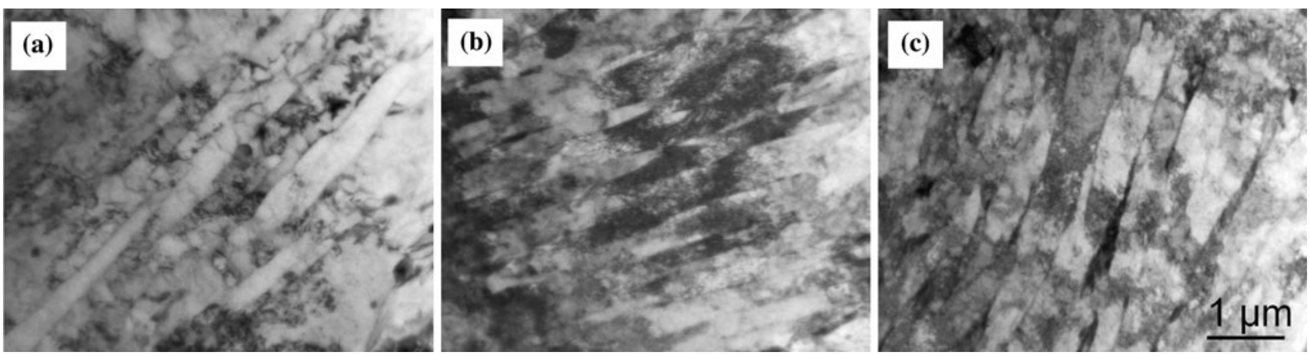

Fig. 4 TEM micrographs of as-quenched and tempered at 873 K (a) DQ-1173K, (b) DQ-1113K and (c) RQ steels depicting martensite laths

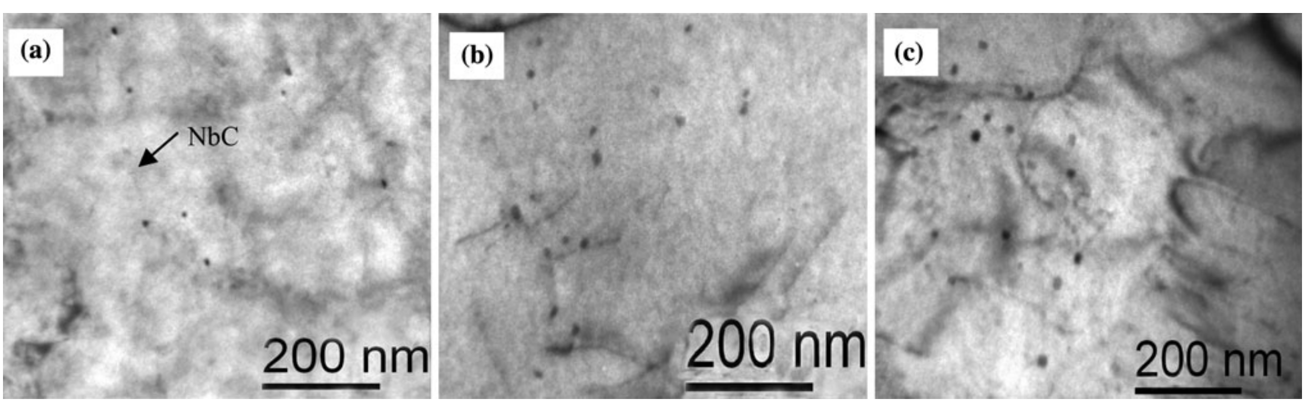

Fig. 5 TEM micrographs of NbC precipitate of as-quenched and tempered at 873 K (a) DQ-1113K, (b) DQ-1173K and (c) RQ steels

of 873 K. Comparing two DQ&T steels, extremely fine NbC precipitates sized less than 10 nm are observed, and there is no significant difference between them (Fig. 5a, b). In DQ&T steel, deformation state of austenite in hot-rolling before quenching persists down until room temperature. In austenite non-recrystallization region, deformation can promote the dislocation density in the martensite, and dislocation configuration becomes entwisting. As a result, more nucleation sites are available for fine particles to precipitate during tempering.

When the tempering temperature is raised to 923 K, NbC carbides get coarsened. In the case of RQ&T, the growth of NbC carbides is more obvious than that in the DQ&T steels. This phenomenon results from the slow growth rate of precipitates in DQ&T steel, which is attributed to the decreasing driving force for the precipitate growth due to the reducing interfacial energy between precipitates and the matrix.

3.3 Mechanical Properties

In high-strength oil storage tank steels, dislocation strengthening due to lath martensite and precipitation strengthening due to NbC precipitated during tempering are the major strengthening mechanisms.

Table 2 Mechanical properties and temperature for DQ&T and RQ&T

	873 K				923 K			
	***Rm*, MPa**	***Re*, MPa**	***A*, %**	***Ak* (253 K), J**	***Rm*, MPa**	***Re*, MPa**	***A*, %**	***Ak* (253 K), J**
1113 K (DQ)	686	594	21	283	667	585	22	291
1173 K (DQ)	683	589	21	279	660	579	22	286
1203 K (RQ)	677	584	22	202	635	560	23	232

Table 2 lists the tensile test results and impact test results. At the same temperature, two DQ&T steels have similar strengths and impact energy values, higher than those of RQ&T steel. The primary reason for the better strength of the DQ steel could be its rolling in the non-recrystallization region which must have led to increased austenite deformation and formation of more deformation structure within the prior-austenite grains. On the other hand, the fine NbC precipitates keep the matrix strength high by delaying matrix softening by the process of sub-boundary pinning. The smaller the radius of the precipitates, the greater the sub-boundary pinning force is. In all the plates, strength decreases with increasing tempering temperature. The decrease in yield strength and tensile strength in the DQ steel are less compared with the RQ steel at the higher tempering temperature. Fine precipitates in DQ&T plate grow slowly and effectively prevent the dislocation movement, thereby improving the tempering resistance and maintaining high strength up to around 923 K. In addition, as the tempering temperature rises, impact energy values increase. The increase in impact energy in the RQ steel is more compared with the DQ steel at the higher tempering temperature. Elongation is maintained nearly constant, not being affected by tempering temperature, but shows higher values in RQ&T plate than in two DQ&T plates.

In 1998, JFE Steel developed Super-OLAC, an advanced accelerated cooling system capable of cooling plates homogeneously at high cooling rates close to the theoretical limits. JFE Steel has completed the installation of three Super-OLAC systems. The first was installed at the West Japan Works (Fukuyama) in 1998; the second at the West Japan Works (Kurashiki) in 2003; the third at the East Japan Works (Keihin) in 2004. The epochmaking on-line induction heating facility, HOP® (Heat Treatment On-line Process), was also installed in the plate mill at West Japan Works (Fukuyama). Super-OLAC and HOP systems have outstanding capabilities for manufacturing high-performance steel plates. The DQ&T process has good product quality, low expend, reduced pollution, energy savings and a 30-40% decrease in production costs.

4. Conclusions

1. Direct-quenching and tempering process can replace traditional reheat quenching and tempering process to produce low-carbon alloy steel plates with excellent strength and toughness.
2. At the same temperature, the two DQ&T steels have similar strengths and impact energy values, higher than RQ&T steel's. In all the plates, strength decreases with increasing tempering temperature. The decrease in strength of DQ steel is less compared with that of the RQ steel at the higher tempering temperature. This confirms the better tempering resistance of the DQ steels compared with the RQ steels.
3. TEM microstructure of the DQ&T steel shows shorter, more irregular and closer martensite laths with extremely fine NbC precipitates, as compared with the RQ steel at the same tempering temperature. When the tempering temperature is raised, NbC precipitates coarsen, and the growth of NbC precipitates in RQ&T steel becomes more obvious than that in the DQ&T steels.

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