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Effect of Quenching Processes on Microstructure and Mechanical Properties of a High Strength Steel

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Abstract. Microstructure and mechanical properties of a high strength low alloy steel with different quenching processes were researched. The results indicated that the prior austenite grains exhibit equiaxed shape in both high temperature rolling direct quenching and tempering steel (refer to as HR-DQ-T steel) and reheat quenching and tempering steel (RQ-T steel), while elongated and severe deformation band in controlled rolling direct quenching and tempering steel (CR-DQ-T steel). Transmission electron microscope of CR-DQ-T steel indicated narrowed refined lath martensite than the other two steels. The tensile strength and yield strength of RQ-T steel was lower than that of two direct quenching steels. The CR-DQ-T steel has excellent strength-toughness matching among three steels.

1. Introduction

The process of direct quenching and tempering (referred to as DQ-T), which was developed as a part in the thermo-mechanically controlled process (TMCP), has been applied to produce high strength steels[1-3]. After hot deformation, direct quenching has been applied through an online cooling device has been considered as a very effective way to improve the strength and reduce the production cost of the steel in the late 20th century[4]. Compare with traditional reheat quenching process (RQ), The direct quenching process has many advantages. First, the strength-toughness balance and the weldability can be improved. Second, it saves alloying elements by control alloy design. Third, the manufacturing cost is reduced by eliminating the reheating and quenching steps[5-11].

The difference between direct quenching process and reheat quenching process is the austenite state[12-13]. In direct quenching process, the repeated recrystallization of austenite brings about the grain refinement by setting the finish rolling temperature at the austenite temperature range, to make fine quenched structure and introduce a large number of dislocations[5]. The processing parameters, such as quenching temperature, rolling ratio, affect the DQ-T microstructure. a various microstructures could be obtained by varying these parameters. Instead, the possibility to obtain the ultimate structure and properties by changing austenite states is very limited in the RQ-T process, since the austenite is recrystallized completely during reheating process, and its grain size is controlled principally by the austenitizing temperature.

In this study, two direct quenching processes (direct quenched temperatures are 840°C and 950°C respectively) and a reheat quenching process were applied to produce a high strength low alloyed steel. The difference between microstructures and mechanical properties was investigated. The precipitation behaviors between direct quenching process process and reheat quenching process was also discussed.

2. Experimental Procedures

The compositions of the investigated steel are provided in Table 1. The steel contained 1.4% manganese, little chromium, niobium, and very little amount of boron to increase hardenability. A

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small amount of titanium was added to stabilize any nitrogen as titanium nitride. The steel was melted in a 150 kg vacuum induction furnace, then forged to a slab with 100mm thickness after casting. The forged slab was heated in a furnace, holding at 1200°C for 2h. After reheating, the slabs were rolled to 14mm thick finally in a experimental rolling mill. For controlled rolling, the rolling ratio in the non-recrystallized austenite region was about 64%. After rolling, the steel plates were quenched to room temperature with a cooling rate of 70°C/s Immediately in direct quenching processes. The quenching temperature was controlled by controlling the start finish rolling temperature. The finish rolling temperatures were expected to be 850°C, but the finally measured direct quenching temperatures were 840°C. The controlled rolling and direct quenching process was referred to as CR-DQ,. High temperature rolling and direct quenching process (referred to as HR-DQ), in which deformation occurs above the austenite recrystallization temperature, was applied. The direct quenching temperature of HR-DQ process is nearly 950°C. In comparison, in reheat quenching process the plate reheated at 930°C for 30min, then quenched to room temperature. All quenched steels were tempered at 530°C for 40min.

Table 1. Compositions of tested steel (wt %).

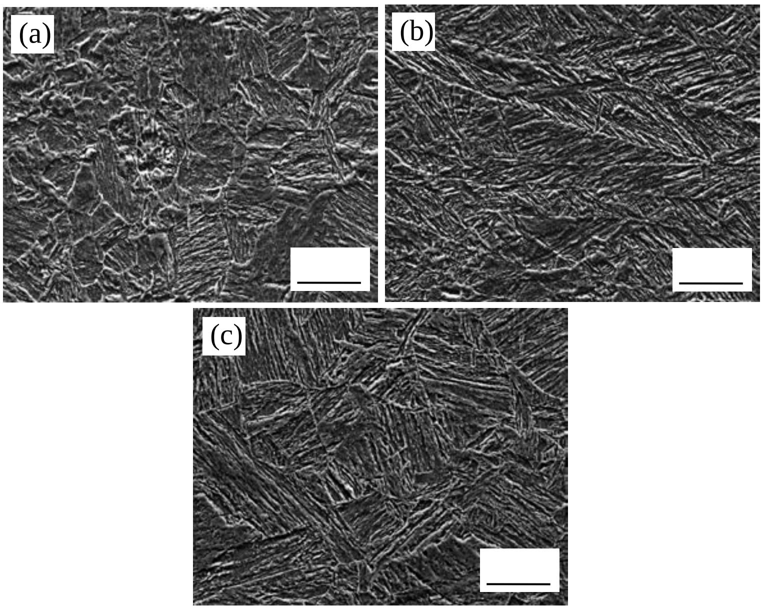
C	Si	Mn	S	P	Cr	V	Alt	Nb	Ti	B
0.08	0.42	1.4	0.0014	0.004	<0.4	<0.1	0.03	0.03	0.018	0.0017

Longitudinal tensile specimens were machined into 5mm in diameter and 25mm in length. Tensile test was carried out at room temperature with a crosshead speed of 1mm/min on the INSTRON machine. The Charpy impact specimens were machined, and the notch is perpendicular to the rolling direction. The impact tests were conducted at -20°C. After the specimens were etched, the shape of prior austenite grains were examined with an optical microscope. The metallographic specimens were etched with 3% of Nital solution, then observed by an optical microscope and FEI Quanta 600 scanning electron microscope (SEM) . The lath structure and precipitates were observed by Tecnai G2 20 transmission electron microscope (TEM).

3. Results

3.1. Microstructure

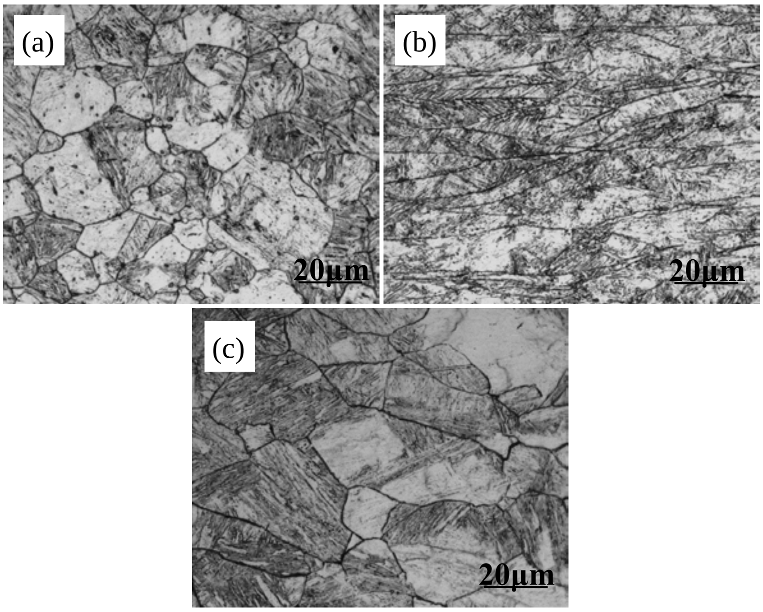
SEM micrographs of RQ-T, CR-DQ-T and HR-DQ-T high strength low alloyed steel plates are showed in Figure.1(a-c), respectively. After tempered at 530°C, all specimens consists of fine lath-type tempered martensite and bainite. The laths are arranged irregularly in RQ-T plate (Figure.1(a)), while most of them are nearly paralleled and with a certain angle with elongated direction of prior austenite grain boundaries in CR-DQ-T plate (Figure.1(b)). In HR-DQ-T plate (Figure.1(c)), the laths are also arranged irregularly, but they are longer and wider compared to that of RQ-T plate. There are a large amount of fine precipitations in laths boundaries and prior austenite grain boundaries inside all plates.



(a)RQ-T; (b)CR-DQ-T; (c)HR-DQ-T

Figure 1. Microstructure of investigated steel with different quenching processes.

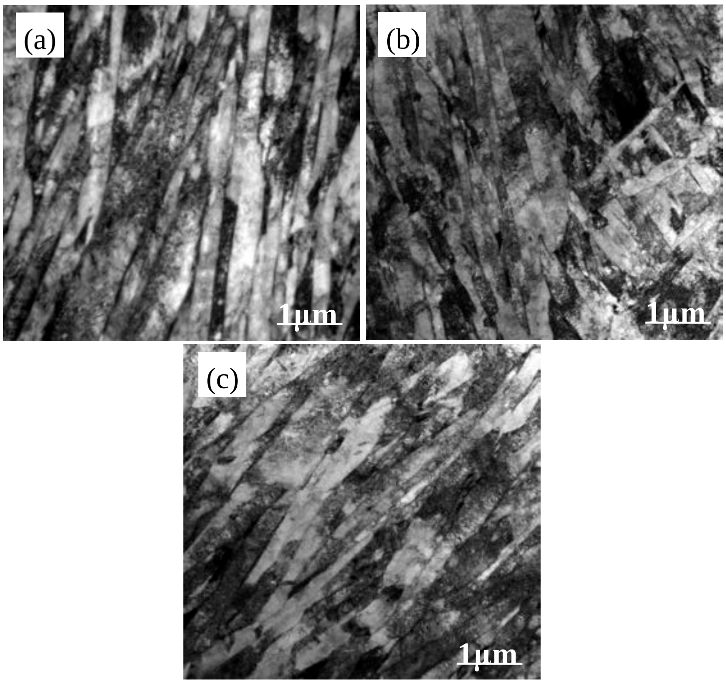
Figure.2 shows optical micrographs of prior austenite grain structures for the three processes. The RQ-T steel shows equiaxed grain shape owing to the recrystallization at 930°C, and the prior austenite grains are sized by about 15μm (Figure.2(a)). Whereas in CR-DQ-T specimen (Figure.2(b)), the prior austenite grains are flat and parallel to the rolling direction, and contain severely deformed band, due to relatively low deformation temperatures. From the pancaked austenite grains, it appears that no recrystallization occurred during finish rolling. For HR-DQ-T steel (Figure.2(c)), The austenite grains are slightly elongated along the rolling direction. Because the sample was deformed at high temperatures, and the complete recrystallization of the grain occurred. Compared to RQ-T steel, the prior austenite grains of HR-DQ-T steel (with the size is nearly 21μm) are much coarser, due to high quenching temperature.



(a)RQ-T; (b)CR-DQ-T; (c)HR-DQ-T

Figure 2. Optical micrographs of prior austenitic grains boundary of as-quenched investigated steels.

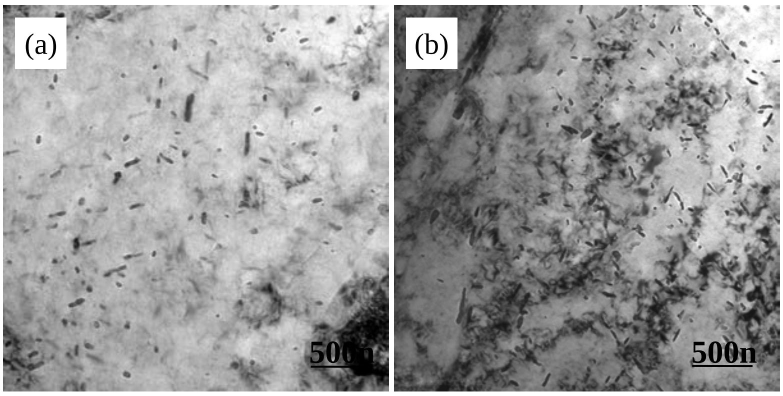
TEM bright field images of lath martensite structures of all as-quenched specimens are illustrated in Figure.3. The laths of CR-DQ-T steel(Figure.3(b)) are wavier, and crossing each other, while the laths are long and straight in RQ-T steel and HR-DQ steel(Figure.3(a) and (c)). The lath spacings of RQ-T steel are wider than CR-DQ-T steel, and narrowed than HR-DQ-T steel obviously.



(a)RQ-T; (b)CR-DQ-T; (c)HR-DQ-T

Figure 3. TEM micrographs of as-quenched investigated steels.

The precipitation of RQ-T and CR-DQ-T steels after tempered at 530°C are showed in Figure.4. It could be see that precipitates in CR-DQ-T steel are more and finer than RQ-T steel. The reason is that deformation state of austenite in hot rolling process before directing quenching in CR-DQ-T plate, increasing the dislocation density of the steel. During tempering, more nucleation sites are available to the precipitation of more fine precipitates.



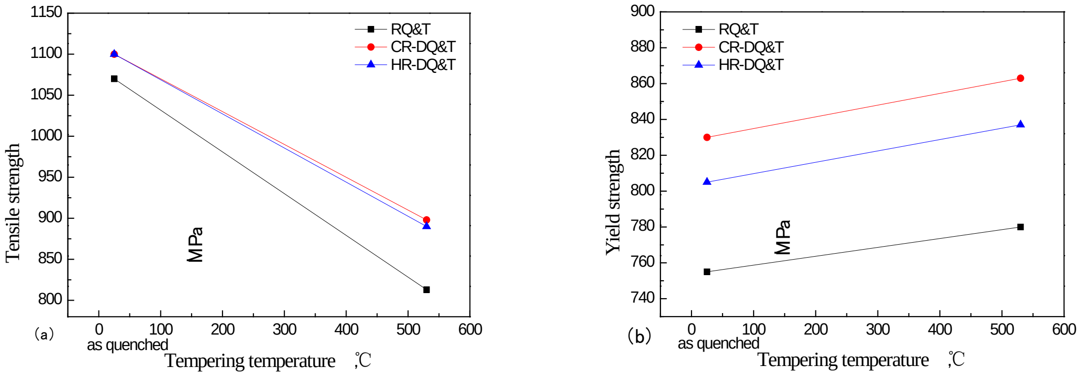
(a)RQ-T; (b)CR-DQ-T

Figure 4. TEM micrographs precipitations of investigated steels.

3.2. Mechanical Properties
Tensile properties of the three specimens are showed in Figure.5. The DQ specimens have higher strengths than RQ-T specimen. As well recognized, to comparison with RQ, DQ process could

increasing effective hardenability easily. This effect is due to high reheating temperatures in DQ processes, and with which both more uniform solution of alloying elements in austenite and coarse austenite grains enhance effective hardenability[10].

For two direct quenching specimens, the tensile strength descends in the order of CR-DQ-T and HR-DQ-T, but the tensile strength values have only a slight difference between them. Yield strength also descends in the same order. Yield strength of HR-DQ-T specimen is inferior to CR-DQ-T specimen. Different from tendency of tensile strength, the yield strength are increased after tempered at 530°C. The main reason for the better yield strength of the CR-DQ-T steels could be the lower finish rolling temperature in the austenite non-recrystallization region, and which had brought about deformation structure in the austenite grains.



(a) Tensile strength; (b) Yield strength

Figure 5. Tensile strength and yield strength of investigated steels.

Figure.6 illustrates the impact energy(-20°C, AKv) and elongation for specimens of RQ-T, CR-DQ--T and HR-DQ-T. The impact energy of CR-DQ-T, HR-DQ-T are 170J, and 103J, respectively. Contrary to tensile and yield strength, the DQ-T specimens exhibit inferior impact toughness to the RQ-T specimen. It may be deduced that the direct quenching process may increase the hardenability effectively, and resulting in higher strength than RQ-T process. HR-DQ-T specimen has lowest impact energy. It illustrates that coarse austenite grain could be reduce not only strength but also impact toughness. In RQ-T specimen elongation also shows higher values than DQ-T specimen.

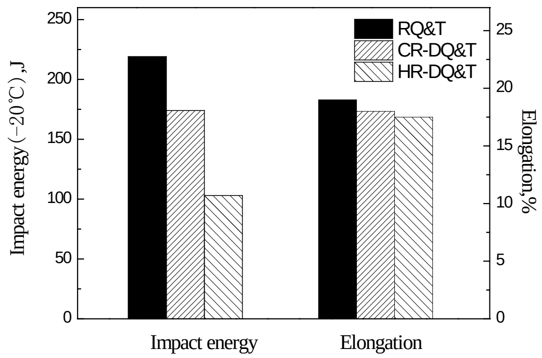


Figure 6. Impact energy and Elongation of investigated steels.

From above, it could be see that for investigated steel, CR-DQ-T process could provide a obvious increase in the strength, while the slight decrease in impact toughness over that obtained by RQ-T

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process. HR-DQ-T process could increase strength as well, but decrease the impact toughness more significantly compared to RQ-T process. The variation of mechanical properties of these different quenching process steels could be mainly attributed to austenite grain structures before quenching. In an attempt to acquire excellent strength and toughness, the process parameters should be carefully optimized during DQ process.

4. Conclusion

In the present research, the CR-DQ-T, HR-DQ-T and RQ-T processes were applied to a 800MPa high strength low alloy steel, and the correlation between mechanical properties and microstructure was discussed. The conclusions are as follows:

1) The prior austenite grains are flat and have severe deformed band in the CR-DQ-T steel, while equiaxed in RQ-T steel. However, for HR-DQ-T steel due to high deformation temperature, the prior austenite grains are nearly equiaxed.

2) The CR-DQ-T and HR-DQ-T processes are indicated to increase the hardenability effectively, resulting in high strengths than RQ-T steel. But the impact toughness value of CR-DQ-T and HR-DQ-T steels are lower than that of RQ-T specimen.

3) The HR-DQ-T steel has poor strength and toughness balance due to coarse austenite grains. CR-DQ-T plate have good strength-toughness matching, and can take the place of RQ-T process to produces high strength low alloy steel.

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