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Materials

Effect of tempering temperature on the mechanical properties and microstructure of an copper-bearing low carbon bainitic steel

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Abstract: The effect of tempering temperature on the microstructure and mechanical properties of ultra-high strength, copper-bearing, low-carbon bainitic steel has been investigated in the experiment. The results showed that the microstructure was mainly the laths of bainite in the as-quenched steel. The bainitic laths were restored and combined after the steel tempered at various temperatures. There were martensite/austenite (M/A) islands and numerous dislocations within and between the bainitic laths, while very fine precipitates of ε-Cu were also observed within the laths. With increasing the tempered temperature from 400 to 600°C, the yield strength (YS) increased from 877 to 957 MPa, whereas the ultimate tensile strength (UTS) decreased from 1020 to 985 MPa. The Charpy V-notch (CVN) varied from 68.5 to 42 J, and the value was minimal for the steel tempered at 500°C.

Key words: low carbon bainite; copper-bearing steel; precipitation; mechanical properties

1. Introduction

The ultra-high strength, copper-bearing, low-carbon bainitic steels with excellent comprehensive mechanical properties based on the strengthening mechanisms of grain refinement, solid solution strengthening, dislocation strengthening, and particle precipitation have been paid increasing attention in the past decades [1-3]. Thermomechanical controlled processing (TMCP), which involves prior austenite grain refinement and dislocation substructure strengthening has become another technique to improve its strength and toughness by controlling the final microstructure of the steel [4-6]. Yoo and his coworkers found that the steels which were subjected to TMCP and direct quenching and tempering processes (DQ & T) had higher strength and tempering resistance than reheat quenching and tempering processes (RQ & T) steel due to the finer ε-Cu and niobium carbide precipitates [7]. In this study, the influence of tempering temperature and ε-Cu precipitation on the microstructure and corresponding mechanical properties has been researched for an ultra-high strength (900 MPa), copper-bearing, low-carbon bainitic steels, which has been subjected to TMCP and DQ & T processes.

2. Experimental

A Cu bearing ultra-low carbon steel was melted in a 50-kg vacuum-induction furnace and was cast into ingot. The ingot was then soaked at 1250°C for 2 h and controlled rolled to a 16-mm thick plate; subsequently, the rolled plate was quenched in water at 550°C and then cooled in air to room temperature. Its chemical composition is given in Table 1.

Table 1. Chemical composition of the investigated steel wt%

C	Si	Mn	P	S	Cu	Ni	Mo	Nb	Ti	B / ppm
0.045	0.32	1.43	0.007	0.005	1.52	0.71	0.30	0.027	0.018	13

To study the effect of the tempering temperature and ε-Cu precipitates on the microstructure and

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mechanical properties, the as-quenched steel was tempered at 400, 500, and 600°C, respectively. Microstructure examination of DQ and tempered steels were conducted by an XJL-02A microscope. Thin foil specimens were prepared by a twin-polishing technique using an electrolytic solution containing 95% acetic acid and 5% perchloric acid. These foils were examined in a JEM2000FX-II transmission electron microscope operated at 150 keV to observe the details of the microstructure. Tensile test was carried out on a 6-mm-diameter specimen in a 30-t capacity model universal testing machine.

3. Results and discussion

3.1. Microscopy

(1) Optical microscopy.

Figs. 1(a)-(d) shows the microstructures of steel in quenched condition and after tempering at 400, 500, and 600°C for 1 h, respectively. The microstructure appears to be a lath-like bainite in the as-quenched condition. The bainitic laths were restored and combined after the steel had been tempered at different temperatures.

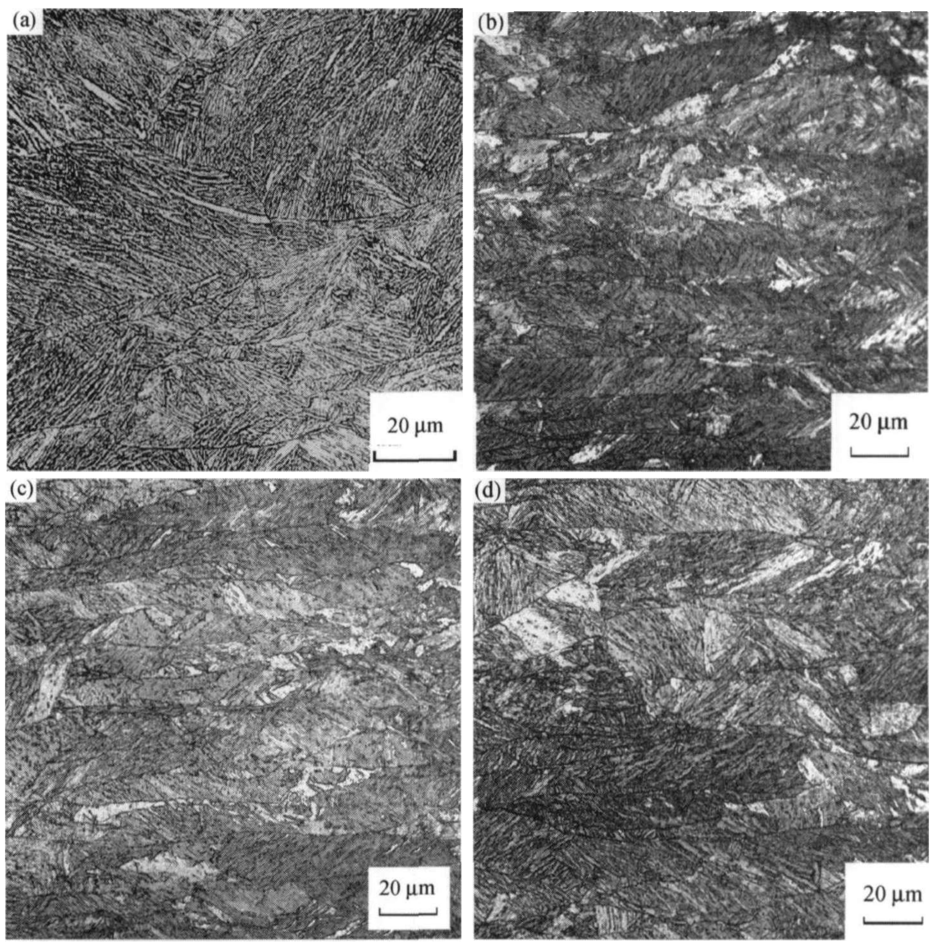

Fig. 1. Optical micrographs of the steel: (a) quenched condition; (b) tempered at 400°C; (c) tempered at 500°C; (d) tempered at 600°C.

(2) Transmission electron microscopy.

Figs. 2(a)-(c) shows the transmission electron micrographs of the steel tempered at 400, 500, and 600°C, respectively. The bainitic laths were found to be associated with martensite/austenite (M/A) islands at lath boundaries after the steel was tempered at 400°C (Fig. 2(a)), there were numerous dislocations within and between the bainitic laths, and very fine precipitates of Cu were also observed within the laths. The micrographs in Figs. 2(b)-(c) show partially recovered matrix with Cu precipitates. The austenite was transformed to bainite or sorbite, and the dislocation density decreased after the steel was tempered at 500-600°C.

Figs. 3(a)-(c) shows the fine ε-Cu precipitates of the steel tempered at 400, 500, 600°C, respectively. It can been seen that the Cu precipitates in the steel tempered at 400°C were very fine. The precipitates became coarse, when the tempering temperatures increased from 500 to 600°C. Osamura *et al.* [8] in their study of Fe-Cu alloys indicated that bcc copper-rich clusters precipitated first from supersaturated α-iron, which subsequently transformed to fcc phase when they grew beyond a critical size. However, none of the early investigators observed bcc Cu clusters by transmission electron microscopy, whereas Pande *et al.* [9] used small-angle neutron scattering method of characterization to study the coherent Cu precipitates, which had bcc structure in their early stage of nucleation and precipitation. There were also a few of Nb(CN) precipitations after the steel was tempered at 600°C.

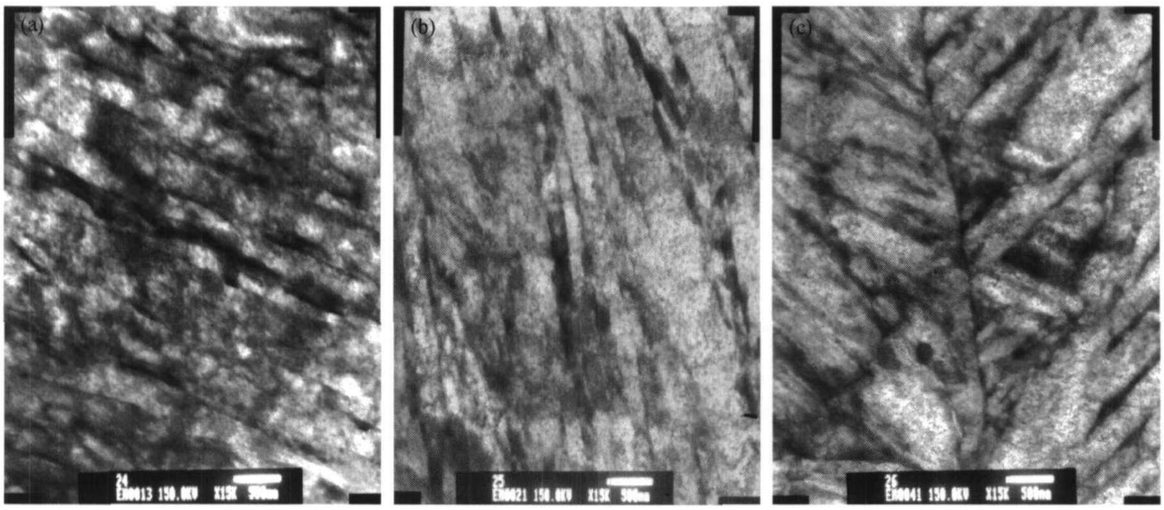

Fig. 2. Transmission electron micrographs of the steel at different tempering temperatures: (a) 400°C; (b) 500°C; (c) 600°C.

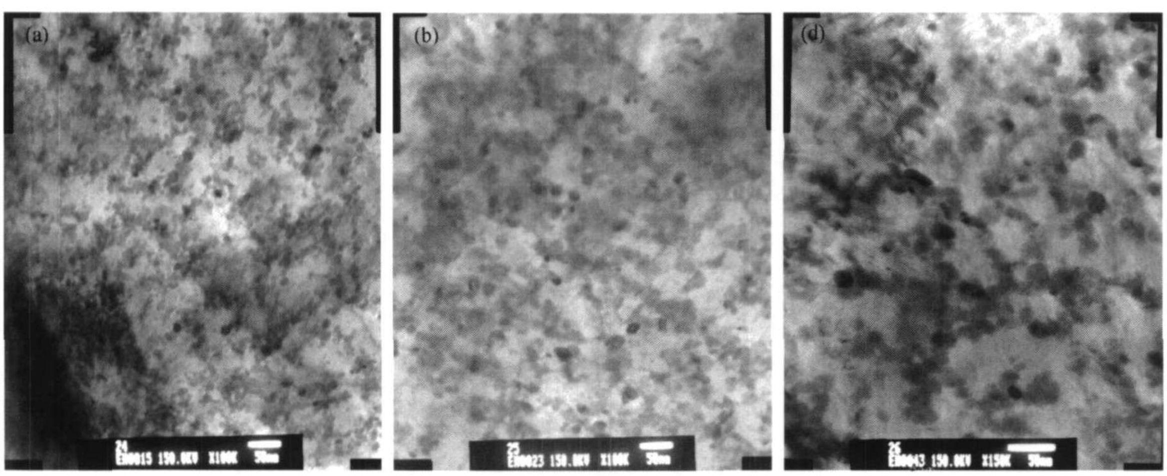

Fig. 3. Fine ε-Cu precipitates at different tempering temperatures: (a) 400°C; (b) 500°C; (c) 600°C.

(3) Fractography.

Typical SEM fractographs of Charpy impact specimens of tempered plates tested at −20°C are shown in Figs. 4(a)-(c). The fracture topographies of specimens tempered at 400 and 500°C exhibited microvoids, whereas there was a slight cleavage also. The fracture surfaces of the steel tempered at 600°C, essentially showed cleavage. This can be attributed to the partially recovered lath bainitic matrix and coarsening of Cu precipitates that could cause the propagation of cleavage cracks.

3.2. Mechanical properties

(1) Yield and tensile strength.

Fig. 5 shows the variation of yield strength, tensile strength, and YS (yield strength) /TS (tensile strength) of the steel under the quenched condition at different tempering temperatures. In quenched and tempered condition, the YS was found to vary between 862 and 957 MPa for the steel. The YS increased with increasing the tempered temperature from 400 to 600°C. The yield strength of steel is related to the movable dislocation density. The effect of ε-Cu precipitates in the matrix of tempering steel on the strength is related to the number, shape and dimension of precipitate phase. The ε-Cu precipitates were small in the quenched steel; thus, the yield strength was lower compared with the tempering steel. Precipitation of ε-Cu increased when the tempering temperature increased from 400 to 600°C. Thus, the movable dislocation density reduced in the matrix that led to the increase in yield strength with the increase in the tempering temperatures.

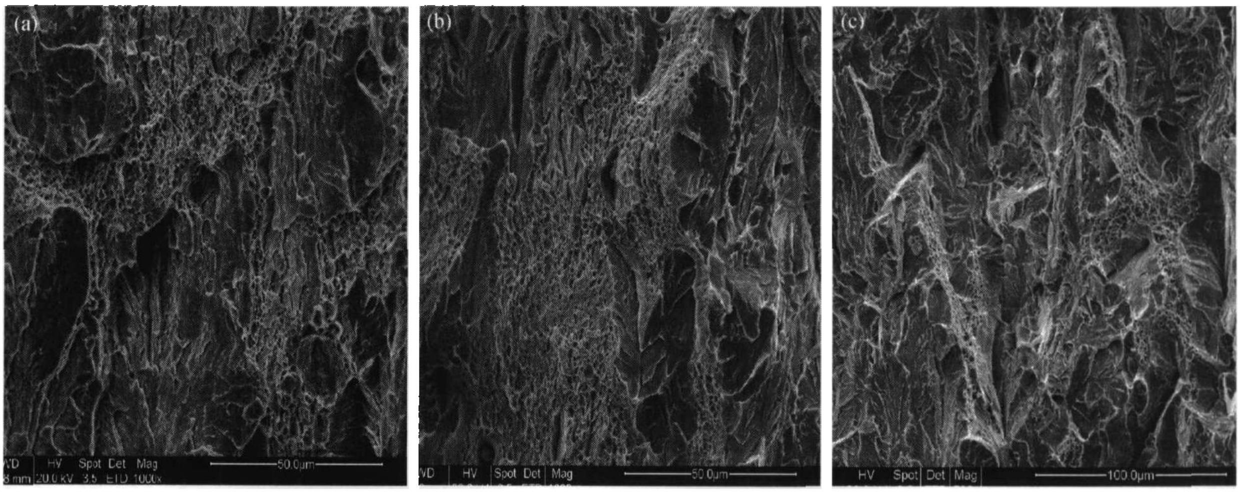

Fig. 4. SEM fractographs of Charpy impact tested samples of tempered steel at –20°C: (a) tempering after 400°C; (b) tempering after 500°C; (c) tempering after 600°C.

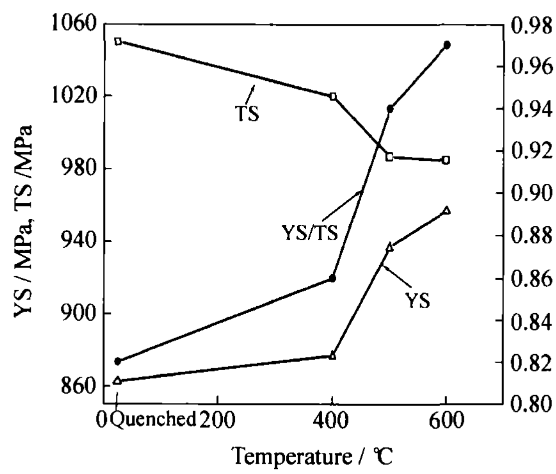

Fig. 5. Variation of yield strength, tensile strength of the steel under the quenched condition at different tempering temperatures.

The ultimate tensile strength (UTS) of quenched and tempered plates varied from 1050 to 985 MPa, the TS decreased with increasing the tempering temperatures from 400 to 600°C. The varying trend is contrary to that of YS. The ultimate tensile strength of steel is related to stacking fault energy (γ). The quenched steel dissolved a considerable amount of Cu, which reduced the stacking fault energy in the steel [10]. The stacking fault energy (γ) is inversely proportional to the width of stacking fault (d). Therefore, the d is more larger when the γ is more smaller. It is difficult for the dislocation to move, so the ultimate tensile strength was larger for the quenched steel compared with that of the tempering steel. The ε-Cu precipitated from the steel which subjected to tempering, and the precipitates increased with increasing the tempering temperatures from 400 to 600°C; therefore, the stacking fault energy of the tempering steel increased, whereas the width of stacking fault reduced, which led to move the dislocation easily; thus, the ultimate tensile strength reduced with increasing tempering temperatures.

The YS/TS of the steel increased with increasing the tempering temperature. The value was 0.86 after the steel tempering at 400°C, whereas it increased to 0.97 after tempering at 600°C. It is reasonable for the tested steel to temper at low temperature.

(2) Elongation and reduction-in-area.

Fig. 6 shows the variation of elongation (EL) and reduction-in-area (RA) of the steel under quenched condition at different tempered temperatures. It can been seen that the elongation percent of the as-quenched and tempered plates varied from 10.5% to 14.5%. The elongation was maximum for the steel after being tempered at 400°C. The value then decreased when the tempering temperature increased to 500°C, subsequently, the value increased again after 500°C. The reduction-in-area percent of quenched and tempered plates varied from 48.8% to 58.5%. It has the same tendency as that of the elongation.

(3) Charpy impact toughness.

The CVN energy *versus* tempering temperature plot of steels at various tempering temperatures is shown in Fig. 7. The CVN impact energy values of the steels decreased with the increase in the tempering temperature from 400 to 500°C, the value then increased again at the tempering temperature of 600°C due to the recovered matrix. High volume fraction and coarsened ε-Cu precipitates were found to be responsible for the lower CVN energy value compared with the quenched condition.

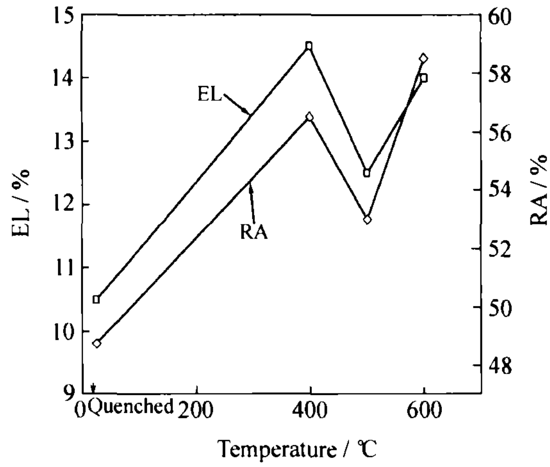

Fig. 6. Variation of elongation and reduction-in-area of the steel at quenched condition and different tempering temperatures.

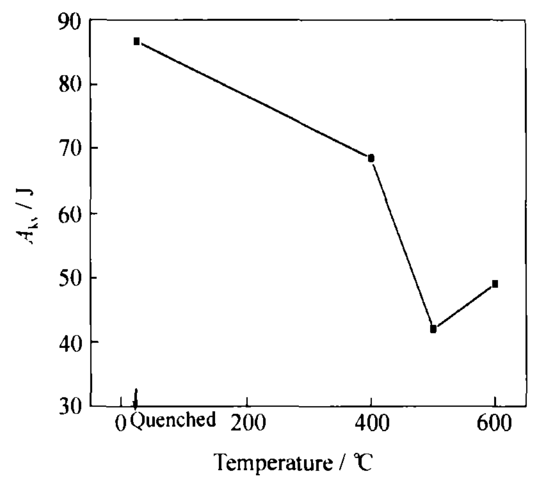

Fig. 7. Curve of CVN energy *versus* tempering temperature of the steels at various tempering temperatures.

4. Conclusions

(1) The microstructures of as-quenched and tempered steel plates showed that the bainitic laths were found to be associated with M/A, There were numerous dislocations within and between the bainitic laths and very fine precipitates of ε-Cu were also observed within the laths.

(2) Increasing the tempering temperatures accelerated the formation and coarsening of copper-rich precipitates.

(3) The YS was increased, whereas the UTS decreased with increasing the tempered temperature from 400 to 600°C. The CVN was lower after the steel tempered at 400°C due to the ε-Cu precipitation coarsening.

Acknowledgments

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