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## Effect of heat treatment parameters on the microstructure of quenching–partitioning–tempering steel

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### ABSTRACT

The effect of quenching temperature and tempering time on the microstructure, content of retained austenite and carbon content in retained austenite of a copper and niobium alloyed medium carbon steel were investigated by using optical, electron microscopy and X-ray diffraction. Results showed the microstructure of the quenching–partitioning–tempering steel consisted of lath martensite, retained austenite and carbides. With the increase of quenching temperature, the martensite laths became coarsened and the content of retained austenite increased. With the increase of tempering time, the content of retained austenite initially increased, reached to the maximum at 600 s and then gradually decreased.

### KEYWORDS

Steels; microstructure; retained austenite; quenching–partitioning–tempering; Q&P

## Introduction



In order to save energy and raw materials, it is an important and urgent task to develop ultra-high strength steel as well as to reduce the weight of equipment [1]. After quenching and tempering process (Q-T), traditional martensite steel has a higher strength but less toughness. In order to improve the comprehensive performance of steels, Speer et al. [2,3] proposed a new heat treatment process of quenching & partitioning (Q&P) for martensite steel. In contrast to the traditional quenching and tempering process, it was to quench the medium carbon steel containing silicon (0.35C–1.3Mn–0.74Si) at a certain temperature between  $M_s$  and  $M_f$  and then hold at a certain temperature for a period of time. The steels applied with this process generally contain elements of Si, Al (or even P) to hinder the precipitation of  $Fe_3C$ . Thus it made carbon diffuse from martensite to austenite, so the stability of austenite improved because it became carbon-rich. Thereby, the Q&P process can obtain a mixed microstructure of martensite and retained austenite. The nanoscale martensitic matrix can improve the strength and a sufficient amount of retained austenite can contribute to considerable plasticity and toughness. The Q&P process suppresses the precipitation of carbides, which means that there is potential for precipitation strengthening of these steels.

In order to further improve the strength of the steels, a quenching–partitioning–tempering (Q-P-T) process was proposed on the basis of Q&P technology

by Hsu et al. [1, 4–6]. For the Q-P-T process, a steel containing Si has a small amount of complex carbide-forming elements added and, after the carbon partitioning, there is a tempering process in which the steel is held at a suitable temperature for certain period in order to enhance the complex carbide precipitation. The present work aims to investigate the effect of quenching temperature and partitioned-tempered time on the microstructure, the content of retained austenite and the final carbon concentration of retained austenite in a Cu + Nb alloyed medium carbon steel.

## 2. Materials and experimental procedures

On the basis of Fe–Mn–Si steel, the medium carbon steel was added with carbide-forming elements of Cu and Nb. The tested steel was smelted in a 50 kg vacuum furnace and then cast into ingots, finally forged into bars (50 mm × 30 mm). The chemical composition of the tested steel was shown in Table 1. According to the calculation of the J-MatPro [7] software, the heat treatment of the tested steel was as follows. It was firstly homogenized in the vacuum furnace at 1150°C for 48 h and cooled in the furnace, and then austenitized at 870°C for 30 min followed by quenching to a temperature of 100°C or 210°C, and finally partitioned-tempered in a salt bath at 450°C for varying times (0–1800 s) followed by quenching to room-temperature water.

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**Table 1.** Composition of the investigated steel (wt%).

C	Si	Mn	Cu	Nb	Fe
0.55	0.75	1.61	1.08	0.22	Bal.

The microstructure characterization was carried out with optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM). The specimens for OM and SEM were ground and polished by using standardized techniques and etched in a 4 vol. % nital solution after heat treatment. Selected specimens for TEM observations were thinned to 0.3 mm with wire cutting and abraded to 0.06 mm with SiC papers. Then the 3 mm punched disk was twin-jet electropolished by using 5% perchloric acid solution to obtain enough thin areas for microstructural observations.

Quantitative X-ray analysis (XRD) was used to determine the volume fraction of retained austenite and the amount of retained austenite. The samples were step scanned in an X-ray diffractometer, operating at 40 kV voltage and 45 mA current, having Cu K $\alpha$  radiation. The  $2\theta$  scan angles ranged from 30° to 100° with a scanning speed ( $2\theta$ ) of 5° min. The calculations were based on the integrated intensities of (200)  $\alpha$ , (211)  $\alpha$ , (200)  $\gamma$ , (220)  $\gamma$  and (311)  $\gamma$  diffraction peaks. Without taking account of the precipitation carbides, the calculation error of the volume fraction of retained austenite was 1.5 vol %. The carbon content of the retained austenite was calculated by the following formula [8], and its error

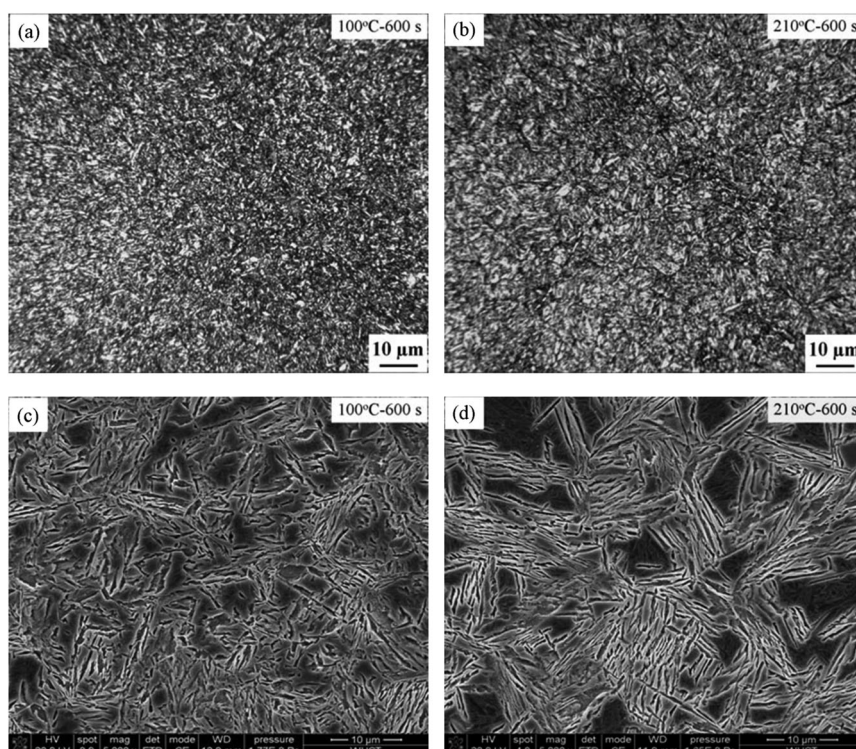
was 0.15 wt%.

$$X_{\gamma} = (a_{\gamma} - 0.3570\text{nm})3.8 \times 10^{-3}\text{wt\%}$$

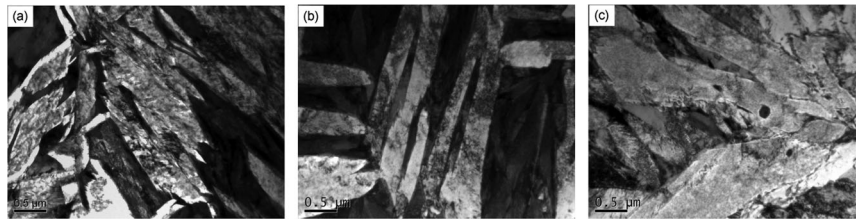
### 3. Results and discussion

Typical OM and SEM micrographs of the steel after Q-P-T process are shown in Figure 1. It is seen that the Q-P-T treated steel consisted of fine-grained martensite (black) and retained austenite (white light) (Figure 1 (a,b)). The typical microstructure of martensite and retained austenite can be seen more clearly in the SEM images (Figure 1(c,d)). With the increase of quenching temperature, the degree of undercooling for martensite transformation was reduced. Therefore, under same tempering temperature, the phase fraction of retained austenite for the specimen quenched at 210°C was higher than the specimen quenched at 100°C, and the microstructures were also relatively coarse.

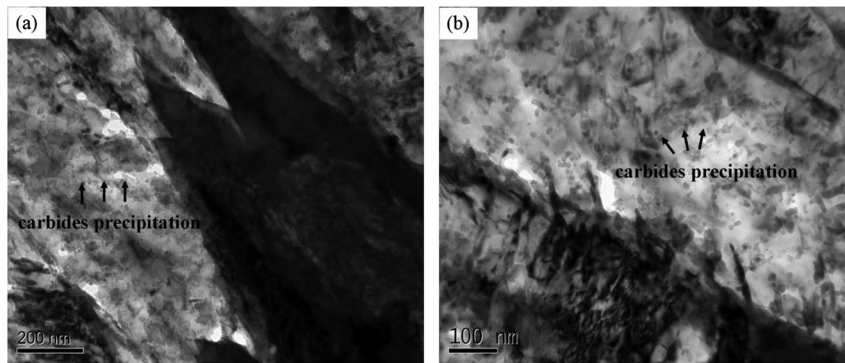
Figure 2 shows the microstructure of the experimental steels treated by Q-P-T by using transmission electron microscopy. The microstructure after Q-P-T treatment was a mixture of typical lath martensite and retained austenite. Nanoscale martensite laths piled up and crossed each other (see Figure 2(a)). When the quenching temperature increased up to 210°C, the phase fraction of retained austenite increased obviously, more than that of the steel quenched at 100°C. It is seen that retained austenite was formed in the interlaths of martensite (see Figure 2(b)). Due to



**Figure 1.** Typical OM and SEM micrographs of Q-P-T steels quenched at 100°C or 210°C and partitioned at 450°C (a) and (c) for quenching at 100°C; (b) and (d) for quenching at 210°C.



**Figure 2.** Typical TEM images of the Q-P-T steel quenched at 100°C and 210°C, and then partitioned at 450°C: (a) for 100°C, 120 s; (b) for 210°C, 120 s; (c) for 210°C, 1800 s.



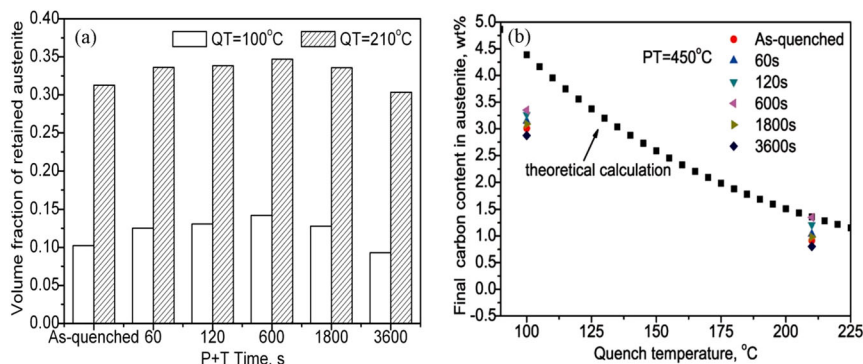
**Figure 3.** High-magnification TEM micrographs of precipitated carbides: (a) quenched at 100°C; (b) quenched at 210°C.

the interface migration of martensite and austenite during the process of carbon distribution, the martensite laths became coarser. The interface of martensite and austenite became irregular and not apparent when the tempering time increased (see Figure 2(c)).

Figure 3 shows the carbide precipitation in the steel quenched at 100°C and 210°C, and then partitioned-tempered at 450°C for 120 s. A large amount of carbide precipitates with the shape of thin strip, circular and rod were dispersed in the martensite laths. With the increase of quenching temperature, the carbon diffusion tended to be more difficult, so it produced large amount of defects in the form of carbon enrichment, thus there were a large number of carbide particles precipitated in the martensite laths. Consequently, the carbide precipitation in the specimen quenched at 210°C was more apparent than that of the specimen quenched at 100°C. At the same

time, a lot of dislocations and dislocation tangles were observed in the boundaries of martensite laths.

Figure 4(a) shows the volume fraction of retained austenite for the tested steels against quenching temperature and tempering time. The volume fraction of retained austenite in the specimen quenched at 210°C was higher than that of the specimen quenched at 100°C. This is because with the increase of quenching temperature, the activity of carbon atoms increased accordingly, which promoted the diffusion of carbon atoms from martensite with supersaturated carbon to retained austenite. In the meantime, the increase of tempering time made the diffusion of carbon atoms to retained austenite more complete. However, longer tempering time was beneficial for carbide precipitation, which consumed carbon atoms; however, it was not conducive to the stability of retained austenite.



**Figure 4.** (a) Phase fractions and (b) final carbon concentration in retained austenite.



Figure 4(b) shows the final carbon concentration of retained austenite for the tested steels against quenching temperature and tempering time. The theoretical calculation curve according to 'constrained carbon paraequilibrium' model was also compared with the measured data. The final carbon concentration of retained austenite mainly came from the diffusion of carbon from quenched martensite. Although the activity of carbon atoms increased with the increase of quenching temperature, which was beneficial for the diffusion of carbon from martensite to retained austenite, but the high-quenching temperature also caused precipitation of carbide and consumption of carbon. There was a larger driving force for the martensite transformation and the retained austenite could also obtain more carbon from the supersaturated quenched martensite at a low-quenching temperature. Consequently, the final carbon concentration of the retained austenite gradually decreased with the increase of quenching temperature. The final carbon concentration of retained austenite for the specimens quenched at 100°C or 210°C with different tempering time were also lower than the theoretical values. Previous works [9] reported that there were other competing reactions to make the partitioning of carbon incomplete during the Q&P process. Therefore, the carbon concentration of retained austenite was lower than the theoretical ones.

#### 4. Conclusions

The designed medium carbon steel treated by Q-P-T process was investigated in this study, and conclusions can be drawn as follows:

- (1) The microstructure of the medium carbon steel treated by Q-P-T process mainly composed of nanoscale martensite and retained austenite. When quenched at 100°C, the martensite laths in the steel were finer than that quenched at 210°C. The interface of martensite and austenite became irregular and not apparent when the tempering time increased.
- (2) With the increase of quenching temperature, the content of retained austenite initially increased, gradually reached a maximum and then decreased again whereas the carbon concentration in the retained austenite showed an opposite trend with the content of retained austenite.

- (3) With the increase of tempering time, the content of retained austenite initially increased, reached to the maximum at 600 s and then gradually decreased.

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#### Disclosure statement

No potential conflict of interest was reported by the authors.

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