Journal of Metals, Materials and Minerals, Vol. 30, No. 3, pp. 15-23, 2020

Effects of quenchants on microstructures and mechanical properties of steel grade AISI 5160

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Received date:
1 October 2019
Revised date:
13 June 2020
Accepted date:
16 June 2020

Keywords:
Quenchant
Microstructure
Mechanical Properties
AISI 5160

Abstract

This research aims to study the effects of the quenchants in hardening process on microstructures and mechanical properties of alloy steel grade AISI 5160. The heat treatments include hardening at 900 (Q1), 870 (Q2), 840 (Q3), 810 (Q4) and 780°C (Q5), respectively, followed by quenching into water, oil and brine solution. Microstructures were measured scanning electron microscopy and energy dispersive X-ray spectroscopy. For each condition, hardness and tensile testing were measured. It was found that the microstructure in the as-sheet condition consisted of ferrite and pearlite. The observed microstructures after quenching process were martensite with a small amount of retained austainite. The hardening at 810°C for 30 min (Q4) showed carbide distribution in martensite matrix. The coarse ferrite grains were occurred after hardening at 780°C for 30 min (Q5). The hardness of as-sheet condition was 40 HRC. Highest hardness was obtained after hardening follow by water quenching. The ultimate tensile strength in as-sheet condition was about 510 MPa. As hardening at all conditions, the maximum ultimate tensile strength was after hardening at 810°C for 30 min (Q4). Heat treatment conditions increased the hardness and ultimate tensile strength compared with the as-sheet condition while %elongation gradually decreased. For heat treatment conditions, however, water quenching is more suitable.

1. Introduction

Steel grade AISI 5160 is a high carbon and chromium steel used in the automotive field in a number of different heavy spring applications, especially for leaf springs due to its outstanding toughness, a high level of ductility, and excellent fatigue resistance [1]. Recent results have shown that the improvement in properties reached by quenching is of such magnitude that the content of alloying elements in steel can be reduced. Steels are normally hardened at 830-870°C [1-3] to improve their mechanical properties, particularly their strength and wear resistance. Heat treatment has been recognized as an important process in the technology of material development. It brings about various noble microstructural changes leading to improved material properties [4]. The process starts with a partial or full austenization followed by rapid cooling to a temperature between martensite start and finish to obtain a controlled amount of martensite. The materials then subjected to an isothermal treatment at the same or higher temperature to migrate carbon from the supersaturated martensite into untransformed austenite. Finally, the steel is quenched to room temperature and thus the austenite that is sufficiently carbon enriched retains at room temperature [5]. In hardening, the steel is heated to a temperature high enough to promote the formation of austenite, held at that temperature until the desired amount of carbon has been dissolved and then quench in oil, brine or water at a suitable rate.

The kind of quenching medium, selection of quenching medium temperature and the selection of the medium state (unagitated, agitated) are determining factors [6,7]. Quenching is an essential element in developing the desired properties of many steel and alloys. Agitation, or forced circulation of the quenchant, is required to shorten the cooling times. Without agitation, natural convection of the quenchant [8-10] and quenchant vaporization limit the heat transfer rate through the fluid film boundary at the surface of parts. Under these conditions, changes in the quenchant medium temperature have little effect on the cooling rate. Obtaining a forced convection fluid regime greatly reduces the resistance to heat flow at the fluid film boundary layer [11]. This can be accomplished by mechanically moving the parts through the bath, pumping to recirculate the quenchant, or mechanically inducing agitation/ circulation of the fluid. Since control over the cooling rate is important, mechanical agitation provides the best performance at the lowest energy costs. The cooling rate is however influenced by such factors, such as bath temperature, quenchant type, immersion temperature, agitation and immersion speed [12-14].

However, the medium used in quenching process are the important factors to phase deformation occurring into the processing material which is respect to the heat transfer related to the applied used. Thus, this paper is focused on the effects of quenchant in heat treatment parameters on microstructures and mechanical properties of steel grade AISI 5160.

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DOI: 10.14456/jmmm.2020.33

2. Experimental

2.1 Materials preparation and heat treatments

An industrial hot-rolled sheet 5160 alloy steel sheet with 1.20×6×102 cm dimension was used as the base metal. The chemical composition of the steel is given in Table 1. The heat treatment composed of hardening, followed by quenching in different media. In this conventional heat treatment, hardening was performed at 900, 870, 840, 810 and 780°C, respectively, for 30 min followed by quenched into the selected medium. Three types of quenching media, water at room temperature, oil at room temperature and brine at 200°C, were used to quench the samples. The different heat treatment conditions and corresponding specimen codes were summarized in Table 2. Phase defined Q1, Q2, Q3, Q4 and Q5 in the experimental procedures.

Table 1. Chemical composition (wt%) of the experimental sheet 5160 alloy steel.

Element	wt%	Element	wt%
C	0.58	Cr	0.73
Si	0.23	Ni	0.04
Mn	0.77	Cu	0.03
P	0.02	V	0.01
S	0.01	Fe	Bal.

Table 2. Specimen code and heat treatment conditions.

Specimen code	Heat treatment condition
Q1	Quenching at 900°C
Q2	Q1 follow by quenching at 870°C
Q3	Q2 follow by quenching at 840°C
Q4	Q3 follow by quenching at 810°C
Q5	Q4 follow by tempering at 780°C

2.2 Characterization

The 5160-heat treatment samples were cut from the position and then polished on silicon carbide papers to 2000 grit, and then progressively polished with 1 µm Al_2O_3. The etchant used for optical microscopy (OM) and scanning electron microscopy (SEM) samples was 3% Nital. The SEM image and energy dispersive X-ray spectroscopy (EDS) spectra were measured on a FEI QUANTA 250.

2.3 Hardness and tensile measurements

Hardness testing was performed on the unetched specimens with a Rockwell hardness tester using the C scale (HRC) with 120° diamond cone, 150 kgf load with 15 s indenting time. The mean values were based on ten different areas on each specimen. A tensile testing was carried out using H10ks Hounsfield make tensile testing machine and the test samples conformed to the standard ASTM E8 round sample (50 mm gauge length).

3. Results and discussion

3.1 Microstructural investigation

From Figure 1(a), the microstructure of ferrite and pearlite phase in the as-sheet condition can be observed. The microstructure at higher magnification in a scanning electron microscope of a highly-ordered layered structure of ferrite (dark) and cementite (white) that sticks out of the ferrite matrix is shown in Figure 1(b).

Microstructure after hardening at 900°C for 30 min (Q1) followed by water quenching to the room temperature showed martensite structure as seen in Figure 2(a). SEM image in Figure 2(b) exhibited as lath and plate-like martensite. However, the retained austenite was found to be stabilized by a pinning mechanism. Three different quenching media (water, brine and oil) were used to compare the effect of cooling rate on the microstructure and mechanical properties of 5160 steel. The result has demonstrated that the microstructure for water quenched specimen was the lath and lower plate martensite, while for oil and brine quenched specimens were mostly plate martensite and a little lath martensite. During hardening treatment, carbon is redistributed by diffusion out of the martensite. The structure is then stabilized by interstitial carbon atoms pinning the austenite-martensite interface [15]. After hardening at 810°C for 30 min (Q4), the secondary carbides were occurred.

Figure 2(c) to 2(d) clearly showed that some of the bright carbides appear to align into grain boundary-like patterns, most attacked due to the solid solution reduction caused by the carbide precipitation in nonisothermally tempered carbon steel. The carbides precipitates in the quenched microstructures also exerted effects on the material properties (hardness, wear and corrosion resistance) [16-17] that might explain the increasingly important of ultimate tensile strength. SEM micrographs (Figure 2(e-f)) of 5160 after hardening at 780°C for 30 min (Q5) clearly depicted the ferrite matrix (dark regions) along with decomposed lathy morphology (gray regions) typical of tempered-martensite in contrast to severely decomposed isothermal tempered-martensite and solid morphology of martensite phase in as-sheet condition. The difference in structural changes in martensite substructure during tempering at high temperature, which strongly influences the softening behavior of carbon steel, is clearly explained by Hernandez [18].

The extensive degree of softening in isothermally tempered carbon steel was attributed to spheroidization and coarsening of cementite, and complete recovery of the lath martensite substructure. Earlier researches [19-20] indicated that fine ferrite grain could be coarsened due to fast grain growth at high temperatures. Furthermore, in these researches works, the steels were deformed by quenching of virgin martensite before subsequent intercritical annealing. Therefore, the stored energy after deformation was higher and the recrystallization was promoted [21].

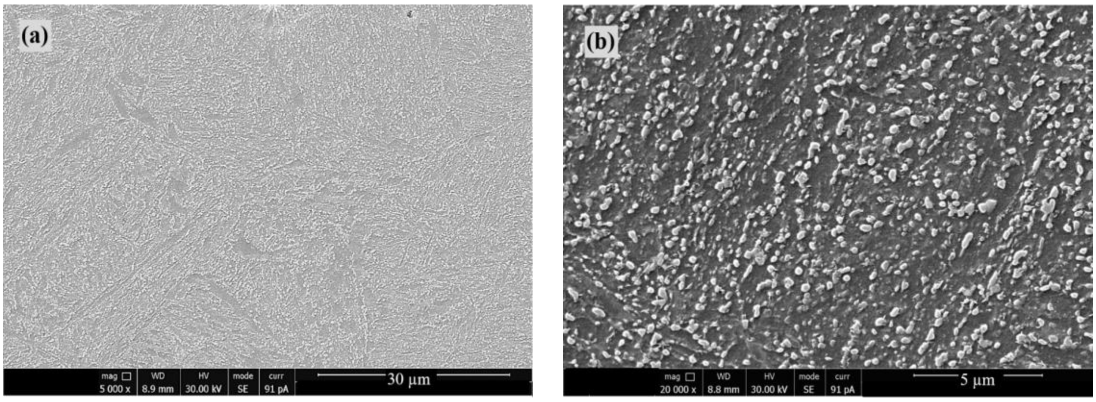

Figure 1. SEM micrographs showed the microstructures of as-sheet condition by scanning electron microscopy magnification of (a) 5000x and (b) 20000x.

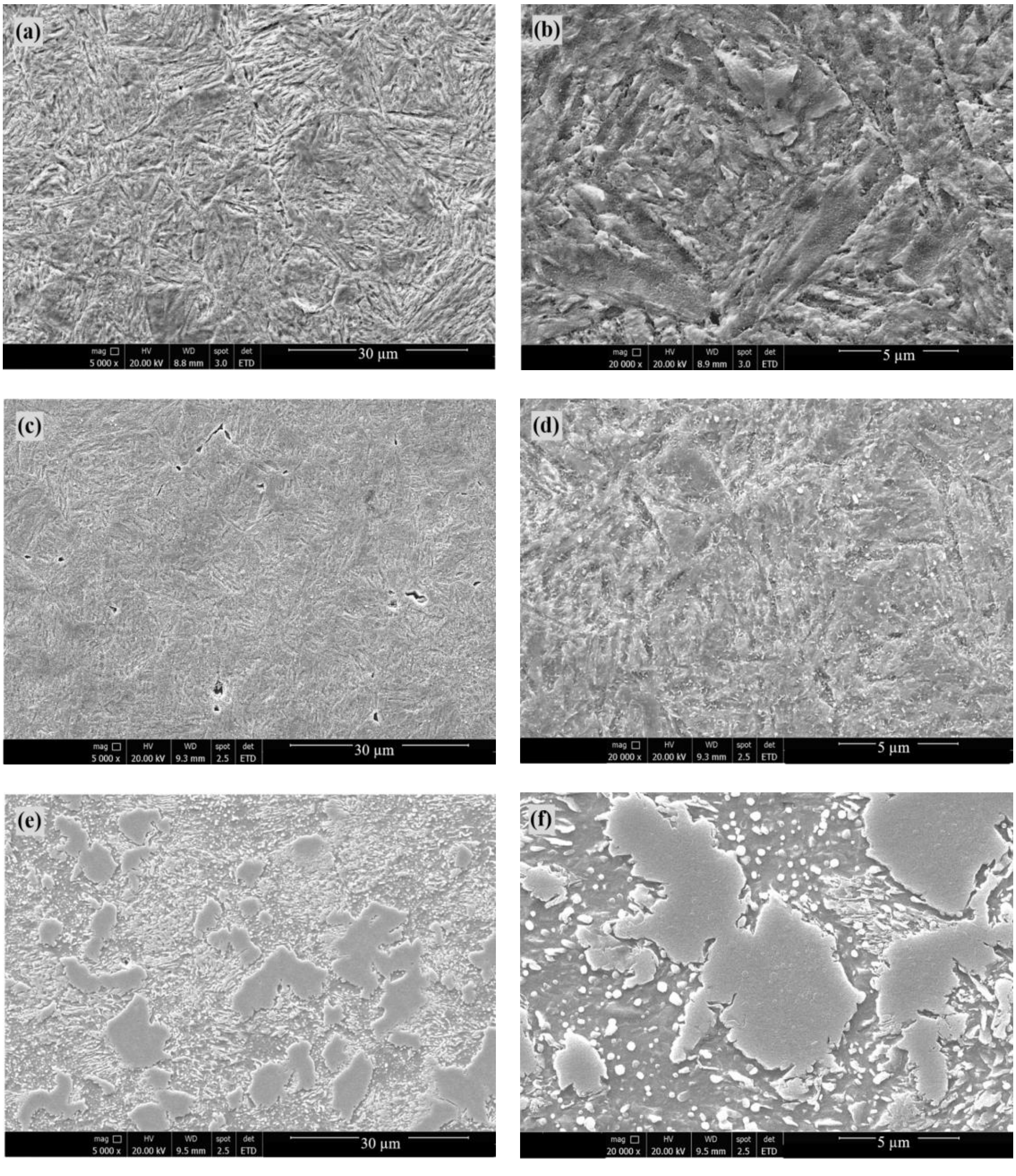

Figure 2. SEM micrographs showed the microstructures after quenching into water by (a-b) Q1, (c-d) Q4 and (e-f) Q5 heat treatment conditions.

According to the microstructures after quenching into oil and brine observed in Figure 3(a-f) and Figure 4(a-f), respectively, they were similar to those of the quenching into water condition. EDS analysis revealed that the phases present in 5160 steel after quenching at 900°C (Q1) contained C, Si, Cr, Mn, Ni and Fe-rich of martensite phase as shown in Figure 5 and Table 3. Bright carbides within martensite phase after Q4 heat treatment condition contained alloying additions and identified as Cr, Si, Mn, Ni and Fe-rich were shown in Figure 6 and Table 4. The phase present, matrix, coarse grain and fine structures, were Fe, Si, Cr, Ni and Fe-rich, with the carbides after Q5 condition consisted of Cr, Si, Cu and Fe-rich as shown in Figure 7 and Table 5. The alloy composition has a strong effect on the morphology [22], there was a morphological change of the martensite microstructure from lath martensite at low carbon contents after quenched into water media to plate martensite at high carbon contents after quenched into oil and brine.

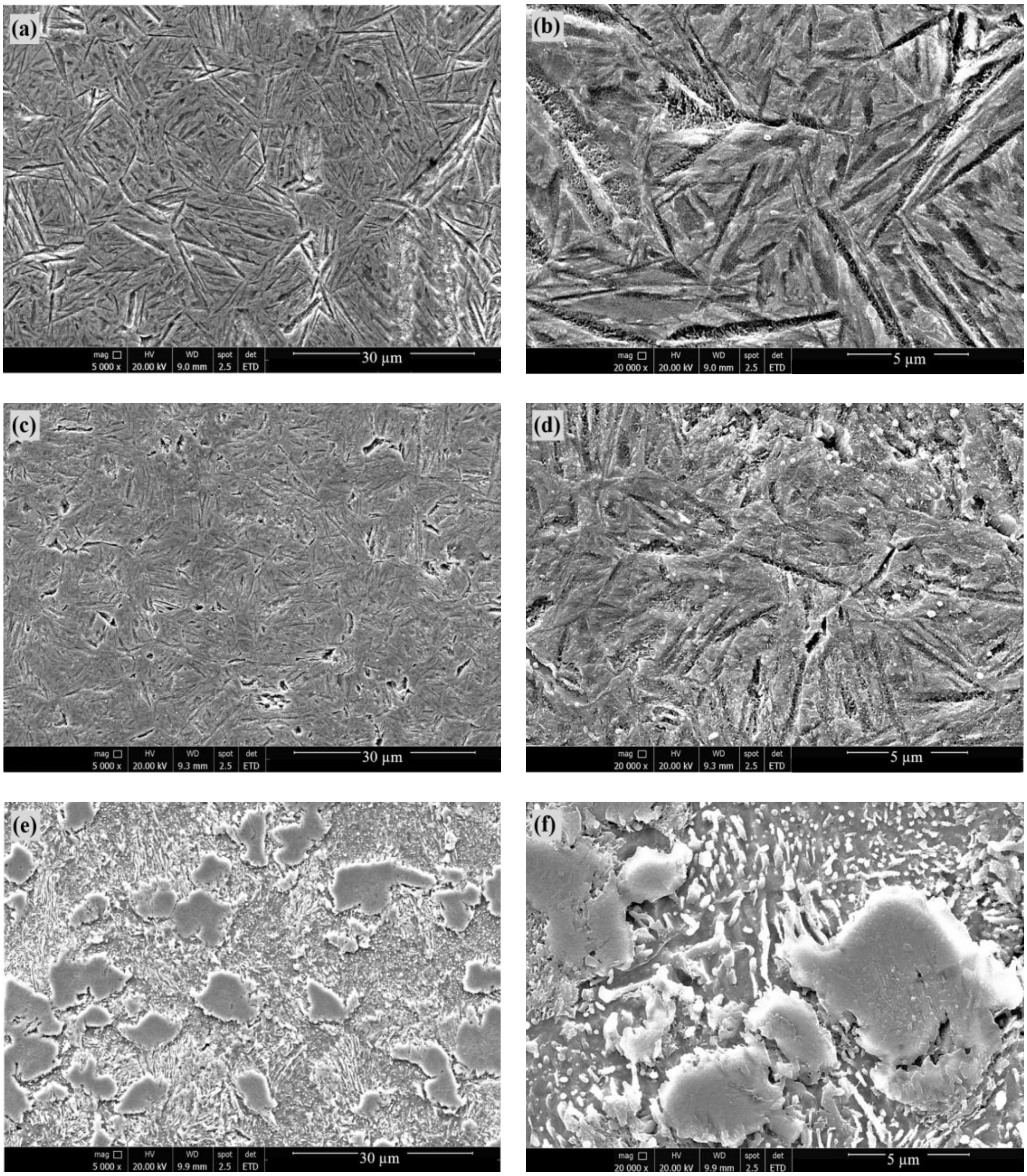

Figure 3. SEM micrographs showed the microstructures after quenching into oil by (a-b) Q1, (c-d) Q4 and (e-f) Q5 heat treatment conditions.

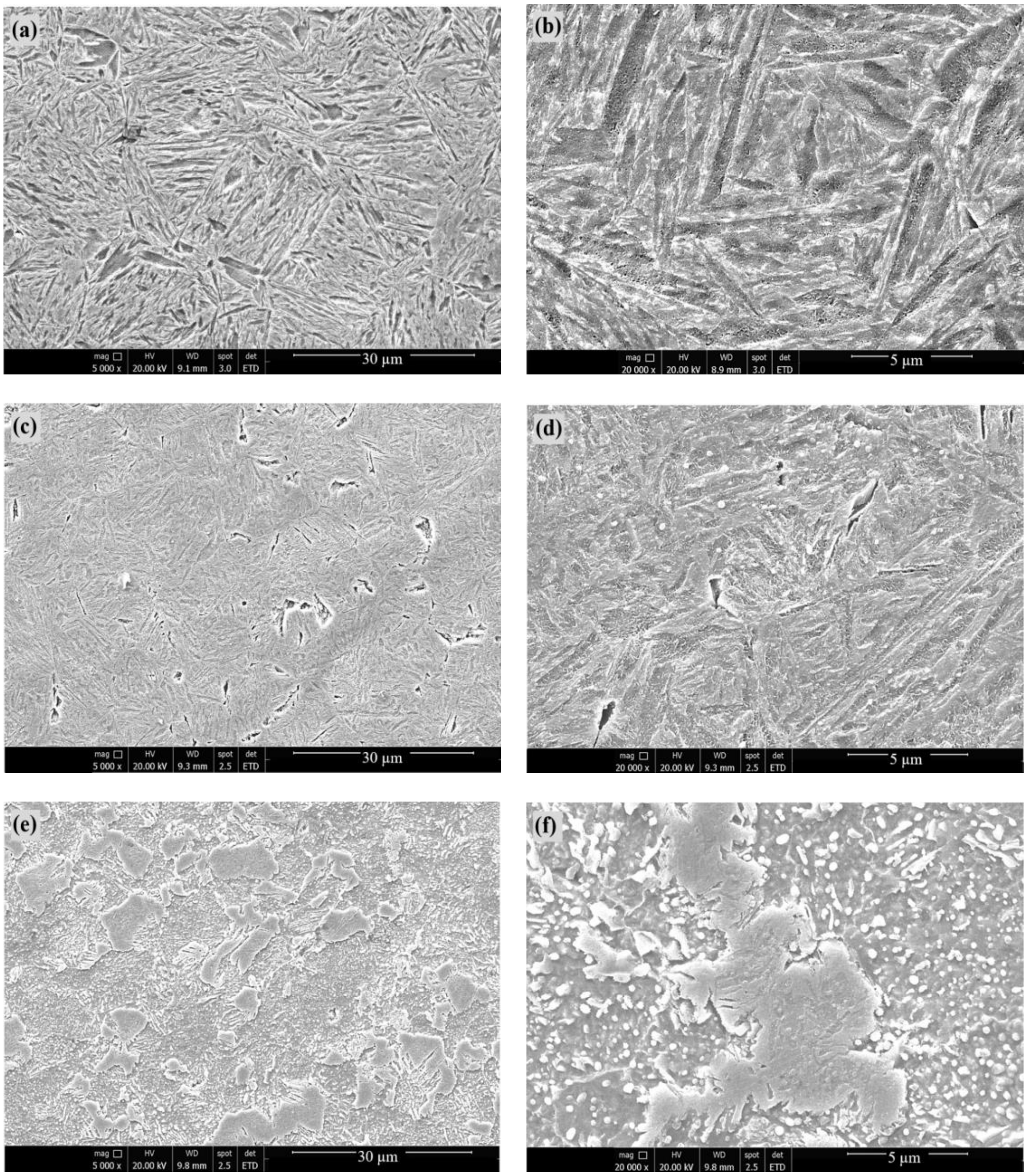

Figure 4. SEM micrographs showed the microstructures after quenching into brine by (a-b) Q1, (c-d) Q4 and (e-f) Q5 heat treatment conditions.

Table 3. Element (wt%) of Q1 condition, under different quenchants.

Heat treatment	**Spectrum**	**Element (wt%)**					
		Cu	**Si**	**Cr**	**Mn**	**Ni**	**Fe**
Water	1	0.13	0.43	0.63	0.94	-	20.78
	2	-	0.33	0.48	0.85	-	19.50
	3	0.30	0.47	1.04	0.59	0.17	16.93
Oil	1	-	0.20	0.86	-	-	-
	2	-	0.61	1.26	-	0.58	-
	3	0.31	0.53	1.17	-	-	-
Brine	1	-	0.35	0.62	0.73	0.07	29.38
	2	0.63	0.70	1.11	1.32	-	-
	3	0.13	0.28	0.63	0.49	-	30.48

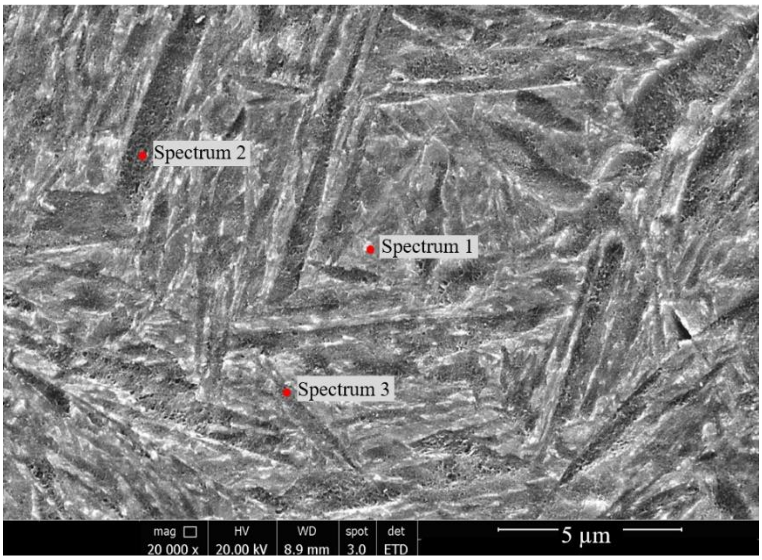

Figure 5. SEI showed the phases present and EDS spectrum after Q1 heat treatment.

Table 4. Element (wt%) of Q4 condition, under different quenchants.

Heat treatment	**Spectrum**	**Element (wt%)**					
		Cu	**Si**	**Cr**	**Mn**	**Ni**	**Fe**
Water	1	0.22	0.25	1.26	-	-	98.27
	2	-	0.02	0.73	-	0.42	98.83
	3	-	0.25	1.62	0.25	0.45	97.43
Oil	1	-	0.25	1.17	-	-	98.58
	2	-	0.21	1.20	-	0.27	98.32
	3	-	0.46	1.96	-	-	97.58
Brine	1	-	0.10	0.27	-	-	99.63
	2	1.19	0.44	1.19	-	-	98.17
	3	-	0.58	1.69	-	-	97.73

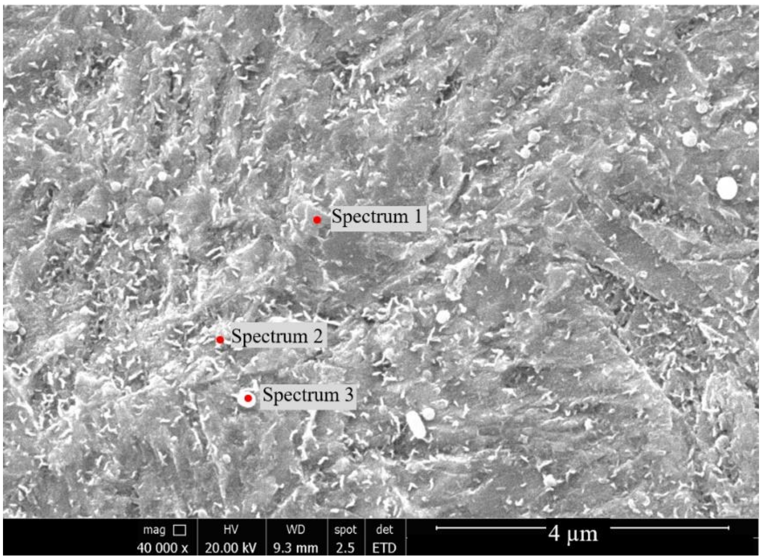

Figure 6. SEI showed the phases present and EDS spectra after Q4 heat treatment.

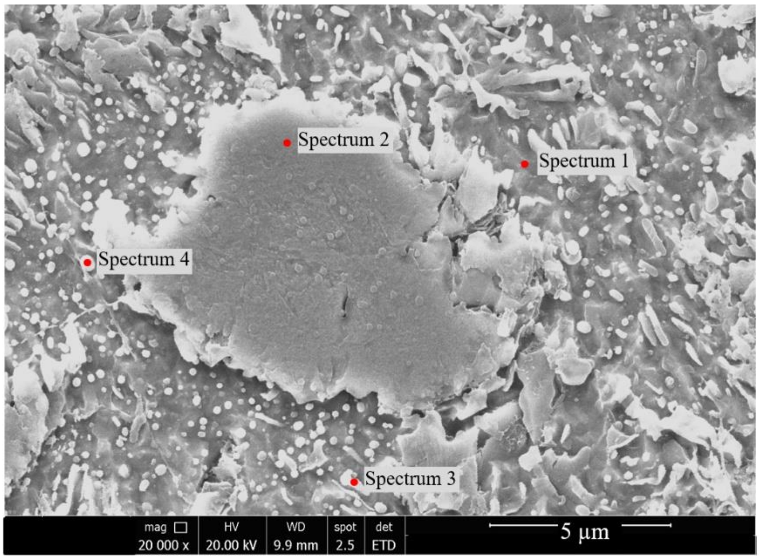

Figure 7. SEI showed the phases present and EDS spectra after Q5 heat treatment.

Table 5. Element (wt%) of Q5 condition, under different quenchants.

Heat treatment	**Spectrum**	**Element (wt%)**					
		Cu	**Si**	**Cr**	**Mn**	**Ni**	**Fe**
Water	1	-	1.08	1.02	-	-	97.90
	2	-	0.33	1.23	-	-	98.44
	3	-	0.29	0.86	-	-	98.85
	4	0.14	0.28	1.01	-	-	98.57
Oil	1	-	0.25	1.08	-	1.19	97.48
	2	-	0.73	1.09	-	0.63	97.55
	3	-	0.52	0.73	-	0.14	98.61
	4	0.18	0.08	2.08	-	-	97.66
Brine	1	-	0.20	0.92	-	-	98.88
	2	-	0.71	1.10	-	-	98.19
	3	-	0.99	0.51	-	-	98.50
	4	0.86	1.00	1.02	-	0.20	96.92

3.2 Hardness and tensile testing

Rockwell hardness for all heat treatment conditions performed at room temperature and results were illustrated in Figure 8. The hardening increased hardness compared to the as-sheet condition. Hardness in the as-sheet condition was about 40 HRC. Figure 8 showed the hardness results after hardening at various temperatures. After hardening at 900°C for 30 min (Q1) followed by quenching into water, oil and brine, it was found that the maximum hardness of about 65, 60 and 61 HRC, respectively.

While the hardness was slightly decreased after hardening at 870°C for 30 min (Q2) to hardening at 810°C for 30 min (Q4) conditions. Furthermore, it sharply decreased to about 26, 24 and 27 HRC after hardening at 780°C for 30 min (Q5) for each quenchant in quenching due to the martensite to coarsening temperd-martensite transformation. However, water quenching was the most efficient quenching media where maximum hardness was obtained, but it may cause distortion and tiny cracking. When hardness was sacrificed after brine and oil quenched due to slow the rate of cooling. These brine and oil fluids often oxidize and form a sludge during quenching, which consequently lowers the efficiency of the process.

Figure 9 and Figure 10 showed the ultimate tensile strength and %elongation in the as-sheet condition were about 510 MPa and 6.8%, respectively. After hardening at 900°C for 30 min (Q1) followed by oil quenched, the ultimate tensile strength was slight decreased to 447 MPa while the %elongation was increased to 13.88%. Coarsening eventually caused an increase in the ultimate tensile strength while the %elongation was decreased after hardening at 900°C for 30 min (Q1) to hardening at 810°C for 30 min (Q4) conditions.

Due to the process reduced brittleness by plastic deformation and ductile fracture. The highest ultimate tensile strength of 878 MPa after hardening at 810°C for 30 min (Q4) was obtained followed by water quenching. Moreover, the ultimate tensile strengths decreased after hardening at 780°C for 30 min (Q5) conditions whereas the %elongation increased due to the coarse phase transformation in tempering process. Furthermore, the hardness and ultimate tensile strength decreased after hardening at 780°C for 30 min (Q5) conditions followed by each quenchant in quenching process, while %elongation increased.

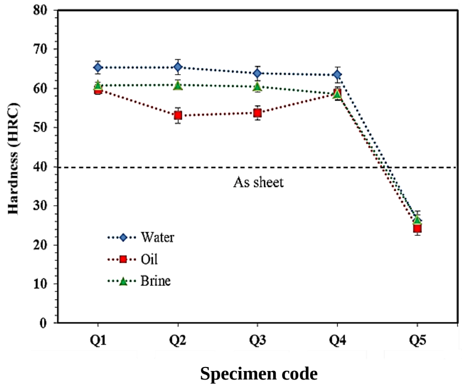

Figure 8. Effects of heat treatment conditions on hardness after quenching into different quenchants.

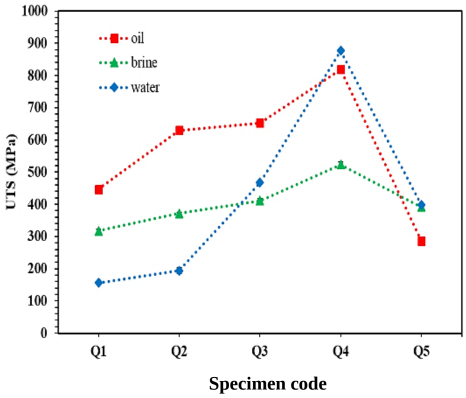

Figure 9. Effects of heat treatment conditions on ultimate tensile strength after quenching into different quenchants.

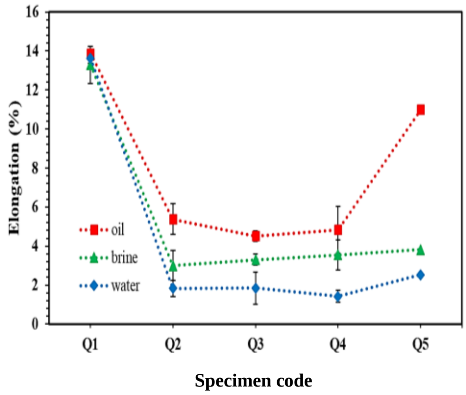

Figure 10. Effects of heat treatment conditions on %elongation after quenching into different quenchants.

4. Conclusions

The microstructure in the as-sheet condition consisted of ferrite and pearlite. After hardening martensite late and plate and a small amount of retained austenite were observed. The hardening at 810°C for 30 min (Q4) followed by water, oil and brine showed carbide distribution in martensite matrix. The coarse tempered-martensite grains were occurred after hardening at 780°C for 30 min (Q5) followed by quenching into each quenchants. While quenching in water resulted in lath martensite structures, the plate martensite was found in oil and brine quenched specimens.

The hardness of as-sheet condition was 40 HRC. Heat treatment conditions increased the hardness compared with as-sheet condition. The ultimate tensile strength in as-sheet condition was about 510 MPa. As hardening at all conditions, the highest hardness was obtained after hardening by water quenched while the maximum ultimate tensile strength and %elongation were gained after quenching into oil solution. The results show that the quenched samples in water after hardening at 810°C for 30 min (Q4) were brought the best combination of mechanical properties as compared with other quenched media and hardened samples.

5. Acknowledgements

This work was supported by Lampang Rajabhat University, the National Research Council of Thailand, NRCT and would like to thank Asst. Prof. Dr.Amporn Weingmoon and Mr.Monchai Ngamrung.

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