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ENHANCING S45C STEEL FOR THE PRIMARY COMPONENT OF AN AUTOMATIC COUPLER USING QUENCH-TEMPERING TECHNIQUES

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Coupling links and hooked plates constitute the primary components of automatic couplers in trains, enduring substantial tensile and compressive loads during train connections. This study endeavours to enhance the strength of S45C material through heat treatment techniques. The research commenced with the preparation of JIS S45C tensile test specimens adhering to ASTM E8 standards. The material's chemical composition was validated using an Optical Emission Spectrometer (OES). Six heat treatment variations were employed, including quench oil without tempering (QO), quenching water without tempering (QW), quenching oil tempered at 660°C (QOT660), quenching water tempered at 660°C (QWT660), quenching oil tempered at 550°C (QOT550), quenching water tempered at 550°C (QWT550), alongside untreated conditions (NT) for comparison. The efficacy of heat treatment was evaluated through tensile testing, optical metallographic analysis, and micro-Vickers hardness tests. QO and QW scenarios were excluded from the tensile tests. Results revealed that QWT550 demonstrated the most substantial enhancement in material yield, exhibiting a 115% increase. Moreover, hardness testing indicated superior hardness in QWT550 specimens compared to other tempered variants. The metallographic analysis illustrated the formation of identical and smooth martensitic structures. Overall, the combination of cooling heat treatment and tempering proved sufficient to meet the design requirements of hooked plates and coupling links for automatic couplers.

Keywords: automatic coupler, quench-tempering, S45C, material characterization

1 INTRODUCTION

The automatic coupler is a connecting device on a train that must have sufficient strength to pull the train under full load without experiencing permanent deformation. The main components in the automatic coupler are coupling links and hooked plates that pair with each other, lock each other when coupled conditions, and receive tensile and compressive loads when the train is operating. In addition to the ability to handle tensile and compressive loads, coupling links and hooked plates must have sufficient resistance to friction due to the locking process. Therefore, the coupling links and hooked plates must have good hardness. To avoid failure in the couplers, the coupler manufacturing industry requires steel with high material properties at an economical price. Researchers have widely researched materials for couplers. Chunduru et al. [1] investigated the failures in AAR couplers type E. The mechanism of brittle fracture failure in knuckle couplers caused by micro-cracks is reported by Huang et al. [2]. Steed et al. [3] improved a coupler design and checked for failures. Morsy et al. [4] analyzed failures in semi-permanent couplers resulting from improper heat treatment. Based on these studies, coupler failures caused by materials must be avoided for the safety of train operations.

Presently, advancements in automatic coupler research are underway, as evidenced by the work of Valentino et al. [5], who conducted numerical simulations adhering to EN 16019:2014 standards to assess coupler performance under tensile loads. These simulations underscored the necessity for steel materials with a minimum yield stress of 704.21 MPa to withstand operational stresses. The automatic coupler model was carried out numerical simulation in the form of a tensile test with the loading of 1000 kN following the EN 16019:2014 automatic coupler standard — Performance requirements, specific interface geometry and test method [6]. Notably, AISI 1045 or JIS S45C steel has emerged as a popular choice for its favourable balance of cost, manufacturability, and availability. S45C steel is medium carbon steel with a carbon content of about 0.3-0.5%C [7] [8]. A medium carbon content allows this steel to improve its mechanical properties by providing heat treatment [9]. To improve its mechanical properties, steel can be given heat treatment such as annealing, tempering, normalizing, and quenching [10]. It is necessary to improve mechanical properties in the form of yield stress and ultimate tensile stress so that S45C steel can be used as the main material for couplers.

Effective heat treatment methods to control mechanical properties in steel are quench and tempering. Quench converts the austenite phase into martensite with a very rapid transformation using water or oil cooling media [11] [12]. Some reference states that water quench has a higher hardness value than oil quench, but oil quench has a better toughness [13]. The mechanical properties formed in martensite are hard and brittle, so they are unsuitable for engineering applications. The hard and brittle properties of martensite can be controlled by tempering by reheating the quenched steel below eutectoid temperature and then cooling at room temperature to obtain a martensite tempering phase with a lower hardness than martensite but having better toughness and ductility [14] [15]. The effect of tempering is determined by temperature and time [16]. The higher the tempering temperature will cause the hardness to decrease and the ductility to increase [17]. Research on heat treatment in S45C steel was conducted by Nunura [18] and Phi [19], who discussed the factors that affect the hardness of steel in three austenitization temperatures above its critical temperature. Mocko [20] analyzed the effect of fatigue loading on S45C steel. Akhyar [21] researched the effects of heat treatment and microstructure on S45C steel. Haeju [22] investigated the mechanical properties of steel to obtain high strength and toughness by using heat treatment in the form of quench and tempering. Vieira [11] conducted quenching research using aqueous polymer solutions to increase hardness and mechanical strength. Yazdania et al. [23] report on the effect of tempering temperature on fatigue behaviour in S45C steel.

This study aims to enhance the properties of S45C material to make it suitable as the main material for coupler, in accordance with the allowable stress criteria of the designed structure. The study was conducted with several variations in tempering temperatures within the high-temperature range and with variations in the quench media. Tensile tests, metallography and hardness tests are carried out as validation. Although S45C steel heat treatment has been well studied in the literature to date, a more thorough investigation into high-temperature tempering variations in conjunction with a variety of quench media is necessary to improve our comprehension of material behaviour in crucial coupler components.

2 METHODOLOGY

2.1 Materials

In this experimental study, the coupling links and hooked plates components were represented by S45C material test specimens. Specimens for heat treatment are prepared in the form of a tensile test specimen with dimensions according to ASTM E8/E8M standard [24], and their dimensions are presented in Figure 1 and Table 1. After sample preparation, chemical composition was tested using the Optical Emission Spectrometer (OES) method with the Spectromaxx from Ametek. This method quantitatively determines the percentage of elemental compositions of various metals and alloys on the sample. Based on the results of the OES, the chemical composition in Table 2. was obtained.

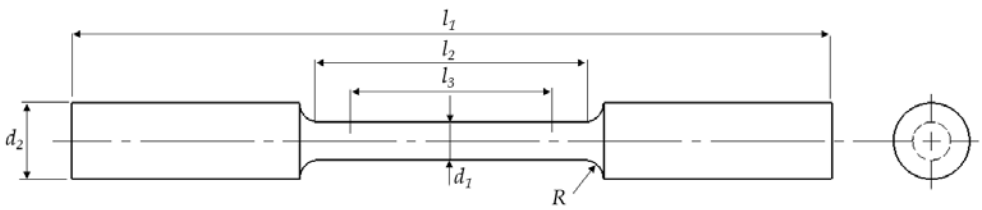

Fig. 1. Tensile test specimen

Table 1. Dimension of specimen

Symbol	Description	Dimension (mm)
L1	Length overall	200
L2	Length of the narrow section	56
L3	Gage length	50
D1	Diameter of the narrow section	12.5
D2	Diameter of the grip section	20
R	Radius of fillet	10

Table 2. S45C chemical compositions

Component	C (%)	Si (%)	Mn (%)	P (%)	S (%)
S45C	0.45	0.35	0.9	0.03	0.035

2.2 Methods

In this investigation, heat treatment scenario, particularly focusing on austenitizing and tempering durations, were established in accordance with the EN 10083-1:1991 standard for Quenched and Tempered Steels [25]. In this study, 6 treatment variations were used, namely, quench oil without tempering (QO), quench water without temper (QW), quench oil with a tempering temperature of 660°C (QOT660), quench water with a tempering temperature of 660°C (QWT660), quench oil with a tempering temperature of 550°C (QOT550), quench water with a tempering temperature of 550°C (QWT550), and with no treatment conditions (NT) as a comparison as in the scenario in Table 3**.** In this study, a total of 35 specimens were employed, with each treatment scenario comprising five specimens, as illustrated in Figure 2a. Subsequently, all treated specimens underwent tensile testing.

Table 3. Heat treatment scenario

Specimen Code	Austenite Temperature (°C)	Austenitizing Time (minutes)	Quench Media	Temper Temperature (°C)	Temper Time (Minutes)
NT	-	-	-	-	-
QO	860	30	-	-	-
QW	860	30	-	-	-
QOT 660	860	30	Oil	660	60
QWT 660	860	30	Water	660	60
QOT 550	860	30	Oil	550	60
QWT 550	860	30	Water	550	60

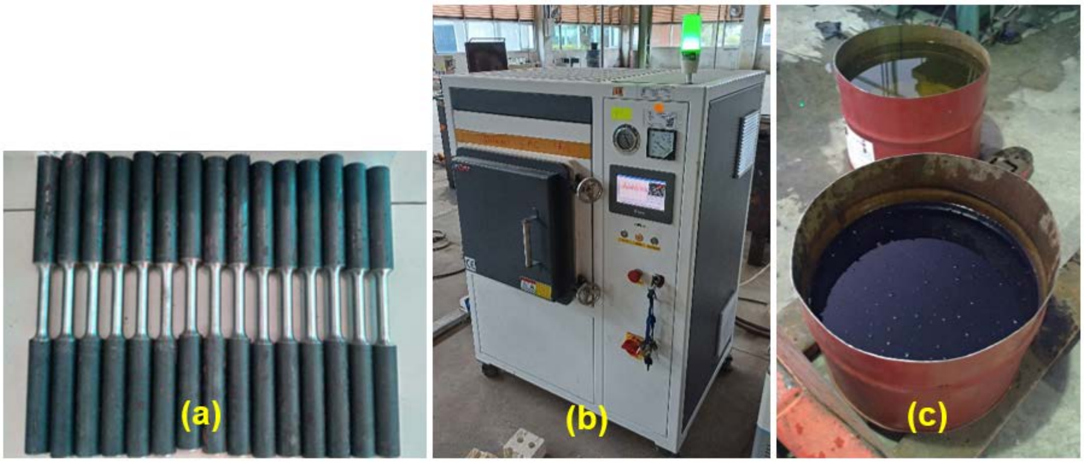

Fig. 2. Test specimens and setup equipment: (a) ASTM E8 specimens; (b) electric furnace; (c) quench media

The heat treatment process utilized electric furnaces, specifically the Hernan Sante STQ-8-17 model, capable of reaching temperatures up to 1100°C at a heating rate of 4°C per minute (refer to Figure 2b). Additionally, the quenching media consisted of 20 litres each of water and SAE 20W50 oil (refer to Figure 2c). The specimen was placed into a preheated electric furnace set at an austenitizing temperature of 860°C, where it underwent a 30-minute warm-up period. Subsequently, the specimen was withdrawn from the electric furnace and subjected to quenching using a combination of water and oil. Once the material reached room temperature post-quenching, the subsequent step of tempering commenced. Tempering was conducted in a conventional furnace for 60 minutes for each treatment variation. Upon completion of the tempering process, the specimen was removed and allowed to cool in ambient temperature air. The procedural sequence employed in this study is delineated in Figure 3**.**

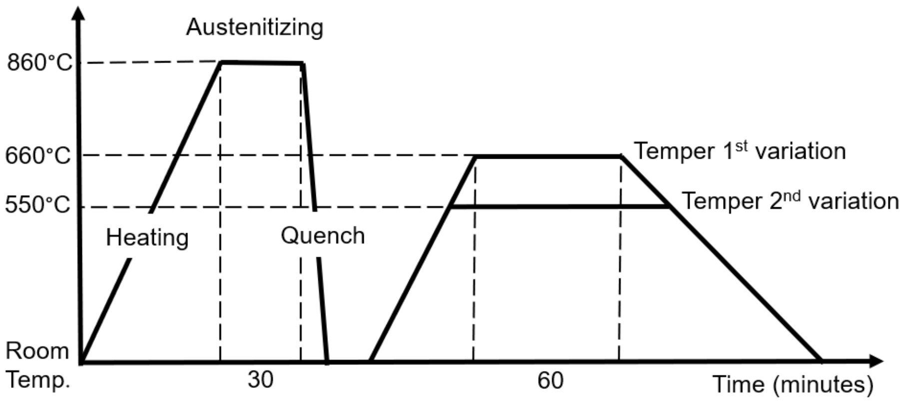

Fig. 3. Heat treatment procedure

The characterization methods employed in this study primarily included tensile testing and metallography. Tensile testing, recognized as the most commonly utilized method for evaluating the mechanical properties of materials [26], was conducted using the Shimadzu Universal Testing Machine with a maximum capacity of 250kN, following the ASTM E8 standard. Metallography, aimed at observing microstructures in specimens both pre- and post-heat treatment, was performed utilizing the Olympus BX53M optical microscope. Sample preparation involved cutting the specimen across the base of the gauge length and subsequently mounting it to facilitate the grinding and polishing processes. Etching using nital, a mixture of nitric acid (HNO3), was carried out to enhance the optical visibility of the metal material's microstructure, facilitating grain size determination and phase identification. The initial observation point selection commenced from the specimen's surface, followed by sequential shifts towards the centre, monitoring microstructural changes. Additionally, hardness testing was conducted using the Vickers method due to its capability for micro-hardness testing. The Mitutoyo HM-200 Hardness Testing Machine was employed for this purpose. Initial observations were made at the specimen surface edge, with subsequent shifts up to 1 mm towards the specimen's centre diameter.

3 RESULT AND DISCUSSION

3.1 Tensile Test

The ultimate tensile stress (UTS) and yield stress are plotted for each test specimen as in Figure 4, with the x-axis being the variation of the test specimen and the y-axis being the tensile stress (MPa). Specimen NT has the smallest value with a yield of 365 MPa and UTS of 600 MPa. The highest yield strength and UTS are in QWT 550 specimens. Yield strength increased by 116% compared to NT, and UTS increased by 43% compared to NT. The next highest increase was QOT 550, with an increase in yield strength of 99% and UTS of 40% compared to NT. QWT 660 and QOT 660 have almost the same result. QW and QO specimens were not successfully tested for tensile due to slippage in the specimen when pulled due to the specimen being too hard. The results of the tensile test found that the best strength increase was obtained at a tempered temperature of 550 °C. It agrees with the research of Chuaipan et al. [13], which states that quenched water has a higher tensile strength compared to quenched oil, and according to the research of Akhavan et al. [27] and Clarke et al. [17], which states that the higher the tempering temperature, the tensile strength decreases. According to numerical calculations, the yield strength of QWT 550 and QOT 550 satisfies the design specifications with an allowable stress limit of 704.21 MPa.

Elongation analysis needs to be known to show the degree of ductility of the material. Figure 5 explains that elongation results with the x-axis are variations of the test specimen, and the y-axis is the elongation percentage. The elongation of QWT 550 and QOT 550 decreased by about 21-24% compared to NT, while QWT 660 and QOT 660 elongation did not change much compared to NT. This trend is in line with Akhavan et al. [27] and Clarke et al. [17], which state that elongation increases with the same quench medium if the tempering temperature rises.

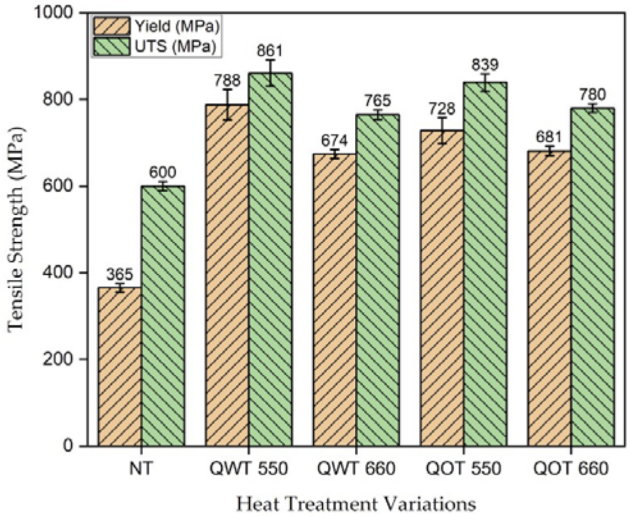

Fig. 4. Tensile test S45C

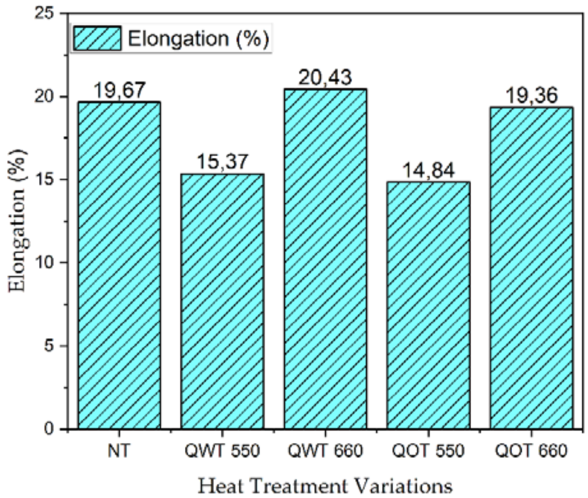

Fig. 5. Elongation S45C

3.2 Microhardness Vickers

The Vickers microhardness test applies a 1 Newton load for a test duration of 12 seconds per point. This method generates indents in the form of vertical and horizontal diagonal lengths. The specimen selected for this hardness test corresponds to the one with the highest tensile test results within each scenario. Six observation points are designated on each specimen, beginning from the edge and spaced at intervals of 0.1 mm, 1 mm, 2 mm, 3 mm, 4 mm, and 5 mm. Figure 6 indicates the hardness value of Vickers on the y-axis and the distance of the indentation point on the x-axis. QW and QO are the specimens with the highest hardness. QW has an average hardness of 627.2 HV, or 56.6 HRC and QO has an average hardness of 548.1 HV or 52.1 HRC. Specimens that are tempered have a lower hardness. The penetration of hardness in samples due to quenching and tempering is quite uniform, QWT 550 has an average hardness of 330 HV or 33.3 HRC, QWT 660 has an average hardness of 279.3 HV or 26.9 HRC, QOT 550 has an average hardness of 326.3 HV or 32.9 HRC, QOT 660 has an average hardness of 269 HV or 25.5 HRC. For comparison, NT specimens had an average hardness of 272.4 HV or 25.9 HRC. The chart's trend is that at the very edge of 0.1 mm, it has a lower hardness, and then the hardness rises as it goes further towards the centre of the specimen. QWT 550 has the best hardness in tempered materials, while QOT 660 has a lower average hardness compared to NT.

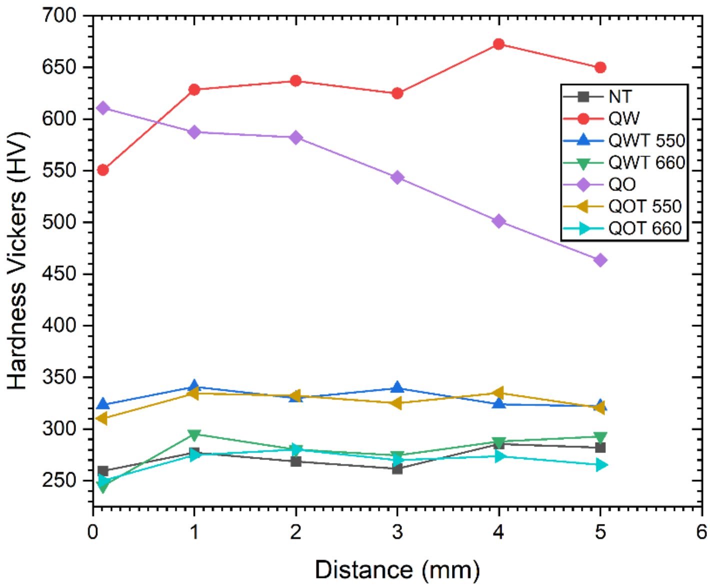

Fig. 6. Microhardness Vickers

3.3 Metallography

Metallography is performed with an optical microscope with a magnification of 1000x. The specimen selected for metallography corresponds to the one with the highest tensile test results within each scenario. In Figure 7, the observation point is carried out at the centre of the specimen, which is 5 mm from the edge of the specimen. In the NT sample, ferrite with a white colour and pearlite with a blackish colour is visible with a visible grain border. The pearlite phase looks lamel domineering. Both have a large grain size. In QW samples, ferrite and pearlite are already out of sight. The microstructure martensite has been formed and is quite noticeable with the shape of irregular needle-shaped lines. The QO sample still has subtle pearlite and clear martensite with its grain borders. In the QW sample, pearlite was not visible, only martensitic. Samples of QWT 550, QWT 660, QOT 550 and QOT 660 look identical, with fairly fine transformations of martensite tempering compared to non-tempered conditions (QW and QO). In all samples, a uniform microstructure phase with the same shape, grain size and distribution was seen at each observation site. Grain size in heat-treated materials is smaller and smoother than in NT. This result proves the higher properties of the material as Vieira et al [11]. S45C steel is classified as hypo eutectoid steel, so the phase that appears (phase present) is ferrite and pearlite, as shown by NT. After being given heat treatment, a martensitic phase appears in the QO and QW images. After tempering, the phase turns into martensitic tempering as in the QWT and QOT images.

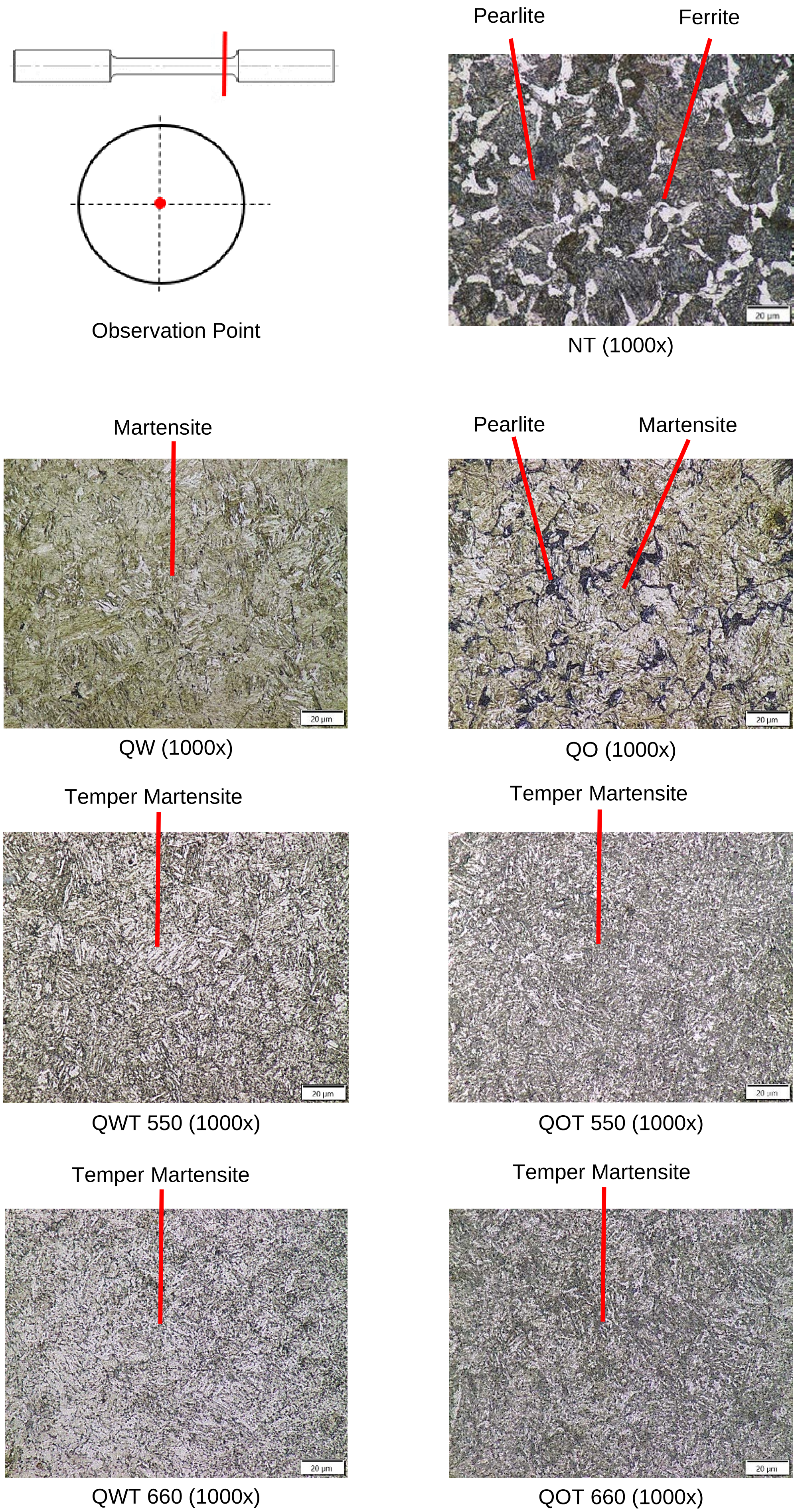

Fig. 7. Metallography of the core region of the specimen

4 CONCLUSIONS

This work investigated the effects of different quenching media and high tempering temperatures on the microstructural evolution and final properties—such as yield strength and hardness—of S45C steel for the main component of the automatic coupler. The following conclusions can be drawn:

- There is a change in mechanical properties in S45C steel due to heat treatment in the form of quenching and tempering. It is evidenced by changes in microstructure resulting in differences in tensile strength and hardness.
- Based on the tensile test results, quench water specimens with a tempered temperature of 550°C (QWT 550) have the best mechanical properties. Yield strength increased by up to 116% with lower elongation than S45C steel without treatment. Based on the hardness test results, quench water specimens with a tempered temperature of 550°C (QWT 550) have the best hardness compared to other tempered specimens. Based on the metallography results, the martensitic temper formed in tempered specimens looks identical and smooth.
- The experimental findings establish that quenching methods utilizing water as the quenching medium, tempered at 550°C, and quenching in oil with tempering at 550°C, successfully fulfil the allowable stress criteria, surpassing minimum yield stresses of 704.21 MPa mandated by design specifications. These results underscore the potential of these techniques for practical implementation within the automatic coupler industry. Specifically, they offer a viable means of fortifying coupling links and hooked plates fabricated from S45C material, thereby enhancing their performance and durability in operational settings.

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