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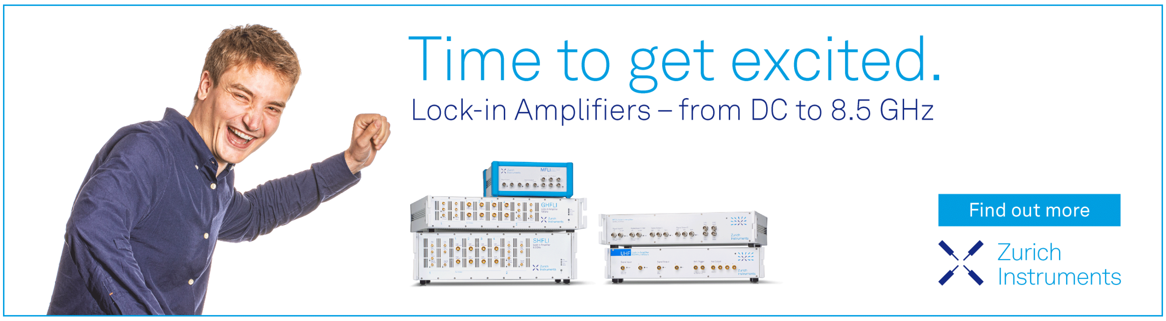

Effect of Single and Double Quenching-Tempering Heat Treatments on Microstructures and Tensile Strength of AISI 4140 in Annealing Condition

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Abstract. Low alloy of AISI 4140 steel in annealing condition was heat-treated by single quenching-tempering (SQT) and double quenching-tempering (DQT) processes. Quenching process was done by heating steel at 850 °C for soaking time 1 h and followed by immersion into oil bath at 10 °C. Tempering heat treatment was performed at 650 °C for 1 h and followed by cooling sample into oil bath at 10 °C. The tensile strength properties of heat-treated steel were evaluated from quenched and tempered specimens for single and double heat treatment conditions. The microstructures of heat-treated sample were characterized by means of Optical Microscope (OM). The DQT heat treatment results higher tensile strength than those of SQT heat treatment with relatively low ductility. The finer austenite grains resulted by subsequent austenization in DQT heat treatment is believed to produce small many packets consisting of finer lath tempered martensite. The microstructural observation indicates that the finer grain size consisting of solid solutions of tempered-martensite phase in ferrite matrix may be responsible to sharply increase of the steel strength properties in DQT condition.

INTRODUCTION

AISI 4140 steel is widely used for engineering applications which components are manufactured such as gears, stubs, pinion shaft, spindles, oil industry drill collar and etc. The initial microstructure of the steel dominantly determines suitable certain applications in an initial engineering design which directly correlates to loading condition [1]. Conventional heat treatment process is still trending issues in physical metallurgy as subject of considerable research interest for a metallurgical engineer for improving the mechanical properties of low alloy steel [2,3]. Quenching process followed by subsequent tempering has been proved enable to the mechanical strength of steel with appropriate ductility [4,5] resulting a high ratio of strength and weight component as requirement in initial design. In addition, the final microstructure and mechanical strength of steel are depending on some heat treatment parameters including an austenizing and quenching temperatures, the quenching media and the tempering temperature and time [6,7].

Previous studies have reported that the effects of quenching-tempering heat treatment on the microstructure and mechanical properties of different steels, such as the electro casting 5 Cr steel [2], 25CrMo48V martensitic steel [4], H13 die steel [5], and AISI 4140 steel [8,9] have successfully applied on those steels for achieving optimal mechanical properties. From those results, quenching-tempering heat treatment process resulted in a significant improvement of the steel strength. Their study results [2,4,5] showed that strength and ductility of those steel were directly correlated to the appearance of the dislocation density of martensitic laths. The refinement of microstructure can be achieved by subsequently quenched and tempered heat treatment processing. To achieve optimal combinations of mechanical strength properties of low alloy steel and suitable ductility, double quenching and tempering by heat treatment has been applied to improve low alloy steel properties [8,9]. Cyclic repetitions in austenizing process of low alloy steel had proven decreasing of austenite grains. In addition, refinement of austenite grains may be carried out predominantly by considering the addition of microalloying, cyclic heating, initial microstructure, austenitizing temperature and

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holding time at an austenite temperature. The present study, therefore, was aimed at investigating the microstructural changes on increasing of tensile properties of AISI 4140 in annealing condition. The microstructures and tensile properties of the steels after different heat treatment were discussed.

EXPERIMENTAL PROCEDURE

Material and Specimen Preparation

Eleven pieces of round bar of low alloy of AISI 4140 steel with 16 mm in diameter and 200 mm in length were subjected to annealing heat treatment which chemical compositions of the steel and the procedure of annealing heat treatment had been reported in citation [1]. Eleven tensile specimens according to ASTM E8M standard [10] were machined by a lath CNC. The shape and dimension of tensile specimen is shown in Fig. 1.

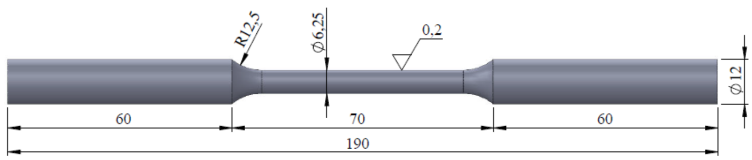

FIGURE 1. Shape and dimension of tensile specimen (unit in mm)

Heat Treatment Procedures

In the present research, quenching media used SAE 20 machine oil that a temperature of oil bath was kept a constant at 10 °C. The oil bath temperature was controlled using Type K thermocouple (XCIB from Omega-USA) with an Autonics controller. Cooling water from chiller was circularly flowed in opened tank where the oil bath was installed for cooling oil in bath continuously.

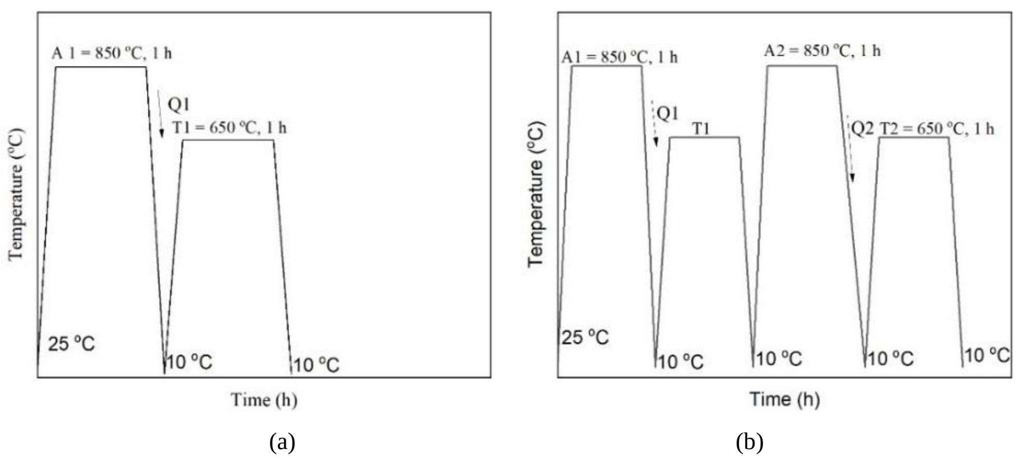

FIGURE 2. Schematical diagram of quenching and tempering processes on AISI 4140; (a) SQT and (b) DQT

A total numbers of tensile specimen heat treated to quenching and tempering processes were eight specimens. A respective two specimens were provided to quenching (Q1), quenching-tempering (Q1T1), quenching (Q2) and quenching-tempering (Q2T2) processes as shown in Fig. 2. Sample with RM code (as untreated steel) from AISI 4140 steel is in annealing condition. Samples with SQ, SQT, DQ and DQT codes are in single quenching (Q1), single quenching-tempering (Q1T1), double quenching (Q2) and double quenching-tempering (Q2T2) conditions, respectively. Schematic heat treatments processing for AISI 4140 in annealing condition can be seen in Figs. 2a and 2b.

Tensile Testing and Sample Characterizations

The strength performance of heat-treated and -untreated steel conditions were carried out using a computerized servohydraulics MTS Landmark 100 kN. An axial extensometer (MTS 634.25F-24 type) with gage length 50 mm attached in gage length area of specimen was used for incrementally measuring axial length until specimen broke. A constant displacement rate of 0.25 mm/min was used for pulling the specimen until failed. The yield strength (σ_y), elastic modulus (E) and ultimate strength (σ_{ult}) were calculated using the tensile template program.

Olympus optical microscope (OM) was used for observing the microstructure of sample from untreated and SQ, SQT, DQ and DQT conditions. Preparation specimens in resin mounting were provided for grinding and polishing specimen surface until the specimen's surface was smooth-like mirror. A 5% nital solution was used for etching specimen surface for a few seconds until featuring clear microstructure of untreated and treated samples.

RESULTS AND DISCUSSION

Tensile Test Results

The typical engineering stress-strain curve for the AISI 4140 steel in untreated and in heat treated conditions are displayed in Fig. 3. For comparison variations in tensile properties consisting of the 0.2% yield strength (σ_y), the ultimate strength (σ_{ult}), elastic modulus (E) and ductility (elongation, e) of heat-treated and -untreated samples are presented in Table.1. From these results, the AISI 4140 steel subjected to DQT heat treatment results higher tensile properties than those of AISI 4140 in SQT heat treatment, which followed by relative low ductility value. The engineering stress-strain trends for DQT sample is show a slightly similar with SQ and DQ samples. An increase in tensile properties of AISI 4140 steel subjected to DQT heat treatment shows a similar increase in tensile properties of AISI 4140 steel reported by Sanij et al. which an increase in tensile properties can be related to a prior austenite grain size variation and lower prior austenite grain size results the low ductility and vice versa [8].

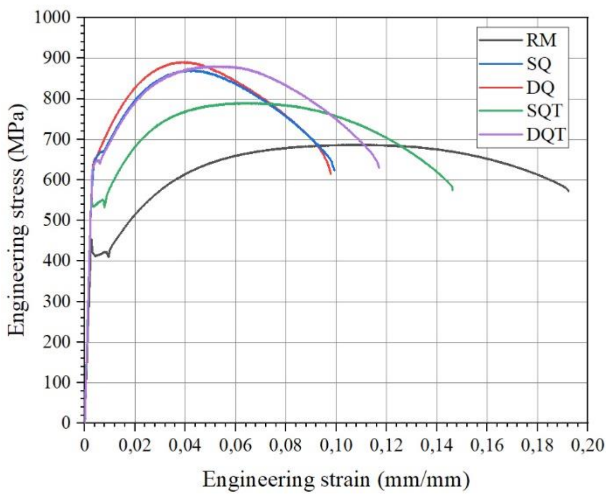

FIGURE 3. Plot of comparisons on engineering stress vs strain curves for heat-treated and -untreated of AISI 4140 steel

Tabel 1. Variation in tensile properties of AISI 4140 as function of heat treatment processes

Sample	Stress (MPa)		Elastic modulus, E (GPa)	Elongation, e (%)
	σ_y	σ_{ult}		
RM	414.01±6.9	689.01±7.5	205.6±10	25.0±1.3
SQ	648.14±14.6	863.31±11.1	211.5±0.7	13.9±1.5
SQT	538,62±3.5	790,06±0.3	207.5±2.3	18.8±1.3
DQ	647,75±1,6	881.18±6.8	214.2±6.6	14.0±1.7
DQT	654.16±9.1	886.01±5.0	216.0±5.1	15.2±1.2

In addition, the significant increase in tensile strength (σ_y and σ_{ult}) of AISI 4140 steel subjected to quenching heat treatment (DQ and SQ samples) (Fig. 3) can be related to the lattice structure changes from the face cubic structure (FCC) of austenite phase to the body centered tetragonal (BCT) of martensite phase after quenching processing. High carbon contents in austenite phase rapidly diffused outward to form a solid solution of BCT structures in ferrite phase. Consequently, the lattice structure changes due to the phase transformation resulted a large amount of dislocation and distortion, which led to significantly increase in the ultimate strength of steel [9].

MICROSTRUCTURES OBSERVATION

The microstructure of AISI 4140 steel in annealing condition is displayed in Fig. 4, which the coarse pearlite grains consist of precipitations of lamellar carbides (Fe_3C). The microstructure of Fig. 4 indicates that the coarse grain of pearlite phase with the coarsening of lamellar carbides structure is believed to result low tensile properties of AISI 4140 steel in annealing condition compared with the steel in quenching-tempering conditions (Fig. 3). However, low phase boundary area of lamellar carbides in ferrite matrix and the coarse grain of pearlite phases gives an advantage when the steel experiences cyclic loading by generating a large amount of effective barrier of dislocations movement [1,12]. In addition, the elongated ferrite phase connection is responsible to result a large ductility (Table. 1).

FIGURE 4. Optical microstructure of AISI 4140 steel in annealing condition

Fig. 5a and 5b show the typical microstructures of the steel in quenched conditions (SQ and DQ). Variations in these microstructures and prior austenite grain size contribute to different microstructures of samples in SQT and DQT heat treatments (Fig. 5c and 5d). In addition, DQ heat treatment produces finer austenite and ferrite grains than that of SQ heat treatment which these results are evident to observation in the microstructures of Fig. 5a and 5b. The finer austenite grains in Fig. 5b resulted by reaustenization of DQ process is similar with that of reported by Meysami et al. [9].

Subsequent austenization process subjected to AISI 4140 steel in quenching-tempering process is believed to determine size of packet consisting of lath martensite and parallel alignment of individual martensite crystal [7]. Slight similar microstructures of AISI 4140 steel subjected to SQT and DQT heat treatments consisting of many small packets are consistence as reported in literatures [4.8,9]. Therefore, these packets are responsible to give strong block dislocations movement in grain boundary of ferrite phase, and consequently the strength of the steel sharply increased. In addition, the typical microstructure of refinement of lath martensitic steel consisting of tempered martensite can effectively enhance yield strength [4]. Fig. 3 indicates the tensile properties of AISI 4140 steel treated by SQT and DQT processes in this work which has the higher tensile stress and yield strength with an appropriate ductility is consistent to previous researches [8,9] in citation.

The prior austenite grain and martensite packet in microstructure of AISI 4140 steel in SQ and DQ conditions are effectively refined by DQT heat treatment as compared with the SQT condition which the finer microstructure of AISI 4140 steel in DQT is shown in Fig. 5d. As shown in Fig. 3, the higher strength of AISI 4140 steel in DQT condition can be attributed to finer grain size which is evident to Fig. 5b. It has been reported that finer grain size and smaller lath martensite in packet of grain crystal is useful to impede dislocations movement and micro crack propagation [13].

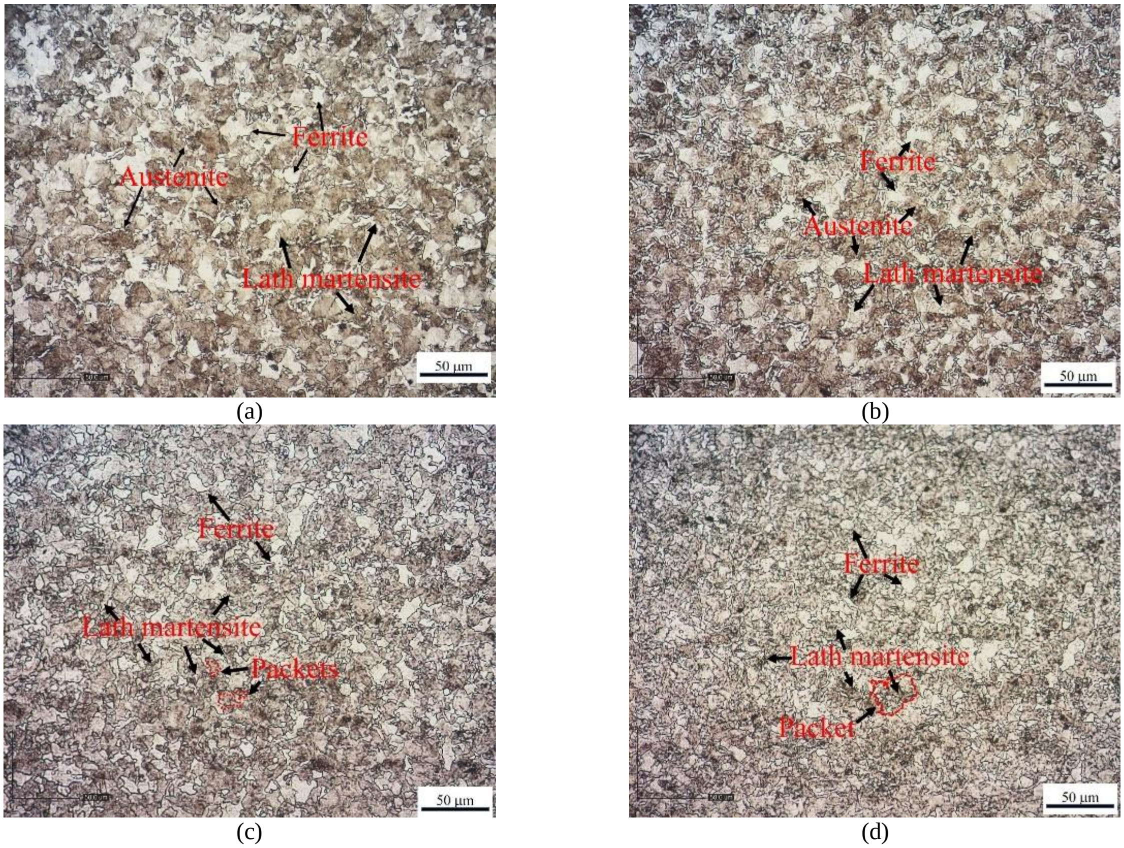

FIGURE 5. Optical microstructures of AISI 4140 steel in: (a) SQ, (b) DQ, (c) SQT and (d) DQT conditions

CONCLUSION

The optimum double quenching and tempering heat treatment process for the investigated AISI 4140 steel in annealing condition exhibits a better combination of tensile steel properties, namely, tensile strength of 886.01 MPa, yield strength of 654.16 MPa, the elastic modulus of 216.0 GPa and the elongation of 15.2%. Typical tempered lath martensite structure can be refined by DQT heat treatment. In addition, the coarser grains consisting of austenite and lath martensite structures in microstructure of the quenched-tempered steel heat treatment were effectively refined by DQT treatment. The microstructural refinement of lath tempered martensitic steel is effective in increasing the tensile properties of AISI 4140 steel. The increase in the tensile strength of AISI 4140 can be attributed to effectively impedes movement dislocation resulted by combination of finer lath martensite structure in solid solution and packets crystal in ferrite matrix.

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