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The effect of single and double quenching and tempering heat treatments on the microstructure and mechanical properties of AISI 4140 steel

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ABSTRACT

This investigation is concerned to evaluate the effect of double quenching and tempering (DQT) with conventional quenching and tempering (CQT) heat treatment processes on microstructure and mechanical behavior of a commercially developed hot rolled AISI 4140 type steel. Comparison of microstructure and mechanical properties of DQT and CQT heat treated specimens have been established in details. Optical and scanning electron microscopies have been used to follow impurity concentration and microstructural changes, and their relation to the associated mechanical properties. The results indicate that the improvement of mechanical properties particularly impact toughness of DQT heat treated specimens is much higher than that of the CQT condition, and this observation is rationalized in terms of finer austenite grain size developed in the DQT condition providing much finer martensitic packets within the grains and a lower level of impurity concentration of sulfur (S) and phosphorus (P) near the prior austenite grain boundaries as well.

1. Introduction

The influence of microstructure on mechanical properties of low alloy steels has been a subject of considerable research interest in physical metallurgy [1–3]. The coarse microstructure of conventionally developed hot rolled ferritic/pearlitic plain carbon steels often makes it impossible to obtain concurrently good ductility, toughness and high strength. Evolution of newer steel with improved combinations of strength, ductility and toughness has led to the emergence of a series of multi-phase or ultra-fine grained high strength low alloy steels [4–6]. Some industrial applications, especially transportations are still demanding economical higher strength steels with good ductility and impact toughness in order to lighten structural parts [7–10]. It is well known fact that the mechanical properties of low alloy steels can be improved by austenite grain refinement. The refinement of microstructure in quenched and tempered martensitic steels is expected to improve both strength and toughness especially the latter. Lath martensitic structures usually have a higher strength, and improving toughness of lath martensitic heat treatable low alloy steels is a major concern, especially for industrial applications used at low temperatures. To achieve even a higher combination of strength and toughness in quench and tempered low alloy steels by heat treatment, refinement of the austenite grain has to be predominantly carried out by considering the microalloying addition, cyclic heating, starting microstructure, austenitization temperature and holding time at the austenitizing temperature. These factors are related to each other during heat treatment and only the overall effect can be determined from the prior austenite grain size measurements. Besides microalloying addition and thermal cyclic treatments, the formation of austenite grain from various starting microstructure is also another attractive technique adopted in industry to refine the microstructure. Speich and Szirmate investigated the formation of austenite grain formation from the various starting microstructures consisting of polygonal ferrite, spheroidized cementite particles with ferrite, and pearlite [11]. They found that the refinement of prior austenite grain could be achieved by pearlite structure and the beneficial effect of pearlite on the austenite refinements were attributed to the preferred higher interfacial boundaries developed between the closely spaced ferrite and cementite lamellae reduce the diffusion distances of carbon and iron atoms for austenite formation. Earlier study showed that a double quenching heat treatment process resulted in a significant improvement of strength and toughness by 40% of austenite grain refinement in a bearing AISI 52100 steel [12]. With respect to the differences in high energy carbide interfacial boundaries found between ferrite, pearlite, bainite and martensite initial microstructures, Krauss suggested that the prior austenite grain size can be controlled from a starting microstructure by new austenite grain formation at the preferential high energy nucleation sites [13]. Therefore, these starting microstructures should be carefully examined in order to investigate the separate effect of each microstructure on the prior austenite grain size

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refinement. In this study, the austenite grain refinement from various pre-treated microstructures (hot rolled ferrite/pearlite and low temperature tempered martensite) has been investigated. The objective of this paper is to study the correlation between microstructure and mechanical behavior of DQT heat treated specimens particularly in comparison to the CQT standard condition in an AISI 4140 steel.

2. Material and experimental procedures

2.1. Material preparation

The AISI 4140 steel used in the present study was developed by Iranian Alloy Steel Co, Yazd, Iran. The melt steel was refined by various methods to reduce the level of impurities such as sulfur and phosphorous. The diameter of bar was 25 mm and the chemical composition is given in Table 1.

2.2. Heat treatment processes

The oversized Charpy and tensile specimens were cut from the as received 25 mm ϕ steel rod, and a small hole was drilled at the end of each specimen to locate a thermocouple for recording the temperature. The CQT and DQT heat treatment processes are schematically compared in Fig. 1. Specimens were furnace heated to 860 °C and soaking for 60 min, followed by 80 °C hot oil quenching. The CQT heat treated specimens were finalized tempering at 600 °C for 30 min to achieve a high level of tensile strength and toughness. The DQT heat treatment process consists of two stages of austenitizing, quenching and tempering. To achieve a more homogenizing and refining prior austenite grain, the first tempering stage was performed at a lower temperature of 300 °C for 60 min. The finalized tempering was carried out at a higher temperature of 600 °C for 30 min because of the similarity to that of CQT standard condition.

Table 1
Chemical composition (in wt%) of the AISI 4140 steel investigated.

%C	%Si	%Mn	%P	%S	%Cr	%Mo	%Fe
0.42	0.2	0.79	0.014	0.023	1.07	0.185	Bal.

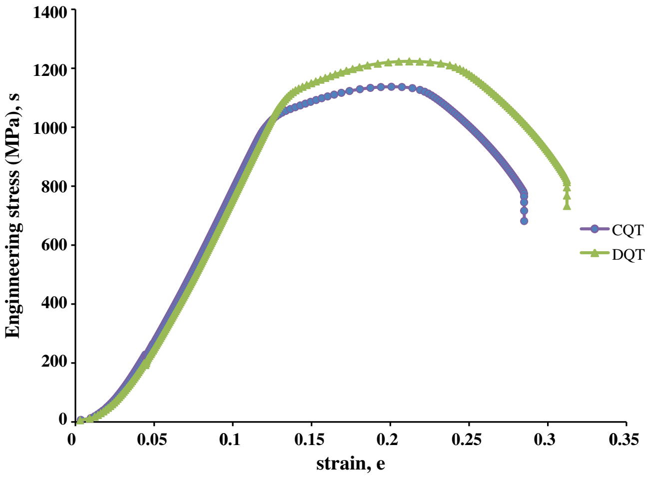

Fig. 2. The engineering stress–strain behavior of CQT and DQT specimens.

2.3. Test methods

To remove oxide and decarburized layers, the machining of finalized specimen size was carried out after all of the heat treatment processes. The mechanical properties including tensile strengths, elongation, reduction in cross-section area, Charpy impact energy and hardness were measured using the average of three experimental results for each heat treatment process. Hardness measurements were done by Rockwell method and reported as RC hardness numbers in accordance with ASTM E18 standards [14]. The size and geometry of the specimens as well as the testing procedure are based on the ASTM E8 standards for tension testing using an Instron test machine, model 5586 [15]. Room temperature Charpy V-notch (CVN) impact testing was also conducted in the *L–T* direction according to ASTM E23 standard condition [16]. The light microscopy specimens were prepared based on the ASTM E3 standard using a 2% nital solution for revealing general microstructural observation under optical microscopy [17]. To detect the prior austenite grains, the Viella etchant reagent was also used. The austenite grain size analysis was carried out by intercept method according to ASTM E112 standard condition using a light optical microscope incorporated with Clemex image analyzing software [18]. Almost 100 grains were selected by the software for grain size measurements. The X-ray diffraction (XRD) analysis was carried out with a Philips X'pert High score X-ray diffractometer using a Kα Cu ($\lambda = 1.5405$ Å) radiation to determine the multiphase microstructures developed in the DQT specimens after first stage of quenching and tempering at low temperature of 300 °C.

The fracture surfaces of impact tested specimens were examined under scanning electron microscope (SEM) model TESCAN-VEGA-II at an accelerating voltage of 15 kV for fractography. An analysis of chemical composition for the nonmetallic inclusions discovered in the fracture surfaces was carried out with energy-

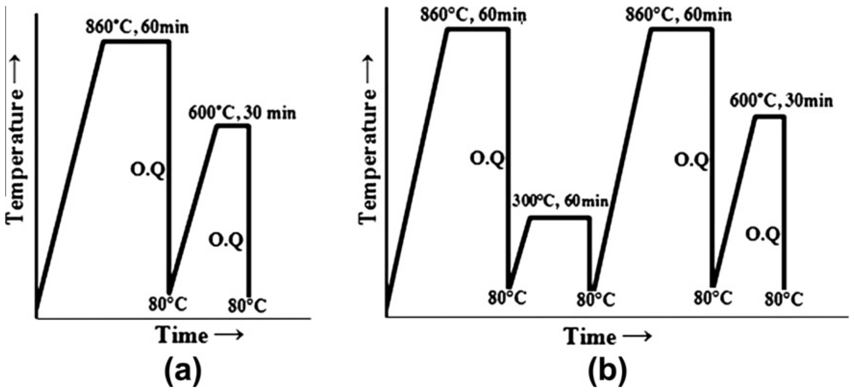

Fig. 1. Schematic representation of heat treatment processes: (a) CQT and (b) DQT.