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Abnormal mechanical behavior of a medium-carbon steel under strong ferrite-pearlite-martensite triple-phase microstructures

A. Sabet Ghorabaei*, S.S. Ghasemi Banadkouki

Department of Mining and Metallurgical Engineering, Yazd University, Safayieh, Daneshgah Blvd, University Main Campus, P.O. Box 89195-741, Yazd, Iran

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ABSTRACT

Understanding the relationships between the structure and mechanical properties of steel, which can be difficult to determine, is important to design and develop various high-strength, multi-phase steels. In the present work, the structure-property relationships of a medium-carbon AISI 1045 steel with ferrite-pearlite-martensite triple-phase (TP) microstructures are investigated and compared to those with ferrite-martensite dual-phase (DP) microstructures. Various step-quenching heat treatment cycles were carried out at 650 °C for different holding times, followed by subsequent water quenching after reaustenitization of the samples at 860 °C for 30 min. Optical microscopy and field-emission scanning electron microscopy equipped with X-ray energy dispersive spectroscopy were used along with macrohardness, tensile, and nanoindentation tests to perform a detailed investigation of the structure-property relationships of the heat-treated samples. An abnormal mechanical behavior due to pearlite formation was observed in the ferrite-pearlite-martensite TP samples in comparison to the ferrite-martensite DP samples. The ferrite-pearlite-martensite TP samples consisting of more than 71% martensite were associated with a higher level of mechanical properties compared to those of the ferrite-martensite DP samples. The results are rationalized in part by the increased hardening response of 50.7% of the constrained pearlite in the TP microstructures induced by the martensitic phase transformation in conjunction with the lower ferrite hardening response of 22.6% in the DP samples.

1. Introduction

The influence of microstructures on the mechanical properties of low-alloy steels has been a long-established and interesting research area in physical metallurgy. In fact, the potential of low-alloy steels to achieve various microstructures with heat treatment cycles is an attractive consideration to further investigate the design and development of various high-strength, multi-phase steels. Among these studies, there are many works performed on the characterization of the microstructural features and mechanical properties of low-alloy, ferrite-martensite, dual-phase (DP) steels [1–14]. Samuel [2] investigated the detailed role of the microconstituent morphology and carbon concentration in the microstructure and mechanical behavior of a low-alloy steel with ferrite-martensite DP conditions, reporting the effect of different microconstituent morphologies on mechanical properties of various heat-treated microstructures. In [9], the characterization results of the structure-property relationships in a commercial grade AISI 4140 steel compared to tempered full-martensite microstructures showed that the optimized mechanical properties were developed in a ferrite-martensite DP microstructure consisting of 7% tough-strong continuous grain boundary ferrite accompanied with the remaining martensite areas. These abnormal variations in the mechanical properties of the ferrite-martensite DP steels have also been reported by several other investigators [11–13]. These works considered the inherent nature of individual ferrite and martensite hardening responses, causing different mechanical behaviors of ferrite-martensite DP steels.

For low-alloy triple-phase (TP) steels, there are contradicting experimental results concerning the structure-property relationships of ferrite-bainite-martensite TP microstructures [15–17]. In a low-alloy grade AISI 4340 steel, it was reported that an increase in the martensite volume fraction increased the hardness, yield, and ultimate tensile strengths under ferrite-bainite-martensite TP conditions [15]. In contrast to this study, it was shown that the yield and ultimate tensile strengths decreased with an increase in the martensite volume fraction in a low-alloy ferrite-bainite-martensite TP steel [16]. The study performed by Zare and Ekrami [17] investigated the effects of the martensite volume fraction on the tensile properties of a low-alloy steel with ferrite-bainite-martensite TP microstructures. They reported that the yield ratio (yield strength/ultimate tensile strength) decreased with an increase in the martensite volume fraction as a consequence of the

* Corresponding author.
E-mail address: amir.sabet_1992@yahoo.com (A. Sabet Ghorabaei).

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Table 1
The chemical composition of the investigated AISI 1045 steel (in wt%).

% C	% Si	% Mn	% S	% P	% Fe
0.411	0.225	0.624	0.018	0.017	Balance

higher internal stresses and increased density of transformational dislocations generated within the ferrite accompanied with increase in the martensite volume fraction. These research studies clearly indicate that there is no clear consensus among the volume fractions of the microconstituents and the mechanical properties of multi-phase steels due to governing complex interactions among the various microphases. Therefore, it is interesting to further study the structure-property relationships of medium-carbon steels under DP and TP microstructures. In the present paper, the effects of pearlite as a third microstructural constituent on the mechanical behavior of ferrite-pearlite-martensite TP microstructures are investigated in detail and compared to that of the ferrite-martensite DP samples using a commercial grade medium-carbon AISI 1045 steel.

2. Materials and experimental procedure

The steel used in this investigation was a 5-mm thick commercial grade hot rolled AISI 1045 medium-carbon sheet sample with the chemical composition that is shown in Table 1.

The heat treatment schedules were designed to achieve multi-phase microstructures with different ferrite, pearlite, and martensite microconstituent volume fractions. The samples were first austenitized at 860 °C for 30 min and then air-cooled (normalized) to room temperature to develop initial homogeneous microstructural features in the proposed heat-treated samples. After reaustenitizing at 860 °C for 30 min, the samples were immediately step-quenched (SQ) in a salt bath at 650 °C and soaked isothermally for holding times of 7, 12, 15, and 30 s for partial decomposition of the austenite to various volume fractions of ferrite and pearlite microconstituents. Then, these samples were water-quenched to achieve martensite from the remaining prior metastable austenite regions. The associated samples were marked as SQ7, SQ12, SQ15, and SQ30, respectively. The full martensitic microstructures were also prepared by direct water quenching of some specified samples from an 860 °C reaustenitizing temperature and symbolized as WQ (water-quenched). The schematic diagrams of the heat treatment cycles with the associated symbol for each group of samples are shown in Fig. 1.

The metallography of the heat-treated samples was carried out on the transverse section relative to the rolling direction of the as-received sheet sample according to the ASTM E 3 standard. Polished samples were etched with a 2% Nital solution (2 ml HNO_3 and 98 ml C_2H_5OH) [18] to reveal the various microstructural features. The microstructures

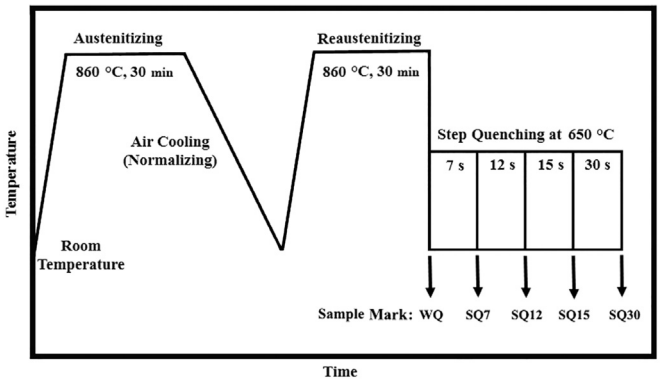

Fig. 1. Schematic diagrams of the heat treatment cycles with the associated mark for each group of samples.

were characterized using an Olympus-PMG3 optical microscope and a TESCAN-MIRA 3-XMU field-emission scanning electron microscope (FE-SEM) operating at an accelerated voltage of 15 kV. The micrographs were analyzed and the associated volume fractions of the microconstituents were estimated using the manual point count method according to the ASTM E 562 standard condition. To qualitatively compare the level of carbon partitioning that was developed during the isothermal phase transformation of the prior austenite regions at a step quenching temperature of 650 °C, the spot-line scanning carbon analysis was carried out at various locations of the ferrite, pearlite, and martensite microconstituents using the energy dispersive X-ray spectroscopy (EDS) technique.

The Vickers macrohardness measurement with a load of 30 kgf was conducted on the heat-treated samples based on the ASTM E 92 standard using an Instron Wolpert GmbH-DIA-Testor 722 universal hardness tester machine. The tensile samples were cut off relative to the rolling direction of the as-received sheet sample according to the ASTM E 8 M standard conditions. Tensile tests were performed using an STM-150 universal servo electromechanical Santam testing machine with a crosshead speed of 5 mm/min. An average of three measurements was considered for the results of each macrohardness and tensile test.

In order to investigate the hardening response of each microstructural constituent, nanoindentation tests were performed based on the Oliver and Pharr method [19] compliant to the ASTM E 2546 standard. An NHTX S/N: 01–03119 CSM instrument equipped with a Berkovich triangular pyramid indenter was utilized, using a peak load of 10 mN and loading/unloading rate of 20 mN/min. The indentation hardness (H_{IT}) was reported as a nanohardness value, averaged over three nanohardness measurements. Seven different locations were considered for nanoindenting as follows: 1) in the interior region of a ferrite grain; 2) in the interior region of a pearlite colony; 3) in the interior region of a martensite area; 4) in a ferrite grain close to the ferrite/martensite interfaces; 5) in a pearlite colony close to the pearlite/martensite interfaces; 6) in a martensite region close to the martensite/ferrite interfaces; and 7) in a martensite region close to the martensite/pearlite interfaces. The associated locations were marked as F, P, M, F_M, P_M, M_F, and M_P, respectively. For a detailed comparison of the hardening response of each microstructural constituent, a ratio was defined as follows:

$$HR^{x_y} = (H_{IT}^{x_y} - H_{IT}^{x})/H_{IT}^{x} \quad (1)$$

where HR^{x_y} is the hardening ratio of microconstituent "x" located adjacent to microconstituent "y", $H_{IT}^{x_y}$ is the nanohardness of microconstituent "x" measured close to the interface with microconstituent "y", and H_{IT}^{x} is the nanohardness value in the interior region of microconstituent "x", far from the surrounding interfaces.

3. Results

3.1. Optical micrographs and microstructural analysis

Fig. 2 shows typical light micrographs taken from various SQ heat-treated samples. Ferrite and martensite microconstituents that create the ferrite-martensite DP microstructures were observed in the microstructures of the SQ7 and SQ12 samples. The morphology of the ferrite grains in the SQ7 marked samples was observed to have more block-like features surrounded by the martensitic regions. After maintaining a longer isothermal holding time of 12 s at 650 °C, the continuous grain boundary ferrite formation increased in the microstructures (SQ12 in Fig. 2). Further isothermal transformation of the metastable austenite from 12 to 15 s caused the microstructural features to change from ferrite-martensite DP microconstituents to ferrite-pearlite-martensite TP features, in which the pearlite colonies nucleated and grew from carbon-enriched austenite areas adjacent to the ferrite/prior austenite interfaces (SQ15 with yellow dashed circles in Fig. 2). Maintaining a