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Impact toughness of an S700MC-type steel: Tempforming vs ausforming

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ABSTRACT

The effect of different thermomechanical treatments, i.e., ausforming and tempforming, on the microstructure and mechanical properties including impact fracture behavior of high-strength low-carbon S700MC-type steel was investigated. The tempforming resulted in the development of ultrafine grained elongated grain microstructure with the transverse grain size of 530 nm, whereas the ausforming led to the formation of typical tempered martensite structure with a distance between high-angle boundaries of 1.5 µm. The tempered microstructures involved the formation of carbides with an average particle size about 50 nm and M(C, N)-type carbonitrides with average size of 10 nm. The tempformed steel exhibited the ultimate tensile strength of 1110 MPa and the impact toughness, KCV, above 450 J/cm^2 at a temperature of 293 K, and KCV of 109 J/cm^2 at liquid nitrogen temperature for impact direction perpendicular to rolling plane. In contrast, KCV of the ausformed steel was 180 and 10 J/cm^2 at 293 and 77 K, respectively. The enhancement of toughness was associated with delamination cracks which occurred in the ultrafine elongated grain structure with anisotropic properties.

1. Introduction

High-strength low-alloy (HSLA) steels are widely used materials due to their low cost and good combinations of strength, ductility and toughness [1–3]. However, this type of steels with high strength typically exhibits low Charpy V-notch impact energy of 10–40 J at lowered temperatures [1–3]. Such low toughness often limits their structural applications. Structural steels have to be both strong and tough. These steels could not be used at temperatures below the ductile-brittle transition temperature (DBTT), at which the steel loses its toughness and fracture occurs in a brittle mode. The grain refinement is one of the most promising approaches to decrease DBTT concurrently with strengthening of structural steels and alloys [4–7]. The ultrafine grained structure decreases the stress concentration at grain boundaries, especially at triple junctions [7].

The water-cooled thermo-mechanical processes are widely used to obtain high strength and superior toughness in HSLA steels through grain refinement [5]. The direct water spray quenching after controlled rolling results in martensite structures in HSLA steels. The lath martensite consists of prior austenite grains, packet, blocks and laths with high dislocation densities [3,8–10]. The use of thermo-mechanical process with direct quenching (ausforming) allows remarkable refinement of the martensite structural elements [5]. Other effective methods for grain refinement involve cold rolling of martensite followed by annealing or warm rolling of tempered martensite [10,11]. However, the strengthening by refining the grain size to 1 µm or less tends to degrade the tensile ductility and toughness [8]. An interesting approach to increase the toughness and decrease DBTT of HSLA steels was proposed by Kimura et al. [12]. This method consists of the formation of a lamellar structure with the transverse grain size of about 100 nm and a uniform distribution of dispersed nanosized particles of secondary phases in steels owing to specific thermo-mechanical processing, i.e., tempforming, which allows obtaining a promising combination of mechanical properties in low-alloyed steels. It is worth noting that thermomechanical processing with accelerated cooling can produce the same structure in low-carbon steels [5]. Therefore, tempforming and ausforming allow obtaining a superior combination of strength and toughness in low-alloyed steels. In particular, the tempformed steels exhibit delamination phenomenon, which improves the toughness at low temperatures [14–16]. Delamination results from anisotropic microstructures, i.e., the grains/subgrains highly elongated along the rolling direction (RD) and the second phase particles precipitated at the longitudinal grain/subgrain boundaries. Delamination was observed in various structural steels and alloys [12,17–29], leading to so-called delamination toughening. The delamination toughening can decrease DBTT in low-alloy steels by reducing the triaxial stress concentration at the crack tip [18–22,25,26]. The dominating factors controlling the delamination toughening are considered to be the ultrafine grains, the grain shape and the ⟨110⟩ || RD fiber texture [9,13,22,23,29–31], which vary depending on the starting microstructure [9,23] and the

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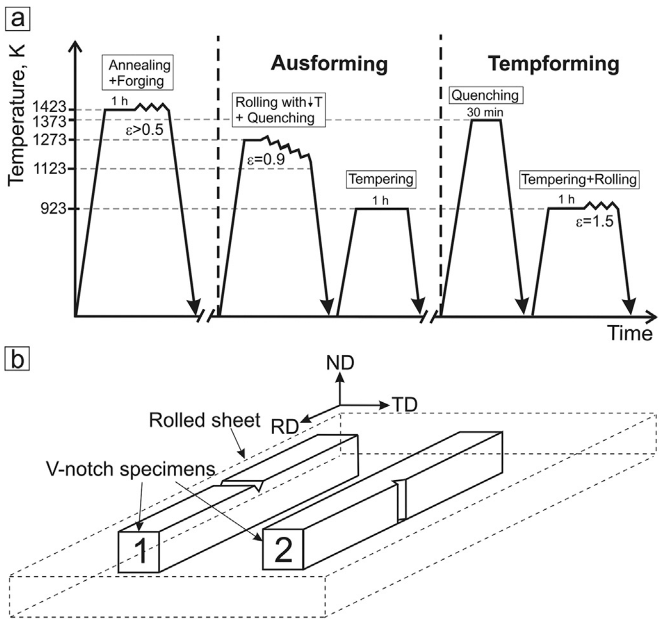

Fig. 1. Schematic diagrams illustrating the routes of thermo-mechanical processing (a) and the specimen orientations for impact tests (b).

processing conditions, such as rolling temperature and rolling reduction [9,22].

The aim of the present paper is to study the effect of thermo-mechanical processing route on the fracture toughness of an S700MC-type low-alloy steel over a range of temperatures from 293 K to 77 K. In order to understand the underlying mechanisms of fracture, the microstructure and mechanical properties of the steel subjected to tempforming and ausforming were comparatively analyzed.

2. Experimental

A high-strength low-alloy steel of S700MC-type with a chemical composition of Fe – 0.09C – 0.12Si – 1.19Cr – 1.55Mn – 0.003P – .005S – 0.05 Nb – 0.025Al – 0.05Ti – 0.42Mo – 0.09V – 0.003B (all in mass%) was subjected to homogenization annealing followed by hot forging at a temperature of 1423 K. Two different routes of thermo-mechanical processing were chosen (Fig. 1a). The first method was ausforming consisting of rolling with decreasing temperature from 1273 K to 1123 K to a total strain of 0.9 followed by quenching and tempering at 923 K for 1 h. The second method included quenching from 1373 K, tempering at 923 K for 1 h and rolling at tempering temperature (tempforming) to a total strain of 1.5.

The structural observations were performed on the RD-ND sections (RD is the rolling direction, ND is the normal direction), using a Quanta Nova Nanosem 450 scanning electron microscope (SEM) with an electron back scattering diffraction (EBSD) analyzer incorporating an orientation imaging microscopy (OIM) system and a Jeol JEM 2100 transmission electron microscope (TEM). The samples for structural characterizations were electro-polished using an electrolyte containing 10% perchloric acid and 90% acetic acid at a voltage of 20 V at room temperature. The OIM images were subjected to clean up procedure setting minimal confidence index of 0.1. The mean grain size was evaluated on the OIM micrographs as an average distance between high-angle boundaries with misorientations of $\theta \geq 15^\circ$. In addition to OIM, the misorientations between the grains/subgrains were analyzed by the conventional TEM Kikuchi line method using the converged-beam technique [31]. The lath/subgrain sizes were measured on TEM micrographs by the liner intercept method, including all clear visible boundaries and subboundaries. The dislocation density was evaluated by counting individual dislocations inside the laths/subgrains on representative TEM images.

Tensile tests were carried out using an Instron 5882 testing machine. The tensile specimens with gauge dimensions of 12 mm in length, 3 mm in width, 1.5 mm in thickness were prepared with the tensile direction along RD. The specimens were tested at ambient temperature at a crosshead rate of 2 mm/min. Standard Charpy V-notch specimens were tested using an Instron 450 J impact machine (Model SI-1M) with an Instron Dynatup Impulse data acquisition system at temperatures ranging from 77 to 293 K. The specimens for impact test were cut out as shown in Fig. 1b, where the sample 1 is that for the impact direction along ND (impact test ||ND) and the sample 2 is that for the impact along TD (impact test ||TD).

3. Results

3.1. Microstructure characterization

Typical microstructures of the present steel subjected to different treatments are shown in Fig. 2. The structural parameters for the S700MC-type steel samples after ausforming and tempforming are summarized in Table 1. The ausforming resulted in the development of tempered martensite lath structure, in which prior austenite grains are subdivided into packets and blocks of martensite laths [10] (Fig. 2a). The mean sizes of the prior austenite grains and martensite blocks are about 20 μm and 1.5 μm, respectively. On the other hand, the tempforming led to the evolution of ultrafine grained microstructure consisting of grains elongated along RD. The mean transverse grain size is 530 nm (Fig. 2b). The tempformed steel is characterized by strong ⟨001⟩ ||ND and ⟨111⟩ ||ND fiber textures (corresponding to red and blue colors, respectively, in Fig. 2b). It was shown that intensity of the {100}⟨110⟩ texture increases in low-carbon steels during multi-pass warm plate rolling at temperatures of 813 – 923 K [13,28]. Indeed, the highest relative intensity of 5 was obtained for ⟨001⟩ ||ND texture component.

The TEM images of the S700MC-type steel subjected to ausforming and tempforming are shown in Figs. 2c and 2d. The ausformed microstructure consists of elongated martensite laths with rather high dislocation density of 5×10^{14} m^{-2}. The transverse lath size comprises approx. 200 nm and the misorientations between the laths are mostly below 3 degrees (Fig. 2c). The tempforming resulted in the development of thin lamellar structure with an average transverse subgrain size of 100 nm and the dislocation density of 8×10^{14} m^{-2}. The boundaries between the elongated grains/subgrains are represented by a mixture of low-to-high angle (sub)boundaries (Fig. 2d). It is worth noting that there are many subboundaries with relatively large misorientations close to 15°. The laths developed by quenching and tempering further increase their misorientations during tempforming, i.e., warm rolling at 923 K to a total true strain of 1.5. The main difference between two structural conditions consists in the size and shape of the blocks being aggregations of the laths with the same crystallographic orientation. Tempforming provides lamellar block shape and refines the thickness of blocks.

Both ausformed and tempformed microstructures are characterized by the formation of dispersed carbides at various boundaries/subboundaries of laths, blocks, packets and prior austenite grains. Typical examples of $Cr_{23}C_6$-type carbides are shown in Figs. 3a and 3b. In addition, M(C, N) carbonitrides with an average size of 10 nm precipitate throughout the tempered martensite. As shown on Fig. 3c the carbide particle sizes range from 7 to 160 nm, and an average size is about 50 nm after both treatments. It is clearly seen that the particle size distributions have maximums in the range of 40–50 nm irrespective of ausforming/tempforming treatment, although tempforming provides more homogeneous carbide distribution (sharper peak in Fig. 3c). It should be noted that the precipitations in the present steel samples and those evolved in low-carbon steels subjected to the thermo-mechanical control process are nearly the same [5].