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Influence of thermal deformation conditions on the microstructure and mechanical properties of boron steel

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ABSTRACT

The influence of thermal deformation conditions on the microstructure and mechanical properties of B1500HS boron steel was investigated based on a series of isothermal uniaxial tensile tests. The relationship model between work hardening rate and temperature and strain rate was established on the basis of Johnson Cook constitutive model. Moreover, the equation of the temperature rise caused by plastic deformation was modified by introducing the conversion efficiency of deformation work to heat. Next, the effects of deformation conditions (temperature and strain rate) on the volume fraction of martensite and ferrite were studied by metallographic observation. It was found that a higher strain rate brought out the martensite lath with a shorter length and thus a better ductility, and the ferrite transformation was restrained at the higher strain rate. Finally, the hardness and dislocation densities of the boron steel were detected by Vickers micro-hardness and X-ray diffraction (XRD) tests, respectively. The dislocation densities of the boron steel were quantitatively characterized by analyzing the XRD peak profiles according to the Williamson–Hall (WH) method. The results show that deformation temperature and strain rate have a similar influence on the dislocation density and micro-hardness, and hence the relationship of dislocation density and micro-hardness was deduced.

1. Introduction

The demand for coupling performances with reductions of cost, weight, fuel consumption and air pollution and improvement of safety in the automotive industry is stronger and stronger [1,2]. Compared to the other lightweight material and process, such as aluminum alloy [3] and tailor welded blank (TWB) [4,5], the application of hot stamping or press hardening of high strength boron steel on automotive structural components is also a solution to meet these requirements, due to prominent formability, low springback and ultrahigh strength [6,7]. Hot stamping is such a process that the austenitized blank is transferred to the press and subsequently stamped and quenched in a closed water-cooled die for martensitic transformation [8]. The final parts can have the objective tensile strength over 1500 MPa.

In hot stamping process, the property and quality of the final automotive products are affected by the thermal-mechanical properties and microstructures of the boron or non-boron steels. In recent years, many researchers have focused on the process modification of the hot stamping process. Gorriño et al. [9] have studied the influence of the stamping pressure on the interfacial heat transfer coefficient (IHTC). Zhang et al. [10] have analyzed the effect of contact state between the blank and the mold on the mechanical properties of the ultrahigh strength steel. Wang et al. [11] have demonstrated that the initial stamping temperature should be above 750 °C, and the holding and quenching time should be up to 15 s in hot stamping process according to the finite element (FE) simulation. Naderi et al. [12] have investigated the mechanical properties and phase transformation of four high strength non-boron alloyed steels which were hot stamped using water and nitrogen cooling media. Ikeuchi et al. [13] have proposed a new valuation method used to measure the effects of hot stamping conditions on product properties as a function of process parameters.

Besides, several researchers investigated the properties and microstructure evolution of boron steel in isothermal and non-isothermal conditions through tension of sheet or compression of cylindrical bar. Abbasi et al. [14] evaluated the influence of isothermal and non-isothermal thermo-mechanical processes on the phase transformations and the final microstructure and mechanical properties of 22MnB5 steel. Min et al. [15] studied the effect of thermal-mechanical process on the microstructure and secondary-deformation behavior of 22MnB5 steels and he found that the appearance of deformation induced ferrite (DIF)

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decreased the yield strength and UTS but increased the elongation of the hot deformed 22MnB5 steel. In the study of 22SiMn2TiB, a kind of high strength steel like 22MnB5, Shi et al. [16] reported that the deformation of austenite at the temperature above 850 °C strengthened the ausformed martensite, while the diffusion transformation was accelerated at the temperature below 800 °C. Nikravesh et al. [17] investigated the influence of hot plastic deformation and cooling rate on martensite and bainite start temperatures (M_s and B_s) in 22MnB5 steel during non-isothermal deformation, and it was concluded that hot plastic deformation decreased M_s and increased B_s especially at lower cooling rates. Further study by Nikravesh et al. [18] showed that the amount of military phases decreased resulted from mechanical stabilization of austenite during the deformation process while bainite and reconstructive transformations, especially ferrite were promoted. Li et al. [19] established a set of unified viscoplastic damage constitutive equations to model the features of fracture and strain hardening of boron steel by isothermal uniaxial tension tests.

It can be seen from the aforementioned literatures that the researches mainly focused on the effect of microstructure on mechanical properties and martensitic transformation. Very few literatures involve the effect of the plastic deformation heat on the deformation behavior of boron steel, and the ferrite transformation has not been thoroughly studied. Besides, it is still in the stage of qualitative analysis by transmission electron microscopy (TEM) to explain the deformation mechanism from dislocation density. Therefore, a comprehensive investigation of the effects of hot deformation conditions on the microstructure and mechanical properties of the B1500HS boron steel is still needed.

In this performed paper, the effects of thermal deformation conditions on the mechanical properties of the B1500HS boron steel were investigated isothermally by the uniaxial tensile test. The microstructure evolution, especially for martensite and ferrite, at various deformation conditions was also analyzed. A relationship model was established to correlate the micro-hardness and the dislocation densities based on the Williamson–Hall (WH) method.

2. Experimental procedure

The chemical composition (wt%) of B1500HS boron steel with a thickness of 1.6 mm used in the present study is 0.23C, 0.25Si, 1.35Mn, 0.19Cr, 0.003B, 0.04Ti, 0.04Mo. The microstructure of as-delivered plates consists of ferrite and pearlite (show in Fig. 1) with a hardness value of 166 HV. According to GB/T4338-2006, the dimensions of the tensile specimens are illustrated in Fig. 2, and the length direction is along the rolling direction. All specimens used for the experiment were machined from the same cold rolled boron steel sheet. In order to control the heating rate and deformation temperature, a pair of K-type

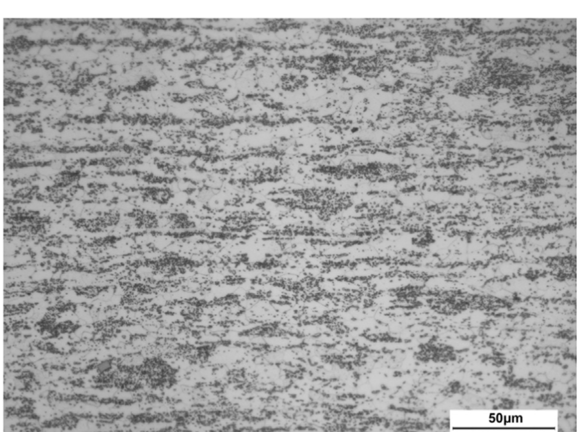

Fig. 1. Optical micrograph of the initial microstructure of B1500HS (Ferrite: White, Perlite: Black).

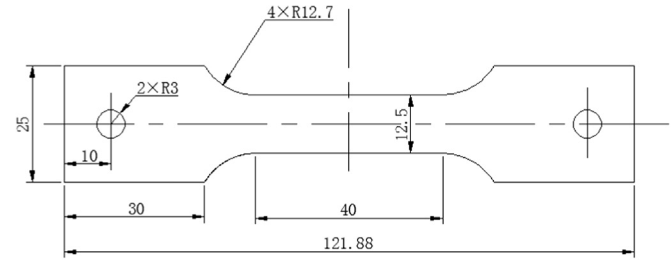

Fig. 2. Illustration for dimensions of the tensile specimen (mm).

thermocouples was welded to the centre of the test piece surface.

The B1500HS boron steel is in the austenite single phase region when the temperature is above A_{e3} (the equilibrium temperature between the austenite and ferrite phases), and the steel locates at the austenite-ferrite phase region when the temperature ranges from A_{e3} to B_s (the bainite start temperature). B_s and A_{e3} for isothermal transformation, being equal to 569 and 810 °C, respectively, depending on the chemical composition (in mass percent) of the boron steel, are considered. The computational formulas are shown in Eq. (1) [20] and Eq. (2) [21]:

$$B_s(°C) = 656 - 58\omega_c - 35\omega_{Mn} - 75\omega_{Si} - 15\omega_{Ni} - 34\omega_{Cr} - 41\omega_{Mo} \tag{1}$$

$$\begin{aligned} A_{e3}(°C) \quad = \quad & 912 - 203\sqrt{\omega_c} - 15.2\omega_{Ni} + 44.7\omega_{Si} + 104\omega_V + 31.5\omega_{Mo} \\ & + 13.1\omega_w - 30\omega_{Mn} - 11\omega_{Cr} - 20\omega_{Cu} + 700\omega_P \\ & + 400\omega_{Al} + 120\omega_{As} + 400\omega_{Ti} \end{aligned} \tag{2}$$

where ω is the chemical composition (in mass percent) of the steel. Therefore, four temperatures, i.e., 600, 700, 800, 900 °C, were selected for executing the tensile test.

The schematic diagram of the isothermal progresses is shown in Fig. 3. The isothermal uniaxial tensile tests were carried out at deformation temperatures of 600, 700, 800 and 900 °C with strain rates of 0.01, 0.1, 1 and 10 s^{-1}, respectively, on the Gleeble 3500 thermal-mechanical simulation system. The plate specimens (Fig. 3a) were first heated up into austenite region at 950 °C with a rate of 10 °C/s and held for 5 min to obtain full austenite, and then cooled down in the air to the deformation temperatures T_1 (600–900 °C). Hereby the process for tensile test was analogous to the actual production process from furnace to press. Once the chosen test temperature was reached, the specimen was deformed isothermally to failure with a specified strain rate (Fig. 3b). After deformation, the specimens were quenched with spraying water to room temperature at a cooling rate of higher than 30 °C/s.

Samples with dimensions of 3 mm × 5 mm, as shown in Fig. 3b, were cut from the homogenous deformation zone on the specimens by wire-electrode cutting. The 3 mm direction is the major strain direction. The samples were ground using abrasive paper, polished by woolen

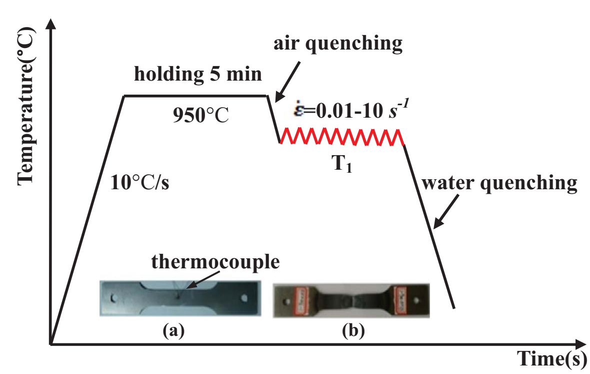

Fig. 3. Schematic procedure and specimens (a) before and (b)after isothermal forming.