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Microstructure and mechanical properties of a 2000 MPa grade ultrahigh strength boron steel

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Abstract. Press hardening steels (PHS) with very high strength are current key materials for lightweight engineering solutions and corresponding CO_2 savings. In the present study, the microstructure and mechanical properties of a 2000 MPa grade ultrahigh strength boron steel for hot stamping were reported. Microstructure evolution experiment revealed that the microstructure of the 2000 MPa grade PHS only consisted of martensite when the cooling rate increased to 20 °C/s. The prior austenite grain size was about 6.8 μm when the sample was austenitized at 900 °C for 300 seconds. The appropriate isothermal quenching process should be austenitized between 900 °C and 950 °C during hot stamping because there is an abnormal grain growth of austenite grains at 950 °C. Following the optimal hot stamping condition, the 2000 MPa grade PHS alloy demonstrated yield strength in excess of 1300 MPa and ultimate tensile strength in excess of 2000 MPa together with a total elongation of about 7%.
Keywords. press hardening steel; microstructure; tensile strength; total elongation

1. Introduction

Press hardening steel (PHS) 22MnB5 with an ultimate tensile strength of 1500 MPa and a total elongation of 5%~7% is widely used as current key engineering material for lightweight engineering solutions and corresponding CO_2 savings [1-3]. For hot stamping technology, during the hot stamping progress, the steel blanks are heated at approximately 900~950 °C in a furnace to achieve a homogenous austenitic microstructure; transferred to press and rapidly quenched by dies with water system and formed into the designed component geometry [2]. Because hot stamping technology can avoid the defects such as severe springback, splits and wrinkles, it is commonly used to fabricate the vehicle parts with ultrahigh strength, such as A-pillar, B pillar, roof rail and bumper. However, with the increasing demand on lightweight, passenger safety and crashworthiness qualities for vehicle, new press-hardening steels with tensile strength of 2000 MPa or higher have been recently developed to replace 22MnB5 steel [1,3]. In order to achieve the strength of 2000 MPa, it is an economic method by adding carbon content. Naderi [4,5] reported the development of a boron steel grade 37MnB4 that exhibits ultimate tensile strength in excess of 2000 MPa, but total elongation of less than 3% following hot stamping.

In this paper, the microstructure and mechanical properties of a new 2000 MPa ultrahigh strength boron steel with good ductility were reported. The microstructure evolution during continuous cooling

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transformation of the steel was studied, which would provide support for the hot stamping process in order to obtain the best mechanical performance. In addition, the tensile properties of the steel after hot stamping were analyzed.

2. Materials and experiments

In this study, the chemical composition of the experimental steel in wt.% is Fe-0.354C-0.32Si-1.48Mn-0.05Al-0.042Ti-0.0038N-0.0025B, which is referred to as 35MnB5. The experimental steel was melted in a 50 kg vacuum induction furnace and casted into an ingot. The ingot was hot-forged into a billet (section dimension 60 mm×90 mm) and then the billet was hot rolled to a thickness of 3.0 mm by seven passes after 1200 ℃×3.5 h homogenization treatment (initial rolling temperature of 1150 ℃ and finish rolling temperature of 850 ℃), then transferred to a furnace with 630 ℃ and then air cooled to room temperature. After hot rolling, the hot-rolled plate was pickled by 20% hydrochloric acid, cold rolled to 1.5 mm and then cut into 100 mm×200 mm blanks. The blanks were austenitized at 900 °C and soaked for 250 seconds in nitrogen protected atmosphere furnace, transferred to the press as quickly as possible and subsequently hot stamped. The punch and die were kept cool by water coolant. The mentioned steels were pressed by flat dies under the condition of about 6 MPa for 6s during hot stamping. After hot stamping, bake hardening process (BH) was performed at 170 ℃ for 20 minutes to simulate the typical paint baking process of automobile.

The critical point temperature of the experimental steel was measured by the JMATPRO software calculation at equilibrium, A_{e1}=695 °C, A_{e3}=775 °C (figure 1), and the annealing temperature of the experimental steel was set to 780 °C. The continuous cooling transformation experiment and simulation of different austenitizing temperatures (900 ℃ and 950 ℃) were performed with a Bähr DIL 805 A/D dilatometer. The samples were cut into the size of 1.5 mm×4 mm ×10 mm from the continuous annealing steel plates. The samples were heated at 10 °C/s to 900 °C and soaked for 300 seconds, and then immediately cooled to room temperature at different cooling rates of 1, 5, 10, 15, 20 and 30 °C/s, as presented in figure 2(a).

Metallographic specimens were mechanically polished to mirror finish and etched with 4% nital solution at room temperature. Microstructural observations were carried out using a combination of optical microscopy (OM, OLYMPUS BX53) and scanning electron microscopy (SEM, ZEISS ULTRA 55). The uniaxial tensile tests of tensile specimens with a gauge length of 50 mm and a width of 25 mm were performed on a Shimadzu AG-X 100 universal testing machine at room temperature with a constant strain rate of $5\times10^{-4}s^{-1}$.

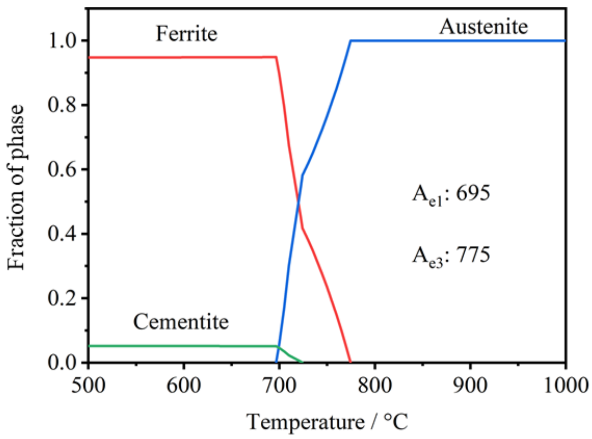

Figure 1. Phase change with temperature according to the calculation in equilibrium.

3. Results and discussion

3.1. Microstructure evolution during continuous cooling transformation

As shown in figure 2(b), the dilatometric curve reveals that the austenite starts (A_{c1}) and finish (A_{c3}) temperatures upon heating and the M_s and M_f temperatures are determined to be 736, 802, 315 and

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161 °C, respectively. The SEM micrographs of different samples are presented in figure 3. The microstructure of the annealing sheet consists of ferrite and pearlite (figure 3(a)). When the cooling rate is 1 °C/s, the microstructure primarily consists of ferrite (α) and interlamellar pearlite (P), marked with red letters in figure 3(b). Large amount of bainite (B), ferrite and a small amount of martensite (α′) are observed at the cooling rate of 5 °C/s. With the increase of cooling rate, ferrite and bainite gradually disappear, and the microstructure is mainly composed of martensite. Almost all of the microstructure is martensite and only a small amount of ferrite when the cooling rate reaches 15 °C/s. The microstructure only consists of martensite when the cooling rate reaches 20 °C/s.

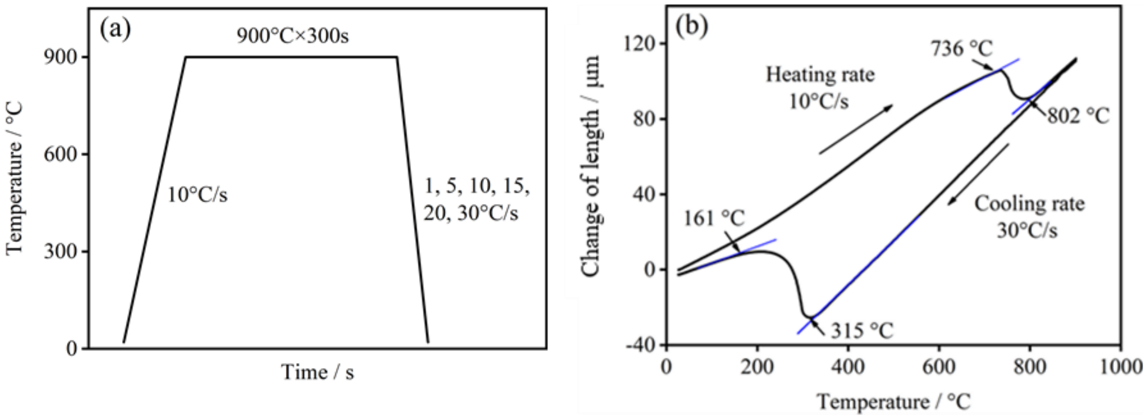

Figure 2. (a) Simulation procedure for the continuous cooling transformation experiment and (b) Dilatometric curve of the investigated steel.

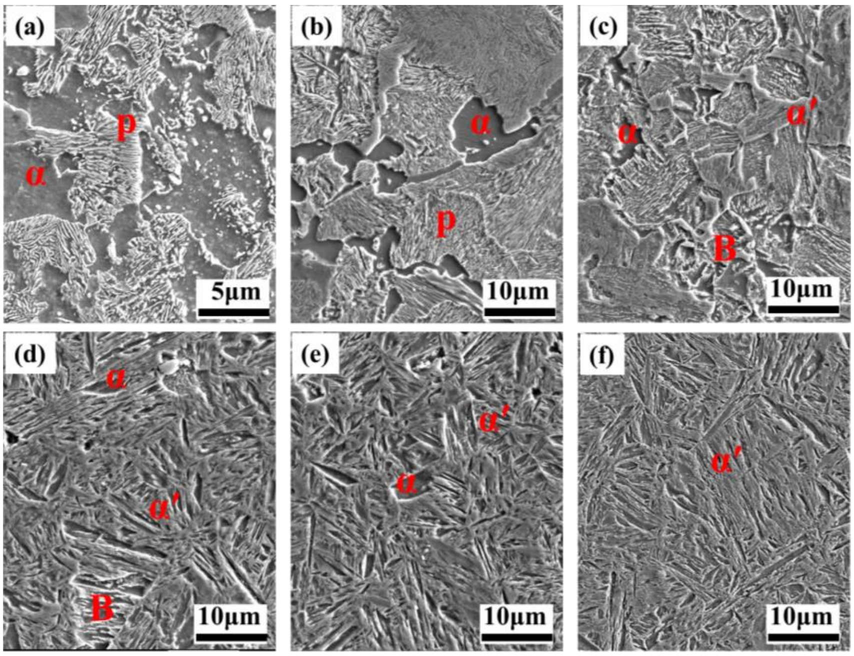

Figure 3. SEM micrographs of specimens for continuous cooling transformation. (a) initial microstructure for continuously annealed sheet and cooled at different cooling rates of (b) 1 °C/s, (c) 5 °C/s, (d) 10 °C/s, (e) 15 °C/s, (f) 20 °C/s, respectively. α: ferrite; P: pearlite; B: bainite; α′: martensite.

3.2. Influence of austenitizing temperature on prior austenite grain size

It is well known that martensitic transformation occurs during hot stamping. The microstructure after hot stamping is mainly composed of lath martensite, which is composed of substructures, i.e., “blocks” and "packets" which are a group of laths with almost the same habit plane. Whereas, a prior austenite grain is divided by several packets which are subdivided by blocks [6,7]. Usually, the packet or block size is taken as the effective grain size for the strength and toughness of low carbon steels. Thus, it is important to study the influence of austenitizing temperature on prior austenite grain size [6]. In this study, the prior austenite grain size of the sample, which was austenitized at 900 °C and soaked for 300 seconds, is about 6.8 μm by OM observation (figure 4(a)). However, it was found that there was an abnormal grain growth of prior austenite grains at austenitizing temperature of 950 °C. The average grain size is about 14.5 μm (figure 4(b)), the mechanical properties such as strength and plasticity will be deteriorated, and it is difficult to meet the better energy absorption during the automobile crash.

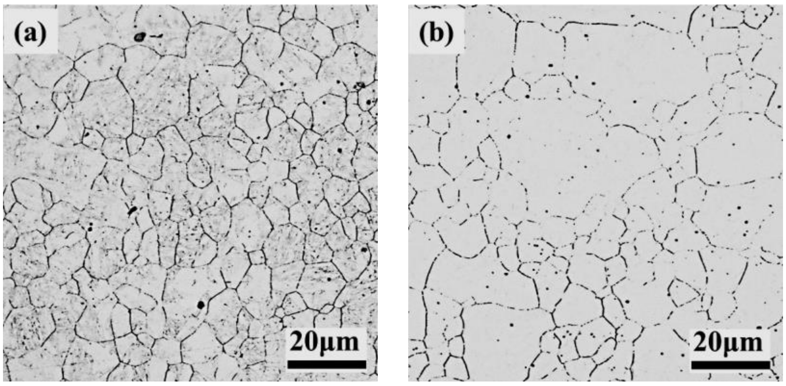

Figure 4. Prior austenite grain of 35MnB5 martensite steel quenched at the different temperatures of (a) 900 °C and (b) 950 °C observed by OM.

3.3. Mechanical properties

Figure 5(a) shows the engineering stress-strain curves of a 2000 MPa PHS samples tested at a strain rate of $5\times10^{-4}s^{-1}$. The flow curves shown in figure 5(a) have no clear yield point, but there is a continuous and smooth elastic-plastic transition from the micro-plastic region into the macro-plastic region. Thus, the 0.2% offset yield strength is considered as the yield strength of the material in the present work. The ultimate tensile strength and yield strength of die-quenched sample are 1301 MPa and 2046 MPa, the total elongation is 6.6%. After an additional low-temperature tempering process simulated with a 20 min soak at 170 °C, the ultimate tensile strength of the 2000 MPa grade PHS decreases to 1908 MPa from 2046 MPa. However, the yield strength increases to 1386 MPa from 1301 MPa and the total elongation also increases to 7.3%.

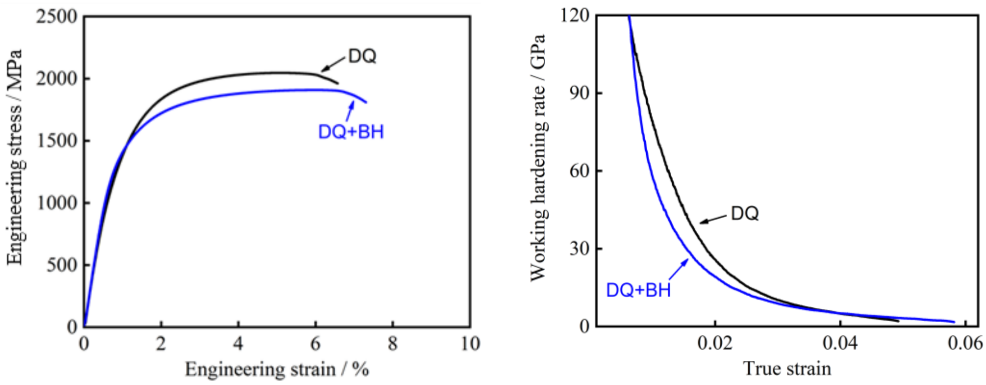

Figure 5. (a) Typical engineering stress-strain curves and (b) work hardening rate of die quenched sample (DQ) and bake hardened sample after die quenching (DQ+BH).

The work-hardening rate-true strain curves of the investigated samples are presented in figure 5(b). The strain hardening is remarkably high during initial stage due to a large amount density of mobile dislocation. However, the mobile dislocation density rapidly decreases as the strain is larger than 0.025, the work hardening rate decreases sharply. Via the paint baking process, the total dislocation density in martensite decreases and the dislocation structure changes from the original dislocation ring or dislocation network to dislocation package [8], the ability of dislocation multiplication become weaker, Thus, the work hardening rate of DQ+BH sample becomes lower compared with that in quenched state.

4. Conclusions

The microstructure and mechanical properties of a 2000 MPa ultrahigh strength boron steel have been investigated. The main conclusions are as follows:

(1) The annealing microstructure of the 2000 MPa grade PHS sheet consists of ferrite and pearlite. Bainite, ferrite and martensite are observed at the cooling rate of 5 °C/s. When the cooling rate is increased to 20 °C/s, the microstructure only consists of martensite.

(2) When the investigated samples were austenitized at 900 °C for 300 seconds, the prior austenite grain size was about 6.8 μm. There was an abnormal grain growth of prior austenite grains at 950 °C, so it should be carried out to finish austenitization below 950 °C during hot stamping.

(3) Die-quenched samples reveal an average yield strength, ultimate tensile strength, and total elongation of 1301 MPa, 2046 MPa and 6.6% respectively. Via tempering at 170 °C for 20 min, the ultimate tensile strength decreases slightly. However, the ductility becomes better. Although the investigated 2000 MPa grade PHS has a good match of strength and ductility, the crash energy absorption needs further detailed evaluated.

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