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Microstructure characterization of fine grains near hot-sheared surface formed during hot-stamping process

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ABSTRACT

Submicron crystallization suppresses hydrogen-induced delayed cracking on hot-sheared surfaces, which are formed during a hot-stamping process. To gain insights into the mechanism of this suppression, in this study, detailed microstructural characterization in the vicinity of the hot-sheared surface was performed. A hot-halfway-cut test, which consists of punch penetration into an austenitized hot specimen followed by water quenching, was conducted for this characterization. This test provided information about the microstructural evolution with respect to equivalent plastic strain by controlling punch penetration. Furthermore, the microstructural analyses were straightforward because this test did not involve the difficult complication of accounting for material fracture during the hot shearing. For this test, a finite element simulation was used to evaluate the strain distribution in the hot-deformed zone. Optical observations and hardness measurements clarified that at 750 °C, the microstructure that covers the hot-sheared surface starts to transform when the equivalent plastic strain is greater than approximately 1.0. In addition, scanning electron microscopy, electron backscatter diffraction analysis, electron probe microanalysis, and transmission electron microscopy revealed the following microstructural details: In the vicinity of the burnished part of the hot-sheared surface, the microstructure is composed mostly of ferrite that contains banded carbides and has grain sizes on the order of 0.4–0.6 μm, rather than bainite or martensite. On the other hand, in the vicinity of the fractured part, the microstructure is composed of ferrite and banded bainite, and has grain sizes on the order of 0.6–2 μm.

1. Introduction

In recent years, CO_2 discharge regulations for the prevention of global warming have increased the need for weight reduction of automobiles, which must also exhibit increased crashworthiness. Strengthening of automobile parts is an effective way to fulfill both of these needs. One such strengthening method is the hot stamping of boron steels, which includes heating, press-forming, and die-quenching steps, and can provide automobile parts whose tensile strengths are over 1500 MPa. Additionally, hot stamping has the benefits of reduced forming force and low spring back in comparison with cold stamping as reviewed by Karbasian and Tekkaya (2010). Thus, hot stamping is now rapidly being adopted.

On the other hand, hot stamping has some disadvantages that impact its productivity. Reducing the trimming (or piercing) cost of hot-stamped parts is one of these concerns. Due to the high hardness of hot-stamped parts, laser cutting is commonly used for trimming (or piercing) in spite of its high cost and low productivity. Although cold shearing is also available as a trimming method, severe tool wear that increases tool maintenance costs has prevented its acceptance (So et al., 2009). Additionally, the cold-sheared surface of a hot-stamped part may suffer from hydrogen-induced delayed cracking because of the high residual tensile stress (Mori et al., 2012).

Considering the above background information, a process involving simultaneous hot shearing and hot stamping, hereafter referred to simply as "hot shearing", has been developed in recent years. In this method, materials are sheared in between the press-forming and the quenching steps of the hot-stamping process. So et al. (2012) have reported that this technique significantly reduces the shearing force compared with cold shearing, and is therefore expected to cause an improvement in tool wear. Mori et al. (2015) have demonstrated the efficiency of hot shearing as a method of

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forming automobile parts. Senuma et al. (2010) have reported that hydrogen-induced delayed cracking is suppressed on hot-sheared surfaces. In their experiments, the residual tensile stress on the hot-sheared surface was lower than 600 MPa when the temperature during shearing was higher than 500 °C; this is in sharp contrast to the much higher residual tensile stress of 1.3 GPa that occurred when the shearing was performed at 400 °C. As a follow-up to Senuma's report, our previous study (Matsuno et al., 2014) clarified that hydrogen-induced delayed cracking does not occur on the hot-sheared surface even under high hydrogen density (approximately 1.5 ppm) and high residual tensile stress (over 1 GPa).

The present study aims to characterize the microstructure of the hot-sheared surface. In our previous study (Matsuno et al., 2014), we found submicron-crystal ferrite and uncertain deformed microstructures in the vicinity of the hot-sheared surface, although other sites consisted of martensite. This hindering of the martensite transformation probably contributes to the high resistance against hydrogen-induced delayed cracking on the hot-sheared surface. Thus, the characterization of these microstructures is expected to provide insights to the mechanism of such high resistance against hydrogen-induced delayed cracking. Additionally, this characterization is also expected to provide possible explanations for other properties in addition to the hydrogen-induced delayed cracking, e.g., ductility and fatigue strength. Sheared surfaces traditionally have a need for improvement in these properties (Matsuno et al., 2010).

Generally, very high strain is imposed on a sheared surface as numerically analyzed by Matsuno et al. (2012). Thus, the microstructures in the vicinity of the hot-sheared surface are clearly plastic strain-induced ferrite and bainite. Indeed, it has been reported that the volume fraction of ferrite and bainite in lath martensite phase increases with tensile strain in hot deformation (e.g., Fan et al., 2010). This behavior has been thermo-mechanically analyzed and discussed by Min et al. (2012), and the strain level and cooling rate with respect to ferrite and bainite transformation have been experimentally clarified by Nikravesh et al. (2012). Afterward, Min et al. (2013) identified the strength and ductility of such microstructures that contain ferrite and bainite in a martensite matrix. Bardelcik et al. (2014) have also analyzed this type of microstructure, and they have clarified how the relationship between strain rate sensitivity and work hardening adds to strength and ductility. Nevertheless, these analyses cannot be directly applied to hot shearing because of subtle differences in the dominant phase of the microstructure. In the previous work cited above, the dominant phase in the tensile-strained part was martensite, but in the vicinity of the hot-sheared surface, the ferrite volume fraction was almost 100% (Matsuno et al., 2014). Furthermore, the grain size of ferrite reported in the above literature was much larger than that of the submicron crystals.

This paper reports on optical observations and hardness measurements at the macroscopic level, along with microstructural analyses on a submicron scale. These were conducted on the deformed zone of the specimens derived from a punch penetration test on heated 22MnB5 steels. In this test, the punch was stopped before material fracture. Afterward, the specimen was immediately quenched. Hereafter, we shall refer to this test as the "hot-halfway-cut test". This hot-halfway-cut test can simulate the hot deformation in hot shearing, and it enables easy microstructural characterization. The area of observation and measurement does not include cracks, and finite element (FE) simulation can easily evaluate strain distribution because the hot-halfway-cut test does not demand fracture modeling.

Firstly, optical observations and hardness measurements for a variety of punch penetrations have captured the critical equivalent plastic strain for transformation to the microstructure observed around the hot-sheared surface. Then, scanning electron microscopy (SEM), electron backscatter diffraction (ESBD), electron probe microanalysis (EPMA), and transmission electron microscopy (TEM) analyzed the microstructures at the two positions in the deformed zone. Finally, the characterization of the microstructures in the vicinity of the hot-sheared surface has been carried out.

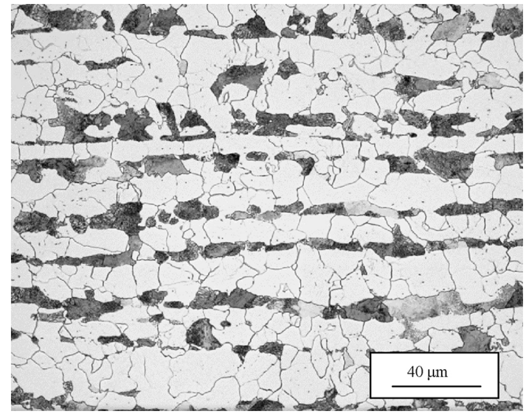

Fig. 1. Microstructure of the material before heating (Ferrite: White, Perlite: Black).

2. Material and methods

2.1. Material

Boron steel sheets with an aluminized coating were used for this study. The specimens were 10.0 mm wide, 150 mm long, and 2.3 mm thick. The grade of the steel sheets was 22MnB5 (C: 0.22, Si: 0.25, Mn: 1.2, B: 0.0028, Cr: 0.22, Ti: 0.025 mass%). Fig. 1 shows the microstructure before hot stamping. The starting temperature of martensite transformation (*Ms*) of this material was identified as 420 °C by a volume dilatation measurement using a thermo-simulator. The temperature of the ferrite transformation at a cooling rate of 8.0 °C/s (*Ar3*) was measured as 580 °C (Matsuno et al., 2014).

2.2. Hot-halfway-cut test

Fig. 2 presents the schematic image of the tooling for the hot-halfway-cut test. As shown in Fig. 2, a 10 mm-long punch penetrated at the longitudinal center of the specimen with a punching velocity of approximately 60 mm/s. The clearance between the punch and the die was set to 0.14 mm (6.1% of the specimen thickness). Two pins with springs were embedded on the tools so that the specimen would not contact the die surface prematurely and experience excessively rapid cooling.

Fig. 3 shows the schematic images of the procedure for the hot-halfway-cut test. First, a specimen was austenitized in a furnace for 90 s at 950 °C. Second, the specimen was placed on the hot-halfway-cut tool until the specimen cooled to 750 °C, which is higher than the *Ar*3 and the same temperature as that used in our previous study (Matsuno et al., 2014). We tried to achieve the highest temperature possible in order to emphasize the different behavior of the microstructural transformation with respect to punch penetration. As reported in the previous study (Matsuno et al., 2014), the deformed microstructure, which causes is difficult to characterize, has been observed at 650 °C. The handling time necessary to position the sample properly on the tool made it impractical to use temperatures higher than 750 °C. The moment when the specimen had cooled to 750 °C was determined by noting the amount of time that it had been placed outside the furnace and utilizing a previously determined cooling rate. Afterward, the punch penetrated