Materials Letters 180 (2016) 322–326

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

Correlation between fracture toughness and stretch-flangeability of advanced high strength steels

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ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form
8 May 2016
Accepted 28 May 2016
Available online 30 May 2016

Keywords:
Hole expansion ratio
Advanced high strength steels
Tensile properties
Metal forming and shaping
Metals and alloys
Deformation and fracture

ABSTRACT

Stretch-flangeability representing the capability of a sheet material to form into a complex shaped part is not a well-known sheet metal forming property. We correlate mechanical properties with stretch-flangeability of various advanced high strength steels (AHSSs) to capture the stretch-flanging phenomenon and improve the stretch-flangeability of steel sheet materials. The stretch-flangeability of materials is usually evaluated using a hole expansion test. During the hole expansion test, the stress state in the hole edge part of the specimen is almost the same as that of the uniaxial tensile test. However, a single parameter in tensile properties of the AHSSs exhibits no clear correlation with flangeability estimated as the hole expansion ratio (HER). Because micro-cracks in the hole edge region of the hole expansion testing samples play a significant role in HER values, we propose and demonstrate that fracture toughness is the key factor governing the HER of AHSSs.

1. Introduction

Recently, needs for advanced high strength steel (AHSS) in the automotive industry have continuously increased to improve safety and to reduce weight of car body [1–4]. Although various AHSSs, such as dual phase (DP), transformation-induced plasticity (TRIP), twinning-induced plasticity (TWIP), and lightweight steels, have an excellent combination of high strength and large elongation [5–8], stretch-flangeability of AHSS sheets estimated as hole expansion ratio (HER) is poor compared with those of conventional strength grade steels [9,10].

Many efforts have been made in order to evaluate the stretch-flangeability performance of the AHSSs using hole expansion (HE) testing [10–16]. Paul [10] investigated the stress state during the HE test and related the resulting HER values with tensile properties of materials. Paul presented that the stress state of the hole edge part during the HE test is nearly identical to the tensile state, but failed to reveal any clear correlations between each tensile property and the HER values. In other reports, tensile properties, such as normal anisotropy (r-value), strain rate sensitivity (SRS, m) [17], ultimate tensile strength (UTS) [12], and UTS/yield strength (YS) ratio [17], had dominated relationships with the HER, but the results are conflicting. For example, Chatterjee and Bhadeshia [12] reported that the UTS is the most important parameter in determining the HER. On the other hand, Chen et al. [13] argued that the HER of steels with the UTS grade less than 590 MPa decreased linearly with increasing UTS, while in AHSSs with the UTS grade greater than 780 MPa, the HER saturates to around 30–40% with increasing UTS.

Meanwhile, the significant function of initial micro-cracks in the hole edge part of the HE test sample on the HER value has already been noted in several papers [11,16,18]. During the HE test, stress concentrates at the micro-crack sites which function as a crack initiation site, however, the relationship between micro-cracks and sheet formability still requires more investigation.

In this study, we propose that fracture toughness, widely known as an indication of fracture resistance of a material containing a crack, can be a key factor that directly influences the HER of AHSSs because the phenomenon in the HE test is primarily similar to the mechanism of fracture phenomenon of material. Similar approach had been performed by Takahashi et al. [19] for the limited kind of steel samples of similar microstructures. In this study, the stretch-flangeability of a wide range of dissimilar AHSS

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http://dx.doi.org/10.1016/j.matlet.2016.05.145
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samples (TWIP, DP, TRIP, and lightweight steels) has been investigated. Finally, the results lead to a better understanding of HER phenomenon of AHSSs and development of superior steels.

2. Experimental procedure

Various cold rolled AHSS sheet samples (TWIP1100, DP980, DP780, TRIP780, and lightweight steels) provided by POSCO were used. The numbers after the steel names indicate UTS values of each steel sheet. Initial thickness of the TWIP1100 and DP980 steel samples was 1.4 mm and initial thickness of other steel samples was 1.0 mm.

Uniaxial tensile tests were conducted using a servo hydraulic universal testing machine (Model 1361, Instron Co., USA) to determine the stress-strain curves and *r*-values of the sheet samples at room temperature. The tensile tests were performed according to the ASTM E-08 standard procedure [20] using dog bone-shaped plate specimens of 5.0 mm gage length, 2.5 mm gage width, and 1.0 mm thickness at a strain rate of 0.001 s^{-1}. Three specimens were tested in each of the three different directions which are 0°, 45°, and 90° with respect to the rolling direction (RD). During the tensile tests, the strains were measured using the digital image correlation (DIC) method in an optical strain gage system (ARAMIS 5 M, GOM mbH, Germany).

The SRS was measured using strain rate jump testing in RD at different strain rates, 0.01 s^{-1} and 0.001 s^{-1}. The strain rate jump tests were performed using dog bone-shaped plate specimens of 5.0 mm gage length, 2.5 mm gage width, and 1.0 mm thickness. The SRS was calculated from the stress-strain curves using the following equation [21]:

$$m = \frac{\ln\ (\sigma_2/\sigma_1)}{\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1)}, \tag{1}$$

where σ_1 and σ_2 are the true stresses at the true strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, respectively, at a certain strain.

Fracture toughness tests were conducted according to the ASTM E1820 standard procedure except the specimen thickness [22]. While the ASTM E1820 requires the specimen thickness to be large enough for a plane strain condition, the test condition does not satisfy the plane strain conditions because the thickness of sheet specimen was not enough. The fracture toughness tests were performed at a strain rate of 0.001 s^{-1} using a single edge notched tensile test specimen of 60.0 mm total length, 15.0 mm width, 1.0 mm thickness, and a 3.0 mm initial sharp notch in RD. Fracture toughness test samples were prepared so that total crack length (notch length+fatigue crack length) is 0.4–0.6 times of the specimen width. The fatigue crack was introduced under frequency of 10 Hz cyclic loading in the specimen in tension between 8% and 39% of the YS. The fracture toughness was calculated using the following equation [22]:

$$K_{Jc} = \sqrt{\frac{J_c E}{1-\nu^2}}, \tag{2}$$

where K_{Jc} is the fracture toughness of elastic-plastic fracture analysis, E is the Young's modulus, J_c is the fracture toughness of J-integral analysis, and ν is the Poisson ratio.

The HE tests were conducted using an Erichsen hydraulic sheet metal testing machine (model 145-60, Erichsen Co., Germany) with a 60° conical punch to measure the HER of each sample. According to the ISO/TS 16630 standard procedure [23], in this test, the 90.0 mm × 90.0 mm square specimens with 10.0 mm diameter central holes were used and a central hole of the specimen was made using a punching process. The HE tests were performed at a punch speed of 10 mm/s with a constant blank holder force of 200 kN. The tests were stopped when the crack of the hole edge completely propagated through the thickness direction. The final hole diameters were measured after the tests stopped. The HER is calculated using the following definition [23]:

$$\mathrm{HER}(\%) = \frac{d_f - d_0}{d_0} \times 100, \tag{3}$$

where d_0 and d_f are initial and final hole diameters, respectively. In this work, $d_0 = 10.0$ mm and the HER was determined after averaging three test results for each specimen.

3. Results and discussion

The engineering stress-strain curves of the samples are presented in Fig. 2. Each test on the AHSS samples was performed three times, resulting in good reproducibility for stress-strain curves. The AHSS samples cover a wide range of tensile properties such as a strain hardening exponent (n), UTS, uniform elongation (U.EL), total elongation (T.EL), post uniform elongation (P.EL), and SRS (m). The tensile properties, fracture toughness, and HER of each sample obtained using the conical HE test with punched holes are summarized in Table 1.

Fig. 3 plots the relation between tensile properties and the HER of the AHSS samples. Interestingly and unexpectedly, one can see that there are no clear correlations between individual tensile property, such as YS, UTS, U.EL, T.EL, P.EL, or SRS, and HER. The tensile properties such as UTS, T.EL, P.EL, and SRS were previously reported to be closely related to the HER of AHSS sheets [10–12,15]. However, in their works, the correlation between tensile properties and the HER was limited to specific AHSSs like TWIP steels or DP steels with different heat treatment or small amount of additional alloying elements. Therefore, their correlations cannot be generalized to various AHSS samples having different microstructures, grain sizes, deformation mechanisms, and processing histories.

From our point of view, the governing factor of the HER is initial micro-cracks of the hole edge part of the HE test specimens prepared using various processes, e.g. punching, laser cutting, or drilling, as well as the material's intrinsic properties. Therefore, the role of micro-cracks should be primarily considered to figure out the key factor, which has a directly effect on the HER of AHSSs. Fig. 1 presents the hole edge surface of the TWIP1100 observed using the field emission scanning electron microscope. Many initial micro-cracks were observed in the hole edge part of the HE test specimen generated by the punching process, which is in agreement with other studies [11,16,18]. Such micro-cracks function as crack initiation sites during the HE test. In addition, there are different dimple patterns at different locations in Fig. 1 because the materials are not isotropic due to their processing history, namely rolling, the characteristics of the shearing surface are anisotropic (0°, 45°, and 90° with respect to the RD). Recent studies [16,24,25] have shown that improvements in the HER of the same materials could be made by different hole making processes such as electrical discharge machining, water-jet, and wire cutting. These hole making processes can produce clear and smooth holes with relatively few defects compared with the punching process. When limited number and small defects reside along the hole edge part, initiation of crack growth is more difficult due to limited crack initiation sites. In fact, when processed with the reamer process, which leaves behind a very smooth hole edge surface, much more improved HERs could be obtained compared with the conventional punching process (i.e. TWIP1100: 32.0%→88.5%, DP780: 27.9%→66.5%, and TRIP780: 24.0%→46.5%). Therefore, initial micro-cracks, which function as crack initiation sites, at the