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Measurement and modeling of simple shear deformation under load reversal: Application to advanced high strength steels

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ABSTRACT

In this paper, the stress–strain behavior under load reversal of advanced high strength steel (AHSS) sheet samples was measured using a modified simple shear (SS) apparatus. The forward–reverse loading behavior was characterized for three different grades of AHSS; namely, DP, TRIP and TWIP steels. For comparison purpose, compression–tension (CT) tests were also carried out for the same materials. For all the cases, a typical complex anisotropic hardening behavior, including the Bauschinger effect, transient strain hardening with high rate and permanent softening, was observed during load reversal. No premature localization and sheet buckling occurred in these experiments, which have been major technical hurdles in CT tests. For example, an engineering shear strain of over 40%, which corresponds to an effective strain of roughly 0.2, at reversal was achieved for DP980 although the uniform elongation of this material in uniaxial tension is only 5%. A recently developed distortional hardening model (HAH) was employed to reproduce the SS stress–strain curves. Using the coefficients determined with these SS data, the CT behavior was predicted with the HAH model and compared with experimental results. This complementary study indicated that the constitutive model determined from the SS flow curves satisfactorily reproduced the CT hardening behavior. As an application, finite element simulations of springback were carried out for 2D draw-bending of a strip sheet.

1. Introduction

Advanced high strength steels (AHSS) have been replacing conventional low strength steels for automotive parts because of weight saving and improved crash performance. However, it is a challenge to successfully introduce AHSS because of their inferior formability and larger springback compared to conventional steels. Especially, springback, the undesirable elastic recovery in a formed part when forming loads are removed, should be compensated to allow the assembly of a component.

In order to understand and predict the mechanics of springback for AHSS, there have been numerous approaches using finite element (FE) simulations [1–8]. The FE approach can reduce the development cost and time significantly by suggesting manufacturing modifications without resorting to numerous experimental trial-and-error steps. Therefore, it is important to increase the accuracy of FE simulations to provide results similar to those obtained in real forming processes.

For this purpose, a reliable constitutive model that properly describes the elastic–plastic response of a sheet metal is necessary. In particular, for an accurate prediction of springback, various constitutive models, which capture the complex material behavior during strain path changes, have been proposed. This is because bending and unbending with a superimposed stretch, which occur in a typical process involving load reversal and the Bauschinger effect, influence the springback behavior significantly. The Bauschinger effect, which is characterized by a lower yield stress and higher strain hardening rate upon load reversal, was successfully captured by advanced constitutive models [9–14].

In order to provide suitable coefficients for such advanced constitutive models, it is necessary to employ the non-conventional testing method. In particular, it is important to probe the material response at large strain without premature plastic flow localization and to achieve a sufficient load at reversal to effectively determine suitable coefficients for AHSS. In this sense, a conventional uniaxial tension test is not appropriate to capture the Bauschinger behavior of high strength materials because of its

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monotonic nature and its tendency to premature flow localization at low strain. Alternate testing methods have been reported, which include torsion-reverse torsion [15,16], tension–compression [17] and forward–reverse simple shear tests [18]. The disadvantage of the torsion-reverse torsion test is that, for a sheet sample, it requires bending and welding prior to testing, which are likely to change the mechanical properties of the original material. In the case of in-plane tension–compression, an anti-bulking system is necessary for sheet specimens, which modifies the stress state and introduces uncertain friction effects [12,17,19]. Moreover, the strains attainable in the tension–compression test are limited due to either flow localization during tension or buckling during compression, phenomena which are a challenge in high strength steels. For example, the uniform elongation of DP980 steel measured in uniaxial tension is less than 5%, which is not sufficient for an accurate constitutive model identification and FE modeling [20].

The simple shear (SS) test has been designed to circumvent the disadvantages of the existing methods. In this test, the specimen preparation is simpler than in other methods and large homogenous strains can be achieved without plastic flow localization. Moreover, reverse loading is easy to control without major changes in the deformation mode. Due to these advantages, several researchers adopted this approach to characterize the anisotropic hardening behavior of metals after load reversal [21–27]. However, most of the previous studies pertaining to the SS test focused on softer materials such as mild steels [21,23,24], aluminum alloys [22,25,27] and polymers [28]. Only few investigations on the SS behavior of AHSS have been published [29,30].

The aim of the present work is first to introduce a modification of the SS device that allows testing for AHSS, sheets for which the tensile strength ranges from 700 to 1000 MPa (or even higher). Then, this improved SS device is used to measure the forward–reverse stress–strain responses of AHSS sheets, which involve complex hardening behavior during load reversal. The measured stress–strain curves are approximated by a recently developed anisotropic hardening model, so-called HAH [31–33]. Finally, the effectiveness of the measurement method is validated by a comparison of the predicted reverse loading behavior in compression-tension (CT) and by the finite element (FE) prediction of springback.

2. Experiment

2.1. Simple shear device

The simple shear (SS) test device for sheet metals consists of two rigid grips, which translate with respect to each other along the sample longitudinal direction [28,34,35]. A rectangular sample is firmly clamped by the two grips, one of them immobile while the other translates along the x-axis (Fig. 1). The constant width h of the deformation area is maintained during the test. In Fig. 1, L and Δx are the current length of the specimen and the relative displacement of the two grips during simple shear deformation, respectively.

Compared to lower strength materials, the main challenge of SS for high strength steels is to achieve a robust clamping. While a mechanical gripping approach relying on friction was successful for soft materials, the same method was insufficient in a preliminary study for materials with strengths of 780 MPa or higher. Therefore, one of the motivations of the present work was to develop an enhanced gripping system in the SS test for AHSS.

The improved SS test device installed in a 500 kN MTS® universal tension–compression machine, is shown in Fig. 2. For a firm and controlled gripping of the rectangular sample, hydraulic clamping is applied on the grip ends of the specimen as shown in

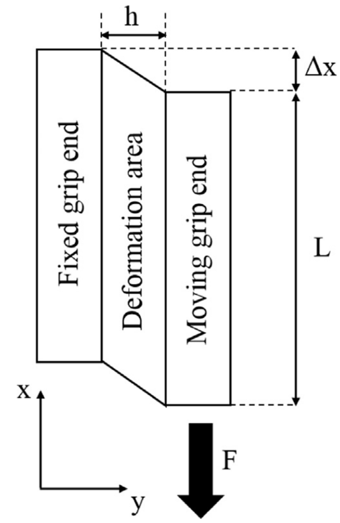

Fig. 1. Schematic description of the SS test.

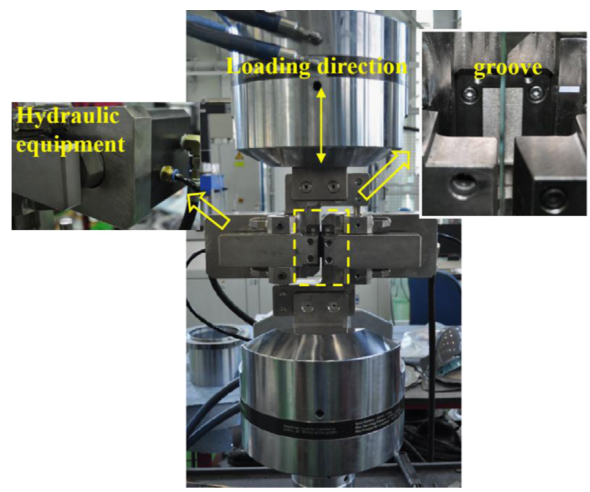

Fig. 2. The modified SS test device.

Fig. 1. Preliminary trials showed that hydraulic pressures up to 30 MPa were not sufficient to prevent the specimen from slipping during the test for steel of 780 MPa strength or higher. To prevent slipping due to this insufficient gripping pressure, the entire specimen is encapsulated within a serrated groove specially designed as shown in Fig. 3. The specimen is inserted into the groove, which is shown as the shaded area in Fig. 3(c). The size of the groove depends on the length of the shear specimen. In this study, the depth of the groove d is 3 mm and the distance h between the two bottoms or top grips is 4 mm. The thickness of the grips is 50 mm, which is large compared with the thickness of the specimen (See Fig. 3). Moreover, a mechanism forces the grips to only translate with respect to each other. Therefore, during testing, any rotational rigid motion of the SS apparatus is prevented. This groove design prohibits slipping of the specimen in a direction perpendicular to its length. For all AHSS sheets, the hydraulic clamping pressure was maintained to 30 MPa.

2.2. Materials

To evaluate the performance of the improved SS device, three AHSS sheet samples provided by POSCO were considered; i.e., a 980 MPa strength (DP980) dual-phase steel, a 780 MPa transformation induced plasticity steel (TRIP780) and a 980 MPa twinning-induced plasticity steel (TWIP 980). The thicknesses of the DP980,