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Identification of post-necking stress–strain curve for sheet metals by inverse method

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ABSTRACT

Simulation of sheet metal forming requires the flow curve (i.e. the true stress–strain relation) over large strains. This paper presents a method for obtaining the flow curve of sheet metals over a large range of strain through the combination of simple tensile test and finite element analyses. The appropriate finite element model for accurate simulation of the anisotropic plastic deformation during diffuse necking was determined. Different hardening functions were evaluated for their capabilities in approximating the entire flow stress curves up to localized necking. A modified Hockett–Sherby function was proposed and its performance was demonstrated.

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1. Introduction

The stress–strain curve is an important property to evaluate the fracture strength of a material. In stamping industry, finite element simulation is a critical step in the optimization of the sheet metal forming processes. An indispensable input to the finite element model is the flow stress curve of the sheet material, also known as the true stress–strain curve. Especially for forming process with large deformation, it is necessary to specify the flow stress curve over a large range of strains. The stress–strain relation of a sheet metal is usually acquired from a tensile test using rectangular specimens. It is hard to obtain the curve for large strains exceeding the strain for the tensile strength. Even the strain at the tensile strength has already lost the ability to describe the material property.

A simple tensile test itself is not enough to achieve a more integrated true stress–strain curve. The stress and strain distributions are not uniform along a rectangular specimen as a result of diffuse necking. Therefore, it is difficult to reveal the true strain in this region with the elongation of the specimen measured by an extensometer. The true stress in the necking zone cannot be obtained directly based on nominal stress due to stress triaxiality, i.e. the multi-axial stress state in the necked area.

To acquire the true stress–strain relation of a material, specimens with two different cross-section shapes are commonly used in tensile tests. Many researchers chose cylindrical specimen whose circular cross-section minimizes the effect of anisotropy (Zhu et al., 2015; Kamaya and Kawakubo, 2011; Joun et al., 2008; Mirone, 2004). For serving the stamping process, the sheet-metal specimen with rectangular cross-section has been used (Iadicola, 2011; Zhuang et al., 2013; Kim et al., 2013; Tardif and Kyriakides, 2012; Nasser et al., 2010; Zhang et al., 1999; Dunand and Mohr, 2010).

According to the predecessors' work, the methodology of acquiring flow curve over a large range of strains can be divided into two main categories. The first category is the direct method (Zhu et al., 2015; Iadicola, 2011; Zhuang et al., 2013). In the direct method, both the strain and the stress of the flow curve are measured directly through experiment.

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Digital image correlation (DIC) is an accurate method for deformation measurement and has the advantages of non-contact and full-field measurement, etc. (Zhu et al., 2015; Iadicola, 2011; Kim et al., 2013; Tardif and Kyriakides, 2012). Zhu et al. (2015) utilized three-dimensional DIC to measure the plastic deformation of cylindrical dog-bone specimens of low-carbon steel and calculated the true stress from the load and the actual cross-sectional area. However, the stress triaxiality in the necking zone was neglected. Iadicola (2011) chose a combination of full-field two-dimensional DIC and X-ray diffraction (XRD) to measure the strain and stress at a localized spot on a sheet-metal tensile specimen during plastic deformation. The measured multi-axial strain and stress tensors were converted to uniaxial equivalent measures using the von Mises and Tresca criteria, where the material anisotropy was not considered. Zhuang et al. (2013) applied different degrees of cold rolling on the 4 mm and 5 mm thick sheet-metal specimens before tensile test and extrapolated the stress–strain curves over large strains by shifting the pre-strain derived from the cold working. It would be difficult to apply this method to thinner materials, e.g. around 1 mm thick sheet metals that are commonly used for automobile body panels.

The second method is by incorporating experimental measurement with analytical solution or finite element analysis to determine the flow curve. A reference stress–strain curve is modified iteratively to minimize the discrepancy between the computed and experimental data (e.g. load–displacement curve, surface displacement field, internal/external work, etc.). This is also known as an inverse method (Kamaya and Kawakubo, 2011; Joun et al., 2008; Mirone, 2004; Kim et al., 2013; Tardif and Kyriakides, 2012; Nasser et al., 2010). The flow curves for tensile specimens with circular cross-section were determined using the inverse method by Kamaya and Kawakubo (2011), Joun et al. (2008) and Mirone (2004). For sheet metals, it is more practical to use specimens with rectangular cross-section. Kim et al. (2013) measured the full-field strains of the sheet-metal specimens using DIC technique and adopted the virtual fields method, i.e. the principle of virtual work describing the global equilibrium, to identify the parameters in Swift and modified Voce isotropic hardening laws associated with von Mises isotropic yielding criterion. Tardif and Kyriakides (2012) not only measured the strains of the AL-6011-T6 tensile specimen but also recorded the boundary profiles of the specimen using the DIC technique. The boundary profiles were used to validate the anisotropic yield criteria of Barlat-Yld04. The tensile test specimen was modeled by 8-node linear brick elements with reduced integration and hourglass control. Nasser et al. (2010) conducted biaxial Viscous Pressure Bulge (VPB) tests and demonstrated that the flow stress data can be obtained to higher strain values under biaxial state of stress. The finite element analysis was used to optimize the parameters in the Hollomon power-law hardening function. Although the primary focus was not obtaining the flow curves of specific materials, Zhang et al. (1999) demonstrated a method for determining the true stress–strain relation from the load versus thickness reduction curves through extensive finite element simulations; Dunand and Mohr (2010) designed tensile specimens with different notch radii and with central hole to study the strain and stress evolutions at fracture.

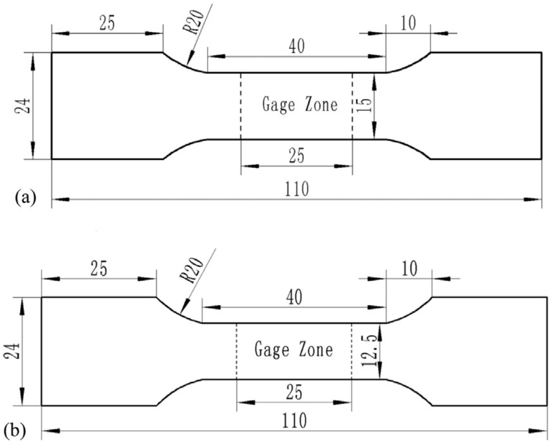

Fig. 1. (a) Dimensions of Q195 and AL6061 tensile test specimen. (b) Dimensions of HSLA350 tensile test specimen.

In this study, tensile tests were conducted on three sheet metals (mild steel Q195, high strength low alloy steel HSLA350, and aluminum alloy AL6061). An extensometer was used to measure the axial strain of the dog-bone type specimen. The true stress–strain curves up to diffuse necking were determined by the measured load and strain. The stress data after diffuse necking and before localized necking were identified by the inverse method with assistance of finite element simulations. The stress values corresponding to the extrapolated strains were modified iteratively based on the difference between the measured and simulated force–elongation curves. As an important property of sheet metals, the material anisotropy was included in acquiring the stress–strain relations. Finally, four hardening functions (Swift (Swift, 1952), Hockett–Sherby (Hockett and Sherby, 1975), modified H–S, and double Voce (Koc and Stok, 2004)) were evaluated for their capabilities in approximating the entire flow stress curves up to localized necking.

2. Experiments

2.1. Experimental description

The materials tested in this study include Q195, HSLA350 and AL6061. Q195 is a structural carbon steel (a type of mild steel). HSLA350 is a high strength low alloy steel. AL6061 is an aluminum alloy. For sheet metals, it is more practical to use specimens with rectangular cross-section. The dog-bone type specimens were designed according to the national standards. The thickness of Q195 and AL6061 is 1.0 mm, and the thickness of HSLA350 is 1.4 mm. Fig. 1(a) shows the dimensions of Q195 and AL6061 specimens. To maintain the same gage length, the HSLA350 specimen was designed 12.5 mm wide in the gage zone as shown in Fig. 1(b). The sheet metals were cut into small rectangular pieces using a mechanical shearing machine along the rolling direction (RD), transverse direction (TD) and diagonal direction (DD) and then finished by wire electric discharge machining (WEDM). The tensile tests were performed on a 100 kN servo electric universal testing machine (UTM5105 manufactured by Suns). An electronic extensometer (25 mm gage length

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