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Forming limit diagram of auto-body steel sheets for high-speed sheet metal forming

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ABSTRACT

This paper is concerned with the uniaxial tensile properties and formability of steel sheets in relation to the strain rate effect. The elongation at fracture for CQ increases at a high strain rate while the elongation at fracture for DP590 decreases slightly in relation to the corresponding value for a quasi-static strain rate. The uniform elongation and the strain hardening coefficient decrease gradually when the strain rate increases. The *r*-value of CQ and DP590 was measured with a high-speed camera in relation to the strain rate. The *r*-value is slightly sensitive to the strain rate. Static forming limit curves (FLCs) and high-speed FLCs were constructed with the aid of punch-stretch tests with arc-shaped and square-shaped specimens. In addition, a high-speed crash testing machine with a specially designed high-speed forming jig was used for the high-speed punch-stretch tests. Compared with the static FLC, the high-speed FLC of CQ is higher in a simple tension region and lower in a biaxial stretch forming region. The high-speed FLC for DP590 decreases in relation to the static FLC throughout the entire region. The elongation at fracture appears to be closely related to the simple tension region of the FLC. The shear fracture is observed from SEM images of specimens tested in the biaxial stretch forming region under the high-speed forming condition. The dimples indicating the shear fracture have elongated horseshoe shape. The high-speed FLC is lower than the static FLC in the biaxial stretch forming region because the shear fracture induces the decrease of ductility. The results confirm that the strain rate has a noticeably influence on the formability of steel sheets. Thus, the forming limit diagram of high-speed tests should be considered in the design of high-speed sheet metal forming processes.

1. Introduction

The concept of a forming limit diagram (FLD) was developed by Keeler and Backofen (1963) and Goodwin (1968) to investigate the formability of sheet metals. The FLD, which has subsequently been widely referenced in the sheet metal forming industry, is now a standard characteristic in the optimization of sheet metal forming processes.

A conventional FLD represents the locus of the necked or fractured position of sheet metals in the space of in-plane principal strains, $\varepsilon_1 - \varepsilon_2$, where ε_1 is the major strain and ε_2 is the minor strain. The locus of the forming limit is called the forming limit curve (FLC), and the FLC is affected by many factors, such as the forming speed, the lubrication condition, the thickness of sheets, the strain hardening, and the anisotropy of the sheet metals. Ozturk and Lee (2005) reported the lubrication effect on FLD in the conventional dome test. The lubrication between punch and blank reduces the frictional forces, improves strain distribution, and delays localized thinning. Lang et al. (2005) investigated the FLDs and thickness distributions of three layers of APP211, soft pure aluminum and DC04 in the multi-layer sheet hydroforming. The FLDs of three layers show large difference according to the rolling directions due to the strong planar anisotropy of the layers.

The forming speed for FLC is particularly significant because the dynamic response of sheet metals differs considerably from the static response. Khan and Liang (1999) showed that the flow stress of three body-centered cubic (BCC) metals of tantalum, tantalum alloy with 2.5% tungsten, and AerMet 100 steel increase over a wide range of strain rates from 10^{-6}/s to 10^4/s. Lee and Lin (2002) investigated the impact properties and microstructural evolution of 304L stainless steel by using a split Hopkinson bar. The flow curve is strengthened by the dislocation multiplication and the α' martensite transformation under conditions of a high strain rate and large levels of deformation. Choi et al. (2006) investigated the uniaxial tensile properties of TRIP steels at high strain rates. Huh et al. (2009a,b) also conducted the uniaxial tensile test at high strain rates for the investigation of the elongation at fracture of conventional steels, advanced high strength steels and nonferrous metals, such as

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AA7003 and AZ31. The local strain rate hardening and the change of the dislocation structure in sheet metals induce the increase of the elongation at fracture as the strain rate increases. Although formability is important and indispensable for the success of complicated sheet metal forming, few studies have investigated the formability of sheet metal at a high strain rate because of the difficulty of conducting a tensile test or a forming limit test at high strain rates in the range of several tens per second to hundreds per second. Auto-body members are fabricated by sheet metal forming processes at a forming velocity of 1–6 m/s, depending on the size and productivity of the auto-body members. During the sheet metal forming process, the strain rate is distributed among the auto-body members in the range of several tens per second to hundreds per second.

Many researchers have investigated the formability of sheet metals in terms of the strain rate. In particular, they have investigated how the strain rate sensitivity affects the forming limits of sheet metals with regard to the necking and instability of sheets. Marciniak and Kuczynski (1967) introduced the concept of an initial imperfection to account for localized necking in biaxial stretched sheet metals. Ghosh (1977) reported that the limit strain, tensile instability and necking in sheet metals were strongly influenced by the strain hardening exponent and the strain rate hardening exponent. The limit strain increases when the strain hardening and strain rate hardening exponent increase. Hutchinson and Neale (1977) showed the relation between the strain rate hardening exponent and the total elongation for various sheet metals. They stated that the amount of strain that could be achieved prior to the necking increases remarkably when the strain rate hardening exponent increases. Li and Chandra (1999) also said that the limit strain increases as the strain rate hardening exponent increases from 0.0 to 0.04. The aim of these studies was not to investigate the formability of single sheet metal with various strain rate conditions, but rather the effect of strain rate sensitivity for various sheet metals.

With regard to the strain rate effect for single sheet metal, most researchers have examined how the strain rate and the temperature affect the forming limit of Al–Mg alloys, such as AA5182-0 (Ayres and Wenner, 1978), AA5083 (Naka et al., 2001) and AZ31 (Lee et al., 2008), because the formability of Al–Mg alloys depends strongly on the temperature. The forming limit strain of Al–Mg alloys increases dramatically at temperatures higher than 423 K when the forming speed decreases. These results confirm that the improvement in formability under conditions of high temperature and low forming speed is related to the high strain rate hardening exponent of sheet metals. On the other hand, few studies have focused on the relation between the forming limit of auto-body steel sheets and the strain rate effect because the formability of auto-body steel sheets is more temperature insensitive than Al–Mg alloys. Nevertheless, it is necessary to investigate the relation between the formability and the strain rate of auto-body steel sheets because most auto-body members are fabricated by a sheet metal forming process under conditions of a high forming speed and a high strain rate.

Although some researchers have investigated how the strain rate affects the forming limits of steel sheets, the forming speed is much higher or lower than the forming speed of a conventional sheet metal forming process. Balanethiram and Daehn (1994) showed that the formability of AA6061-T4 and OFHC copper increases dramatically in high-speed forming. They obtained high strain rates by means of electrohydraulic forming tests. The metal sheets were formed into a conical die with an apex angle of 90° at velocities near 150 m/s. Tamhane et al. (1996) reported that the failure strain of AA6061-T4 and pure copper increases in relation to quasi-static ductility in an electromagnetically driven ring expansion test of the peak velocities in a range of 90–165 m/s. In another study, Seth et al. (2005) stated that the failure strains of cold rolled steel sheets increases beyond the failure strain levels obtained in tensile tests. They conducted the electromagnetically driven forming test with missile and wedge-shaped punches at velocities of 50–220 m/s. Hu (2004) indicated that the strain rate could influence the forming limits of TRIP450/800. Although the punch speeds were varied to examine how the strain rate affects FLDs during the forming test, the punch speeds produced no obvious effects on the forming limits at a forming velocity of less than 200 mm/s. This forming velocity range is lower than the forming speed of a conventional sheet metal forming process.

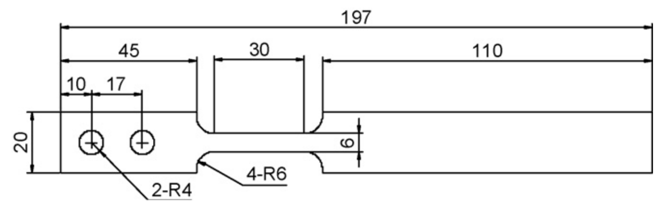

Fig. 1. Tensile specimen at high strain rate with the parallel region of 30 mm.

For this study, we selected two auto-body steel sheets of CQ and DP590 for the purpose of investigating the relation between formability and the strain rate. First, we conducted uniaxial tensile test to see how the strain rate affects the formability of CQ and DP590. Secondly, for a high-speed punch-stretch test, we designed a high-speed crash testing machine and jigs so that we could obtain the FLD under high-speed forming conditions. Finally, we used the constructed FLC to investigate how the strain rate affects the forming limit.

2. Uniaxial tensile test of steel sheets at high strain rates

2.1. Experimental procedure

Uniaxial tensile tests were conducted on low strength steel, CQ and advanced high strength steel, DP590 at quasi-static and high strain rates. The static tensile tests were conducted with an INSTRON5583 static tensile testing machine at a strain rate of 0.001/s and 0.01/s. Tensile tests at high strain rates were then conducted with the high-speed material testing machine used by Huh et al. (2009a,b) at a strain rate of 0.1–100/s. The test specimens were prepared in the loading directions: namely, the rolling direction (RD), the diagonal direction (DD), and the transverse direction (TD). Fig. 1 shows a tensile specimen at high strain rates with the parallel region of 30 mm, the width of 6 mm and the fillet radius of 6 mm. The dimension was tested and verified for its validity with experiments and numerical simulation by Huh et al. (2008). They tested the validity of several specimens with different dimensions and concluded the present specimen dimension was adequate to their equipment for the test.

The anisotropy of sheet metals is characterized by the *r*-value, which according to Hill (1950), can be defined as follows:

$$r = \frac{d\varepsilon_w}{d\varepsilon_t}, \quad \varepsilon_t = -(\varepsilon_l + \varepsilon_w) \tag{1}$$

where ε_l, ε_w and ε_t are the plastic longitudinal, width and thickness strains, respectively. These strains can be obtained from grids marked on the surface of specimen. The shape of grids gradually deforms during the uniaxial tensile test at static and high strain rate. The circle grids (each with a diameter of 2.54 mm) were printed by an electrochemical etching method on the surface of the specimen as shown in Fig. 2. The grid pattern is aligned along the uniaxial tension direction. The deformation of the grid in the gauge length was measured with a high-speed camera (Phantom V.9.0) and a Nikon macro lens so that we could calculate the plastic width and thickness strain of the tested specimens. As the strain rate increases, the