International Journal of Mechanical Sciences 108-109 (2016) 174–187

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Tension/compression hardening behaviors of auto-body steel sheets at intermediate strain rates

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ARTICLE INFO

Article history:
Received 5 September 2015
Received in revised form
21 December 2015
Accepted 13 January 2016
Available online 6 February 2016

Keywords:
Tension/compression test
Intermediate strain rate
DQ steel sheet
DP590 steel sheet
Bauschinger ratio
Permanent softening

ABSTRACT

This paper is concerned with the effect of the strain rate on the tension/compression hardening behavior of auto-body steel sheets. Since the repeated tension and compression prevails in sheet metal forming of deep drawing, accurate material properties under tension/compression loading paths are important to predict deformed shapes of steel sheets with numerical simulation. The in-plane tension/compression tests have not yet been performed for the rate-dependent material properties which are indispensable for practical sheet metal forming simulation. An experimental technique is established to conduct tension/compression tests of DQ and DP590 steel sheets at various strain rates ranging from 0.001 s^{-1} to 50 s^{-1}. A new clamping device for compression tests is designed to suppress a specimen from thickness-directional buckling with H-shaped clamping plates which are optimized for application of the DIC method. Novel devices to impose a designated tensile strain or compressive strain are also developed for tension/compression tests with the high speed material testing machine at intermediate strain rates. Tension/compression hardening curves are obtained with the variation of the strain rate. It is noted from the test results that the Bauschinger ratio is increased according to the increase of the strain rate. It represents the gradual decrease of the Bauschinger effect with the increase of the strain rate. In a transient period which occurs in loading reversal, the decrease of the tangent modulus appear slowly as the strain rate increases, so that the amount of the permanent softening becomes smaller as the strain rate becomes higher.

1. Introduction

The demand for complex-shaped sheet metal parts and high production rates has increased in the automotive industry. Auto-body steel sheets experience not only complicated loading paths, but also intermediate strain rates ranging from 0.1 s^{-1} to 100 s^{-1} in sheet metal forming. In these conditions, sheet metal forming involves undesirable defects that are influenced by reverse loading conditions, such as spring-back, wrinkling, and surface distortion. Numerical simulations are widely utilized to prevent these defects by estimating the deformed shape of materials under reverse loading conditions. Accurate material properties under reverse loading conditions are essential to construct a constitutive model that properly describes material behaviors in numerical simulation. To obtain accurate material properties, material testing should be performed under the environment that is similar to the condition in manufacturing processes. Thus, simultaneous consideration of reverse–loading conditions and intermediate strain rate conditions are necessary for the acquisition of the material properties which appropriately describe the deformation behavior in manufacturing processes.

Many researches have been conducted to investigate material characteristics in accordance with reverse loading paths for the Bauschinger effect. The Bauschinger effect refers to the phenomenon in which the yield strength of a material decreases when the loading direction is reversed. The Bauschinger effect accompanies the transient behavior and the permanent softening in stress–strain relationships [1,2]. Several researchers have developed experimental techniques to obtain material properties along reverse loading paths. They have first introduced torsion and shear tests to impose reverse loading paths, such as reverse torsion tests [3,4] and reverse shear tests [5]. Torsion and shear tests, however, could not display uniform strain distribution and their results were unfavorable to be interpreted as stress–strain responses.

Uniaxial in-plane compression tests are advantageous for the uniform deformation of the specimens gauge section although it has been difficult to realize because of specimens buckling. Thus, various methods have been conducted to prevent buckling of sheet metal

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http://dx.doi.org/10.1016/j.ijmecsci.2016.01.035
0020-7403/

materials during in-plane compression tests. In the early development of in-plane compression tests, small specimens with appropriate ratios of the gauge length to the thickness were utilized for the suppression of buckling [6,7]. These types of tests could be performed to obtain uniform strain distribution while the inhomogeneous strain distribution took place in large strain conditions due to the small size of specimens. For in-plane compression tests with a typical size of tensile specimens, side forces have been additionally imposed to specimens in the thickness direction to prevent specimens buckling. Many experimental systems have been developed to exert the side forces [8–16]. With specimens supported by various methods, tension/compression hardening behaviors have been investigated in uniform strain distribution at large strains. These in-plane tension/compression tests, however, have been conducted only at quasi-static states. None of experimental techniques have yet been developed to be able to consider the effect of intermediate strain rates.

It is well known that the material properties of steel sheets are influenced by intermediate strain rates [17]. At intermediate strain rates higher than a strain rate of tens per second, materials experience the effect of the inertia and the stress wave propagation, so that material properties are remarkably altered. Several methods, such as the mechanical method [18] and the drop weight method [19], have been attempted to measure the material properties at intermediate strain rates. Recently, most researchers utilize servo-hydraulic material testing machines to obtain accurate material properties at intermediate strain rates [17,20–22]. Furthermore, jig systems with hydraulic-servo testing machines have been employed to impose a certain designated tensile strain or compressive strain for bulk materials [23,24]. Nevertheless, in-plane compression tests with hydraulic-servo testing machines have not yet been conducted for steel sheets at intermediate strain rates.

In this paper, tension/compression tests of auto-body steel sheets are performed at intermediate strain rates ranging from 0.001 s^{-1} to 50 s^{-1}, which take place in practical automotive sheet metal forming. An advanced clamping device is newly introduced to exert side force for suppression of specimen buckling and to measure the strain easily. Additional novel devices are also designed to impose a certain tensile or compressive strain. Stress–strain curves of the tension/compression tests are obtained at strain rates ranging from 0.001 s^{-1} to 50 s^{-1}. The effect of the strain rate on the tension/compression hardening behavior is investigated quantitatively from the measured hardening curves.

2. Specimen preparation

Two types of materials, a drawing quality steel sheet (DQ, 1 mm thick) and a dual phase steel sheet (DP590, 1 mm thick), are selected for the tension/compress tests. They are frequently used in the automotive industry. Their chemical compositions are tabulated in Table 1.

In the plane compression tests, buckling of sheet metals may be induced due to eccentric loads and the thin thickness of sheet metals. Three types of buckling failure modes in sheet metals are presented in Fig. 1 [15]. (1) buckling along the thickness direction in the gauge region (T-buckling); (2) buckling in the unclamped region (L-buckling); and (3) buckling along the width direction in the gauge region (W-buckling).

Table 1
Chemical composition of DQ and DP590 (wt%).

Material	C	Mn	Si	P	S
DQ	0.085	0.420	0.040	0.0012	0.0150
DP590	0.326	1.700	0.123	0.0162	0.0009

For successful data acquisition in the plane compression tests, some methods are required to suppress those three buckling modes of sheet metals. In the cases of L-buckling and W-buckling, they can be avoided by properly designed specimen geometry. This method is based on the theoretical approach proposed by Boger et al. [12]. They calculated the attainable compressive strain which is not influenced by L-bucking and W-buckling with the use of the Secant formula and the Euler method as follows:

$$\bar{\varepsilon}_L = \left[\frac{B\sigma_y}{KW}\right]^{\frac{1}{n}} - \varepsilon_0 \quad (1)$$

$$\bar{\varepsilon}_W = \frac{\pi^2 n W^2}{3G^2} - \varepsilon_0 \quad (2)$$

Where B is the width of the specimen in the gripping region, W is the width of the specimen in the gauge region, G is the gauge length of the specimen in the gauge region. K, n, and ε_0 are coefficients of the swift model standing for the strength coefficient, the hardening exponent, and the plastic strain for the yield stress respectively. In this paper, the coefficients of the swift model are used to consider the strain rate effect to prevent L-buckling and W-buckling during the plane compression tests at various strain rates. The coefficients of the swift model for DQ and DP590 are listed in Table 2.

The geometry of a specimen is determined by using the above Eqs. (1) and (2). With the given width of the gripping region and the gauge length, the attainable compressive strain can be expressed as a function of only the gauge width. The width of the gripping region and the gauge length are chosen as 40 mm and 24 mm, respectively, considering the uniform deformation of the gauge region. Fig. 2 shows a diagram to obtain the attainable compressive strain before L- and W-buckling with respect to the gauge width at strain rates of 0.001 s^{-1} and 100 s^{-1}. This

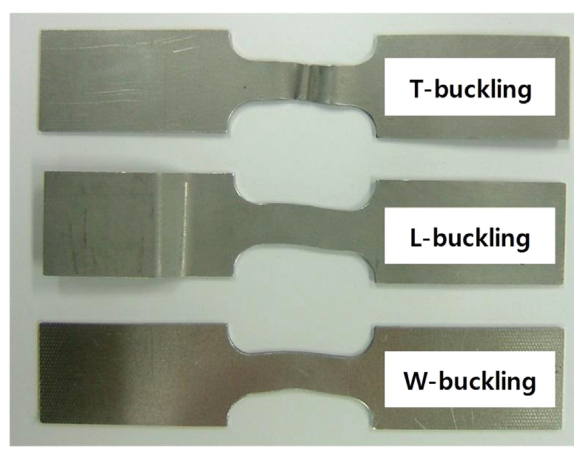

Fig. 1. Three representative buckling failure modes of sheet metals [15].

Table 2
Coefficients of the swift model of DQ and DP590 at strain rates of 0.001 s^{-1} and 100 s^{-1}.

Material	Strain rate (s^{-1})	K (MPa)	ε_0	n
DQ	0.001	538.05	0.0089	0.2638
	100	672.05	0.0156	0.1466
DP590	0.001	1074.41	0.0057	0.2127
	100	1142.75	0.0065	0.1870