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Measurement method for stress–strain curve in a super-large strain range

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ABSTRACT

Flow stress is an essential material property for metal forming. A stress–strain (SS) curve is generally measured by tensile testing or compression testing. In some metal forming processes, the maximum strain exceeds 5.0 (500%); however, standard testing methods can only measure an SS curve up to a strain of 1.0. Therefore, a new method was developed that enables us to measure an SS curve for strains up to 10.0.

High-pressure torsion (HPT) was applied for the measurement. Using HPT, it is possible to deform a specimen without fracture. Therefore, larger strains can be introduced into a specimen than with conventional methods. An SS curve measurement was performed for pure aluminum. The measured torque during HPT and the average strain in the specimen were converted into an SS curve. The SS curve measured using the developed method was compared with that obtained using a compression test. It is confirmed that the flow stress was successfully measured up to a strain of 10.0. In addition, the results for the developed method correspond with those of the compression test up to a strain of 1.0.

1. Introduction

It is well known that bulk material is heavily deformed during industrial metal forming processes. The strain introduced into a material by plastic deformation can be calculated using the finite element method (FEM), i.e., for cold forging [1], hot forging [2], forward [3] and backward extrusion [4], and ring rolling [5]. As shown in those papers, the maximum strain values range from 3.0 to 10.0 (300–1000%). In the design stage for manufacturing, the press load is estimated and the die material is determined using the stress–strain (SS) curve of the material. The SS curve is also used as input data for calculations when using FEM to predict material flow.

Tensile testing is a general method used to measure an SS curve. Stress and strain are expanded uniformly within the gauge length of a specimen. Therefore, the experimentally measured load and displacement are easily converted into an SS curve. The measurable strain range is relatively small. The maximum strain measurable in tensile testing depends on the material and is normally less than 0.5. With recent developments, it is possible to measure an SS curve with a strain over 1.0 by using an optical strain measurement system [6].

Compression testing is also applicable to bulk materials, and its measurable strain range is larger than that of a tension test. The strain distribution in a material during a compression test is not uniform, making it difficult to convert the measured load and displacement into an SS curve. In order to deal with this, a uniform compression test was developed [7]. In this test, a cylindrical specimen is compressed between smooth flat planes using a Teflon sheet and grease as lubricants. The lubricant is renewed at every 3–5% reduction in height. At every 20–30% reduction in height, the specimens are machined into cylindrical shapes. The machining was performed at a very slow speed to avoid heating the specimen. The Rastegaev test is another uniform compression test. In this test, shallow hollows are machined into both the top and bottom surfaces of the specimen to hold lubricant. During the compression test, the lubricant flows outward through the interface between the specimen and the dies. This reduces the friction force which causes non-uniform compression [8]. On the other hand, a method that allows the strain distribution from a compression test to be used to determine the SS curve was also developed [9]. The average strain and the restraint factor are first calculated with FEM, and then the measured load and displacement curve are converted into an SS curve. Using this compression test, an SS curve can be determined for a strain around 1.0.

Using the torsion test [10], a measurable strain range of 1.0–3.0 can be reached, depending on the material. The strain distribution

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from the torsion test is also not uniform. When the measured rotation angle and torque are converted into an SS curve, the non-uniform strain distribution and nonlinearity of the stress evolution must be considered. There are some reports of measuring an SS curve using torsion tests [11,12]. However, the effects of such strain and stress distributions have not been well studied.

Although a large strain is introduced by metal forming, there is no method to measure an SS curve over such a large strain range. When FEM calculations are conducted, an extrapolated SS curve based on the measured SS curve is sometimes used to cover the immeasurable strain range. In the previous study, one of the authors has studied the influence of the difference between the measured and extrapolated SS curves on material flow in FEM simulations. It was confirmed that the SS curve strongly affects material flow even if the difference between the measured and extrapolated SS curves is small, especially when predicting fracturing during the stamping process [13,14]. Therefore, an SS curve should be measured to cover the strain range expected throughout the actual forming process.

In this study, a method of measuring the SS curve for strains up to 10.0 is developed. There are two requirements for this method. The first is that it enables us to deform a material up to a strain of 10.0. The second is that the strain is uniform in the material or that the strain distribution is handled with a certain procedure to obtain the SS curve, as was mentioned for the compression test [9].

It is difficult to introduce strains exceeding 1.0 with general material testing methods. On the other hand, for the last 20 years, some material processing methods have been applied to conduct severe plastic deformation (SPD) and to improve material properties. Examples of SPD processing are equal-channel angular pressing (ECAP) [15,16], high-pressure torsion (HPT) [17,18], and accumulative roll bonding (ARB) [19]. With these SPD processing methods, it is possible to continue to deform a material without fracture. In this study, HPT was used because dimensional changes of a specimen while processing is relatively small compared with other SPD processing methods. This is an advantage when experimentally measured data is converted into an SS curve. The strain introduced into a material by HPT testing is not uniform; therefore, a procedure that takes the strain distribution into account must also be developed.

2. Experimental methods

2.1. HPT test

The material used for the specimens was pure aluminum (99.9%). The specimen dimensions used are shown in Fig. 1, and the

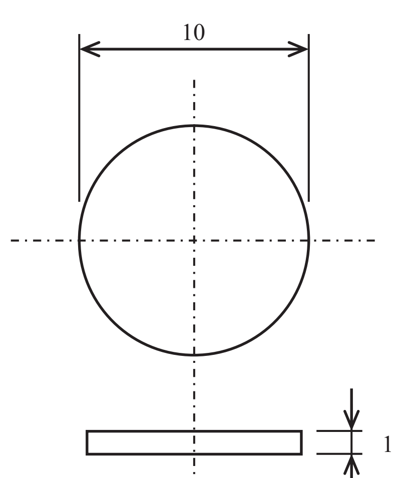

Fig. 1. Dimensions of the specimen for the HPT tests.

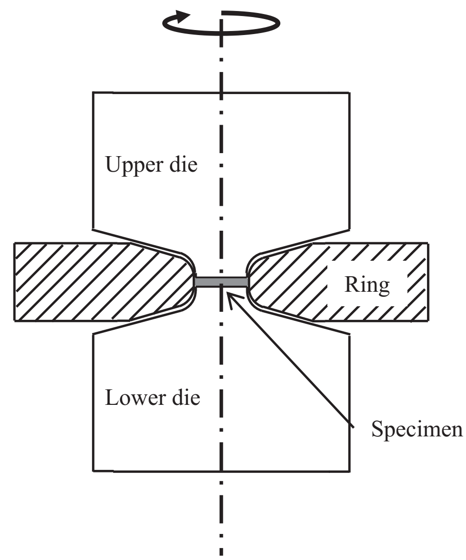

Fig. 2. Schematic diagram of the experimental setup for the HPT tests.

experimental setup is shown in Fig. 2. All the surfaces of the specimen were enclosed by the upper and lower dies and the ring. Therefore, the specimen dimensions did not change during HPT testing. In order to suppress sliding between the specimen and the upper and lower dies, small hollows and grooves were machined into the contacting surfaces of the upper and lower dies, as shown in Fig. 3.

The specimen was compressed at 1 GPa between the dies and was subsequently torsionally strained by the rotation of the upper die. Due to the high pressure, the specimen can be continuously strained without breaking. The rotation speed of the upper die was 1 rpm. The compression load, rotation angle, and torque of the upper die were measured during the test at room temperature.

2.2. Measurement of the actual rotation angle of a specimen in an HPT test

The specimen is torsionally strained by the rotation of the upper die. As reported by Kaveh et al., the rotation angle of the upper die is not always the same as that of the specimen [20]. Therefore, the actual rotation angle of the specimen after HPT testing should be measured to accurately determine the introduced strain.

Thin copper (Cu) foil was included in several HPT specimens. The foil thickness was 0.05 mm. A schematic of these specimens is shown in Fig. 4. After testing, each HPT specimen was inserted into a plate, on which radial lines were prescribed on both the front and back surfaces. Using the plate, the torsion angle of the Cu foil was measured from both the front and back views.

2.3. Compression test

A compression test was conducted to validate the SS curve measured using the developed method. The initial diameter and height of the specimens were 14 and 21 mm, respectively. For the contacting surface of the upper and lower dies, concentric circles were grooved to prevent the sliding of the specimens. The dimensions of the specimens and the contacting surfaces of the upper and lower dies are shown in Fig. 5. The measured load and displacement were converted into an SS curve based on the procedure proposed by Osakada et al. [9].

2.4. Torsion test

As written previously, it is not possible to measure an SS curve accurately with torsion testing. Therefore, torsion testing [10] was