Development of measurement method of work hardening behavior in large plastic strain for sheet metal forging

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Abstract. For the purpose of accuracy improvement of sheet metal forging FE analysis, we have developed a new measurement method of work hardening behavior in large plastic strain by repeatedly performing simple shear test using pre-strained steel sheet. In this method, it is possible to measure work hardening behavior more than equivalent plastic strain 2.0. In addition, it was carried out a comparison between developed method and compression test in order to verify the validity of the results by the developed method. As a result, both results were in good agreement. The validity of developed method has been verified.

Keywords: work hardening, large plastic strain, sheet metal forging, steel sheet

INTRODUCTION

The reduction in weight of automobile parts is significantly required to improve the fuel consumption of automobiles. Therefore, sheet metal forging parts which allow weight reduction by making distribution control of sheet thickness gradually increase. In addition, sheet metal forging allows for the reduction in cost by net-shape and near-net-shape forming without additional cutting and finishing operations [1].

However, sheet metal forging process is very complex because it includes both conventional press forming used tension and conventional cold forging used compression. So, it is essential for highly accurate FE analysis to quickly develop sheet metal forging process. Flow stress strongly affects the accuracy of sheet metal forging FE analysis, but extrapolated flow stress obtained by uniaxial tensile test is applied. Because it is difficult to measure the work hardening behavior in large plastic strain of a thin steel sheet using the conventional experimental procedure, such as uniaxial tensile test, hydraulic bulge test and simple shear test [2, 3]. Among these, simple shear test is difficult to cause plastic instabilities such as necking in uniaxial tensile test. However the sample is destroyed from the edge at large strain and leaded to the measurement limit [4].

Therefore, we have developed a new measurement method of work hardening behavior in large plastic strain by repeatedly performing simple shear test using pre-strained steel sheet. Furthermore, in order to verify the validity of developed method was compared with compression test.

EXPERIMENTAL PROCEDURE TO MEASURE WORKHARDENING BEHAVIOR IN LARGE PLASTIC STRAIN

Test Material

TABLE (1) shows mechanical properties of steel used in the experiment. The sample was used 440MPa grade hot-rolled steel sheet with a thickness of 2.0mm.

| YS /MPa | TS /MPa | u-EL /% | t-EL /% |
|---------|---------|---------|---------|
| 320     | 445     | 18      | 35      |

TABLE (1). Mechanical properties of used sample
Experimental Procedure

In order to suppress the failure from sample edges, we have devised a new method of performing repeatedly simple shear test using pre-strained steel sheet.

Simple shear test is promoted on flat sample shown in FIGURE 1 by fixing the parts with grips that are subjected to parallel displacement. The stress is directly proportional to recorded load while the strain is obtained by measuring the inclination of scribe lines in sample surfaces.

Shear stress and shear strain was converted to equivalent stress and equivalent plastic strain by using the following equation.

\[ \sigma_{eq} = \kappa \sigma_s \quad \text{and} \quad \epsilon_{eq} = \frac{1}{\kappa} \epsilon_s \]

(1)

where \( \sigma_s \) and \( \epsilon_s \) is shear stress and shear strain, \( \sigma_{eq} \) and \( \epsilon_{eq} \) is equivalent stress and equivalent strain, \( \kappa \) is coefficient relating the uniaxial tensile stress and shear stress.

Pre-strain is introduced by cold rolling in order to introduce a large pre-strain as possible. Equivalent plastic strain calculated in using the following equation.

\[ \epsilon_{eq}^p = -\frac{2}{\sqrt{3}} \ln \frac{t}{t_0} \]

(2)

where \( t \) and \( t_0 \) is initial thickness and after rolling thickness.

RESULTS AND DISCUSSION

Experimental Results

The stress-strain curves and work hardening rate obtained by uniaxial tensile test and simple shear test using non-prestrained sample are shown in FIGURE 2 (a) and (b). Stress-strain curves of uniaxial tensile test and simple shear test were in good agreement until equivalent plastic strain 0.2 which meet plastic instability at uniaxial tensile test. From this result, conversion according to formula (1) is reasonable. In addition, the measurement limit of the simple shear test was equivalent plastic strain about 0.5, it was about twice at the uniaxial tensile test.

FIGURE 2. Stress - strain curves and work hardening rates by uniaxial tensile test and simple shear test.
The stress-strain curves and work hardening rate obtained by simple shear test and repeated simple shear test using non-prestrained and pre-strained sample are shown in FIGURE 3 (a) and (b). Stress-strain curve of simple shear test and repeated simple shear test using non-prestrained were in good agreement. The measurement limit of repeated simple shear test using non-prestrained was equivalent plastic strain about 1.3, it was about six times at the uniaxial tensile test. On the other hand, Stress-strain curve of simple repeated simple shear test using non-prestrained sample and pre-strained sample were in good agreement without initial secondary deformation at pre-strained sample. Although high yield stress of repeated simple shear test using pre-strained is believed to cause cross effect that occurs because the slip system of primary deformation and secondary deformation is different, flow stress and work hardening rate is in good agreement with the non-prestrained sample in large secondary deformation. Therefore the results obtained by this method are considered to be reasonable. The measurement limit of repeated simple shear test using pre-strained was equivalent plastic strain about 2.0, it was about ten times at the uniaxial tensile test.

![Stress-strain curves and work hardening rates by simple shear test and repeated simple shear test using non-prestrained and pre-strained sample](image1)

**FIGURE 2.** Stress-strain curves and work hardening rates by simple shear test and repeated simple shear test using non-prestrained and pre-strained sample

The stress-strain curves obtained by repeated simple shear test using pre-strained and extrapolated the uniaxial tensile test by using swift’s power law are shown in FIGURE 4. Although both curves were in good agreement until equivalent plastic strain 0.3, it was significantly different in the more plastic strain range. Flow stress obtained by repeating simple shear test using pre-strained indicates a lower flow stress than the extrapolated curve to a tensile uniaxial test in the large strain region. The difference of flow stress occurred about 12% in the plastic strain 2.0. These differences are likely to affect the accuracy of sheet metal forging FE analysis such as forming load and material flow.

![Comparison of stress-strain curves of developed method and approximate results using swift’s power low.](image2)

**FIGURE 4.** Comparison of stress-strain curves of developed method and approximate results using swift’s power low.
Comparison of the Compression Test

In order to verify the validity of developed method was compared with compression test. Because it is difficult to carry out the compression test by using a thin steel sheet, cut out the sample from 540MPa grade S55C spherical annealing steel bar with a diameter of 55mm shown in TABLE (2). Compression test was carried out by upsetting the cylindrical sample of a height 21mm in diameter 14 mm between grooved plates. The calculation of the equivalent stress and the equivalent plastic strain was used method proposed by Osakada et al [5].

$$\sigma_{eq} = \frac{1}{f} \frac{P}{A_0}, \varepsilon_{eq}^p = g(e) = g\left(\frac{h_0 - h}{h_0}\right)$$

(3)

Where $P$ is a test load, $A_0$ is the initial cross-sectional area, $f$ is constrained coefficients, $h$ and $h_0$ is height of test sample before test and after test, respectively. Relationship of the $e$, $\varepsilon_{eq}$ and $f$ was used literature values [5].

The stress-strain curves obtained by repeated simple shear test using pre-strained and compression test using non-prestrained are shown in FIGURE 5. It was possible to measure work hardening behavior about equivalent plastic strain 1.0 and 1.6 using repeated simple shear test and compression test, respectively. Both stress-strain curves were in good agreement within the measuring range, the validity of the developed method has been verified.

| TABLE (2). Mechanical properties of used sample |
|-----------------------------------------------|
| YS /MPa | TS /MPa | u-EL /% | t-EL /% |
| 365     | 563     | 17      | 40      |

FIGURE 5. Comparison of stress - strain curves by repeated shear test and compression test.

CONCLUSION

For the purpose of accuracy improvement of sheet metal forging analysis, we have developed a measurement method of work hardening behavior in large plastic strain by repeatedly performing simple shear test using pre-strained steel sheet. The results obtained in this study are summarized as follows:

1) The newly developed method could measure work hardening behavior more than equivalent strain 2.0.
2) Both stress-strain curves were in good agreement within the measuring range, the validity of the developed method has been verified.

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