Biaxial deformation and martensitic transformation behaviour observation on type 304 stainless sheet by biaxial bulge test

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Abstract. Metallurgical characteristic phenomenon on type 304 stainless steel is the deformation induced martensitic transformation. To clarify the stress-strain curves and martensitic transformation behaviour, biaxial bulge test apparatus was developed. It enables to control the stress ratio of axial and circumference directions and equivalent plastic strain rate simultaneously. Biaxial bulge tests for uniaxial, equi-biaxial and plane strain cases were conducted at the constant temperature 20°C. The obtained martensite volume fraction vs. equivalent stress curves for all the tests were well agreed, so that it can be said that the martensite volume fraction was predictable by the maximum austenite stress.

1. Introduction

Austenitic stainless steels represented by type 304 stainless steel have excellent mechanical properties such as high ductility, high corrosion resistance etc. The martensitic transformation under large plastic straining is the important phenomenon that leads to the extensively large workhardening. Some constitutive equations that incorporate thus martensitic transformation under monotonic tension or compression have been proposed (e.g. Olson and Cohen [1], Stringfellow, Parks and Olson [2] Iwamoto, Tsuta and Tomita [3]). Geijselaers H J M, Hilkhuijsen P, Bor T C and Boogaard A H [4], and Hamasaki H, Ohno T, Nakano T and Ishimaru E [5] proposed constitutive equations for cyclic deformation which describe the stagnation of martensitic transformation caused by the Bauschinger effect. However, the stress-strain response and martensitic transformation behavior under complex deformation is still unknown because it is difficult to impose large plastic deformation under the constant stress ratio such as biaxial stress state.

In the present study, biaxial bulge test apparatus [6] was developed to perform biaxial bulge experiment. The experiments for uniaxial, equi-biaxial and nearly plane strain cases for type 304 stainless steel was carried out and the stress-strain curves and martensite volume fraction was obtained.
2. Experiments

2.1. Biaxial bulge testing machine

Figure 1 shows the overall view of biaxial bulge test apparatus. The test specimen is hollow and the inside of it is filled with machine oil. Two actuators are connected to the testing machine, and axial force and internal pressure can be loaded on the test specimen. The tension speed and internal pressure are controlled by maintaining both the prescribed stress ratio and equivalent strain rate. Strains in the axial and circumference directions were measured by DIC (Digital Image Correlation) and the curvature of the specimen, which is necessary for stress calculation, was achieved by using stereographic projection using 2 digital cameras. Drawing of the test specimen used in biaxial bulge test is shown in Figure 2.

![Figure 1. Biaxial bulge test apparatus.](image)

![Figure 2. Test specimen for biaxial bulge test.](image)

2.2. Experimental conditions

The specimen and specimen holders were covered with acrylic case and the atmosphere temperature in the case was controlled to keep the specimen temperature constant. The specimen temperature was measured by using thermocouple welded on the specimen and all the tests were performed at 20°C within ±2°C error. Since the martensitic transformation accompanies temperature rise, equivalent plastic strain rates for all tests were set to be $10^{-4}$/s that was slow enough to avoid in temperature rise during deformations. The experiments was carried out under the constant stress ratios $\sigma_\theta: \sigma_z = 0:1$ (uniaxial tension), 1:1 (equi-biaxial) and 1:2 (nearly plane strain) where $\theta$ and $z$ are the circumference and axial directions, respectively. Martensite volume fraction was measured at every 5% of plastic strain by ferrite meter (MP30, FISCHER instruments Co., Ltd) under the complete unloading state. The obtained martensite volume fraction was calibrated by the preliminary X-ray diffraction measurement results.

2.3. Calculation of stress and strain

The curvature radius of axial direction $R_z$ can be obtained by applying the cosine theorem and the sine theorem to three points in the axial direction. From distance between both ends of the same three points $l_{z}$, the axial true strain is given by the following equation in consideration of the curvature radius.

$$\varepsilon_z = \ln \left[ \frac{R_z \sin^{-1} \left( \frac{l_z}{2R_z} \right) - l_{z,0}}{l_{z,0}} + 1 \right]$$

(1)
Since the angle between the two circumferential end points and the radial center of the specimen is constant, the circumferential true strain $\varepsilon_\theta$ can be obtained directly from the distance $l_\theta$ between the two points.

$$\varepsilon_\theta = \ln\left(\frac{l_\theta - l_{\theta_0}}{l_{\theta_0}} + 1\right) \tag{2}$$

The axial true stress $\sigma_z$ is calculated from the balance of forces in the cross section in the radial direction on the specimen, as in equation (3). The circumferential true stress $\sigma_\theta$ is calculated from the balance of forces in the minute element in the center of the specimen, as in equation (4). In addition, $P$ is internal pressure, $D$ is outer diameter of parallel part of the specimen, $t$ is the wall thickness and $T$ is the axial force.

$$\sigma_z = \frac{P\pi(D^2/2-t)^2+T}{\pi t(D-t)} \tag{3}$$

$$\sigma_\theta = \frac{P(D-t)(R_z-t)}{2R_z-t} \sigma_z \tag{4}$$

3. Results and discussions

To validate our experiment, the stress ratios for the case of $\sigma_\theta:\sigma_z = 1:1$ and $1:2$ were plotted in Figure 3. It is obvious that obtained stress ratios were almost the same as those target ones.

![Figure 3. Stress ratio of each test condition.](image)

Fisure 4 shows the obtained martensite volume fraction vs. equivalent plastic strain curves for all the experiments. The results of equi-biaxial and plane strain are almost correlated. On the other hand, martensite volume fraction for uniaxial tension in axial direction is slightly smaller than others from the beginning of plastic deformation. In the author’s previous work, we reported that the martensite volume fraction can be predicted by the maximum stress in austenite applied in the course of deformation. In order to verify if the same tendency assumption is applicable, martensite volume fraction vs. equivalent stress was plotted as shown in Figure 5. Here, equivalent stress was calculated based on the Hill’s quadratic yield criteria (5).

$$f = A_1\sigma_z^2 - A_2\sigma_z\sigma_\theta + A_3\sigma_\theta^2 = \sigma_0^2 \tag{5}$$
This is because Mises’s quadratic yield criteria could not express the experimental results sufficiently. Table 1 shows parameters of Hill’s quadratic yield criteria. Its material parameters ($A_1$–$A_3$) were identified by using three stresses (uniaxial, plane strain and equi-biaxial) where plastic work for three cases were equivalent and one for uniaxial corresponded to that at 5% of plastic strain. The result shows that all the curves coincide better than those in Figure 4 throughout deformations. From these results, we could conclude that the martensite volume fraction can be calculated by the equivalent stress in austenite even in biaxial stress state.

**Table 1.** Parameters of Hill’s quadratic yield criteria.

| Parameters | $A_1$ | $A_2$ | $A_3$ |
|------------|-------|-------|-------|
|            | 1.0000| 0.8609| 1.0940|

**Figure 4.** Martensite volume fraction vs. equivalent plastic strain curves obtained by biaxial bulge tests.
Figure 5. Martensite volume fraction vs. equivalent stress curves obtained by biaxial bulge tests.

4. Conclusion

In the present study, biaxial bulge test apparatus was developed for the biaxial deformation test of type 304 austenitic stainless steel. strains in axial and circumference directions were measured by using DIC and stereographic projection technique. The biaxial tension tests for tube specimens were carried out at 20°C for the stress ratios $\sigma_\theta:\sigma_z = 0:1$, 1:1 and 1:2. The obtained results are summarized below:

1) Biaxial bulge test apparatus could control stress ratio accurately throughout the experiments.
2) Martensite volume fractions for uniaxial tension in axial direction and plane strain cases are almost correlated while it became slightly smaller for equi-biaxial deformation for the given equivalent plastic strain.
3) Martensite volume fractions for all the stress ratios at the given equivalent stress were well agreed throughout deformations. It indicates that martensite volume fraction is predictable by the maximum austenite stress as similar to the cyclic response.

References

[1] Olson G B and Cohen M 1975 Metall. Trans. A 6 791.
[2] Stringfellow R G, Parks D M and Olson G B 1992 Acta Metall. Mater. 40 1703.
[3] Iwamoto T, Tsuta T and Tomita Y 1998 Int. J. Mech. Sci. 40 173.
[4] Geijselers H J M, Hilkhuysen P, Bor T C and Boogaard A H 2015 Mater. Sci. Eng. A 631 166.
[5] Hamasaki H, Ohno T, Nakano T and Ishimaru E Int. J. Mech. Sci. In press.
[6] Yoshida K and Kuwabara T 2007 Int. J. Plast. 23 1260.