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Modelling of cyclic plasticity and martensitic transformation for type 304 austenitic stainless steel

Hiroshi Hamasaki [a,*], Tatsuya Ohno [a], Takashi Nakano [a], Eiichiro Ishimaru [b]

[a] Department of Mechanical Science and Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan
[b] Nippon Steel & Sumikin Stainless Steel Corporation, 3434, Shimata, Hikari, Yamaguchi 743-8550, Japan

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ABSTRACT

Isothermal monotonic tension and cyclic tests are conducted on type 304 austenitic stainless steel at 20, 50 and 80 °C from which stress-strain curves and martensite volume fraction were evaluated. The obtained data showed that deformation induced martensitic transformation was highly temperature dependent in monotonic tensile and cyclic tests. In cyclic test, stagnation of martensitic transformation was observed during the Bauschinger region, which imply that the transformation was triggered by austenite stress rather than the plastic strain. Finally, constitutive model based on stress induced hypothesis was proposed and it was validated by comparing the experimental results and the calculation with the conventional Stringfellow model.

1. Introduction

Austenitic stainless steel shows extensive workhardening even at large strain owing to the precipitation of hard α'-martensite phase by plastic deformation. Many experimental studies have revealed that the shear band (i.e., stacking fault, ε-martensite or mechanical twinning) intersection generated by plastic strain is the dominant nucleation site of α'-martensite [1–5]. The kinetics of α'-martensite formation were first proposed by Olson and Cohen [6] based on plastic strain-induced transformation. Stringfellow et al. [7] generalized the Olson-Cohen model by taking hydrostatic pressure and temperature effects into account. They demonstrated that the proposed model could accurately predict α'-martensite volume fraction vs. plastic strain curves for austenitic stainless steel under monotonic loading at a variety of temperatures. Their model has become a mainstream constitutive equation for austenitic stainless steel [8–11]. In contrast, very little attention has been paid to the stress-strain response and α'-martensitic transformation characteristics under large-strain cyclic deformation. Gallée et al. [12] carried out cyclic shear tests in which the reverse shear strain was up to 30%. However, they only showed shear stress-shear strain curves owing to the difficulty in measuring the α'-martensite volume fraction at the small deformed region of the specimen. Recently, Geijselaers et al. [13] performed large-strain cyclic shear tests and revealed that martensitic transformation stopped at the Bauschinger region because the martensitic transformation was induced by stress in the austenite phase. However, until now martensitic transformation under large-strain cyclic tension-compression has not been investigated. A constitutive modeling for such a cyclic mode starting from tension is vitally important, especially for metal forming simulation.

The present study consists of the experimental and the subsequent model proposal. In experimental part, large-strain monotonic and cyclic tension-compression tests were carried out on extruded type 304 austenitic stainless steel to evaluate stress-strain curves as well as the α'-martensite volume fraction in monotonic and cyclic deformation. The experiment was carried out under isothermal conditions (from 20 to 80 °C). The temperature dependence on stress-strain curve and martensite volume fraction under monotonic and cyclic loadings are discussed. Subsequently, the constitutive model for austenitic stainless steel based on stress induced martensitic transformation hypothesis is proposed. The model is applied for the evaluation of stress-strain curve as well as martensite volume fraction and the results are discussed by comparing with the experimental data and conventional constitutive model calculation.

2. Experimental procedure

2.1. Specimen

Extruded type 304 austenitic stainless steel was used for the cyclic experiments. Table 1 shows the chemical compositions (wt%) of the stainless steel. The hourglass shaped specimen as shown in Fig. 1 was machined and heat treated at 950 °C for 5 min followed by rapid air cool-

* Corresponding author.
E-mail addresses: hamahiro@hiroshima-u.ac.jp (H. Hamasaki), m110623@hiroshima-u.ac.jp (T. Ohno), m135489@hiroshima-u.ac.jp (T. Nakano), ishimaru.eiichiro.7q7@nssc.nssmc.com (E. Ishimaru).

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Table 1
Chemical compositions of type 304 stainless steel (wt%).

C	Si	Mn	Ni	Cr	Mo	Cu	N
0.054	0.47	1.1	8.01	18.02	0.17	0.36	0.0421

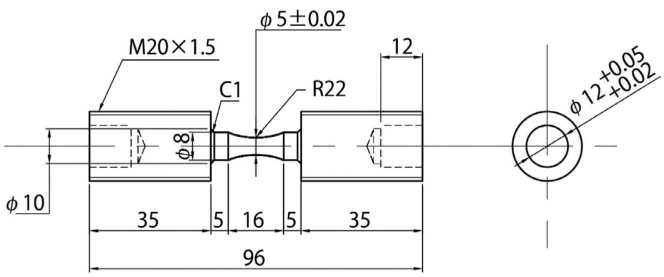

Fig. 1. Hourglass shaped specimen used for cyclic test.

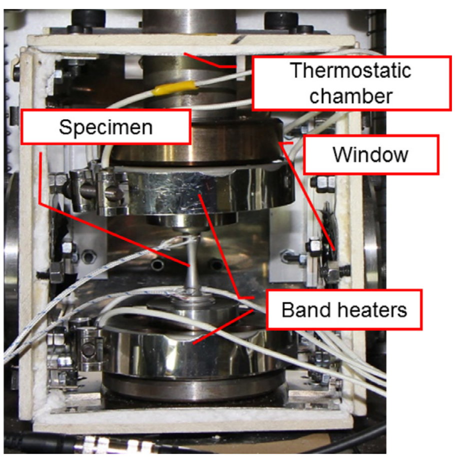

Fig. 2. Isothermal cyclic testing device.

ing. The specimen was made as that the loading direction was correlated with the direction of extrusion.

2.2. Isothermal cyclic testing device and strain measurement

The testing device shown in Fig. 2 was applied on the cyclic testing. The specimen and its grips were covered by the thermostatic chamber. The specimen's temperature was controlled with the error of ±2 °C, using band heaters attached on the surface of grips. For an accurate temperature control, thermocouples were welded on the upper and the bottom rounded parts of the specimen. Temperature difference between upper, center and bottom of the specimen was calibrated by the preliminary experiments. The universal testing machine (AG-IS, Shimadzu Co., Ltd) with load capacity of 50 kN was used for tension and cyclic tests.

Martensite volume fraction was measured at 4 points along the specimen's circumference by using ferrite meter (MP30, FISCHER instruments Co., Ltd) at every 5% of strain. It should be noted that applied load was released for the measurement of volume fraction because Post et al. reported that the measurement of magnetic field was greatly influenced by the applied stress [14]. For an accurate determination of the martensite volume fraction, thus measured volume fraction had been calibrated using the X-ray analysis (PSPC-MSF, Rigaku Co. Ltd).

Diameter of the central cross section was measured during the test by optical micrometer (TM-3000, KEYENCE Co., Ltd). The stress and strain in tensile direction σ_z and ε_z were calculated by the following equation;

$$\sigma_z = \frac{4P}{\pi d^2} \tag{1}$$

$$\varepsilon_z = \frac{1-2\nu}{E}\sigma_z - 2\varepsilon_r + f_m\varepsilon_V \tag{2}$$

where P and d denote applied load and diameter of the central cross section, $E = 198$ GPa and $\nu = 0.3$ are Young's modulus and Poisson's ratio, f_m is martensite volume fraction, ε_r is radial strain, and $\varepsilon_V = 0.032$ is volumetric strain due to the martensitic transformation. As mentioned above, martensite volume fraction was measured at every 5% of strain, it was linearly interpolated in the strain calculation using Eq. (2).

2.3. Experimental conditions

Uniaxial tensile test was conducted at 20, 50 and 80 °C. To achieve the homogeneous temperature distribution in the specimen, specimen was heated up to the target temperature, than the temperature was kept for 10 min. The crosshead speed 0.25 mm/min., which corresponds to the strain rate of about 10^{-4}/s, was applied for all tests to avoid temperature increase due to the martensitic transformation. To validate the hourglass shaped specimen, monotonic tension and compression results at 20 °C were compared with the results with the conventional specimens (JIS 4 for tensile test, and cylindrical specimen with the height of 7.5 mm and diameter of 5 mm for compression test).

For the observation of cyclic stress-strain curve and deformation induced martensitic transformation response of the present material, two tension-compression tests with the pre-strain of 15 and 20%, and ±5% cyclic were examined. Temperature and crosshead speed for cyclic tests were same as those adopted in tension test.

3. Experimental results

3.1. Validation of specimen shape

The hourglass shaped specimen was validated by comparing the stress-strain curves and martensite volume fraction with those from the conventional specimens. Fig. 3(a) and (b) show the stress-strain curves and martensite volume fraction vs. plastic strain curves obtained by the monotonic tension and compression tests at 20 °C, respectively. Solid lines denote results obtained from the hourglass shaped specimen and symbols (● and ○) are from JIS 4 type specimen and cylindrical specimen. Stress, strain and plastic strain for compression are shown by those absolute values. From both figures, it was found that the hourglass shaped specimen is reliable enough for tensile tests while it overestimates stress and martensite volume fraction in compression after −30% of strain where barreling deformation was confirmed. The compressive strain, however, in the present study never exceeds 30%, so that we conclude that the hourglass shaped specimen is applicable for cyclic test.

3.2. Temperature dependency under tensile tests

Stress-strain curves and martensite volume fraction vs. plastic strain curves obtained from tensile tests at 20, 50 and 80 °C are shown in Fig. 4(a) and (b), respectively. Flow stresses at 20 and 50 °C are almost identical up to the stain of 20% while stress is 60 MPa lower than the others at 80 °C. Martensite volume fraction exponentially increased with increase of plastic strain at 20 °C while martensite volume fraction was only 3.5% with the plastic strain of 0.44 at 50 °C and almost no martensitic transformation took place at 80 °C. From those results one can say that the martensitic transformation for the present material is highly temperature dependent and stress-strain curves at 80 °C is almost for the austenite single phase.

3.3. Cyclic response of austenitic stainless steel

Stress-strain curves and martensite volume fraction vs. plastic strain curves obtained at 20, 50 and 80 °C are shown in Figs. 5–7, respectively.