

Large-strain cyclic response and martensitic transformation of austenitic stainless steel at elevated temperatures

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Abstract. Cyclic tension-compression tests were carried out for austenitic stainless steel (SUS304) at elevated temperatures. The significant Bauschinger effect was found in the obtained stress-strain curve. In addition, stagnation of deformation induced martensitic transformation was observed just after stress reversal until the equivalent stress reached the maximum value in the course of experiment. The constitutive model for SUS304 at room temperature was developed, in which homogenized stress of SUS304 was expressed by the weighed summation of stresses of austenite and martensite phases. The calculated stress-strain curves and predicted martensite volume fraction were well correlated with those experimental results.

1. Introduction

Austenitic stainless steel shows extensive workhardening even at large strain owing to the precipitation of hard α' -martensite phase by plastic deformation. The constitutive equations (e.g. Stringfellow et al [1], and Geijselares et al. [2]) for an austenitic stainless steel with which martensitic transformation kinetics are incorporated were suggested. In the present study, large cyclic tension compression tests for an austenitic stainless steel (SUS304) were conducted at various temperatures (from 293 to 473K). The stress-strain curves as well as martensite volume fraction were measured during the deformation. From the obtained results, it was found that austenite phase show extensive workhardening at high temperature even though martensitic transformation did not take place. Additionally, stagnation of martensitic transformation due to the Bauschinger effect was found. The macroscopic constitutive model for the present material was proposed and it was found that the calculation results well predicted the stress-strain curves and martensitic volume fraction observed by the experiment at 293K.

2. Cyclic tension-compression test of austenitic stainless steel at elevated temperature

The material used for this study is an austenitic stainless steel type SUS304. The material was machined in the shape of tension-compression test specimen shown in Figure 1(a), and solution treated at 1223K for 5 minutes. Cyclic tension-compression apparatus is shown in Figure 1(b). A specimen was covered by the thermostatic chamber and specimen was warmed by the heaters installed in the



chamber. Uniaxial tension and cyclic tests were conducted at every 10K from 293 to 473K. The temperature error was found to be within 1K in every experiment.

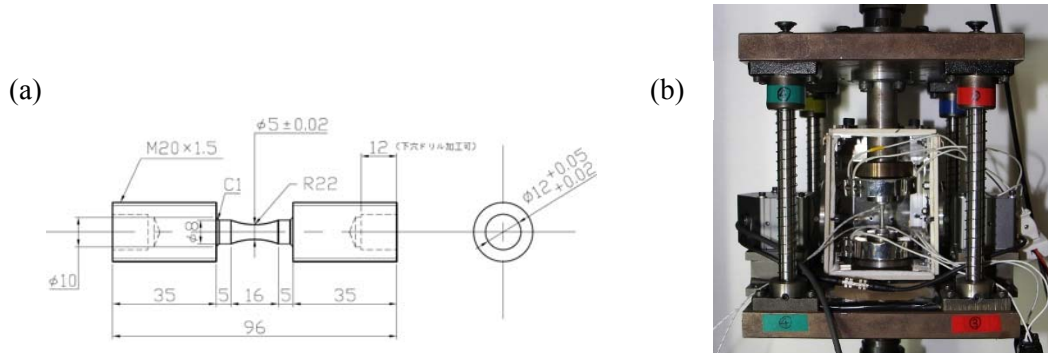


Figure 1. (a) Schematic of tension-compression specimen, and (b) cyclic tension-compression test apparatus.

3. Constitutive model for austenitic stainless steel

Let us assume the stress of austenitic stainless steel σ is expressed by the following rule of mixture;

$$\sigma = f_m \sigma_m + (1 - f_m) \sigma_a \quad (1)$$

where subscripts m and a denote martensite and austenite, respectively, and f_m is the volume fraction of martensite. The objective rates of martensite and austenite stresses are given as;

$$\dot{\sigma}_m = C_m^e \dot{\epsilon}^e = C_m^{ep} \dot{\epsilon}^e, \quad \dot{\sigma}_a = C_a^e \dot{\epsilon}^e = C_a^{ep} \dot{\epsilon}^e \quad (2)$$

where C^e and C^{ep} are the elastic and elastoplastic tangent moduli, and $\dot{\epsilon}$ is the strain rate tensor.

A linear isotropic hardening model was assumed for martensite as;

$$F_m = \bar{\sigma}_m - (Y_m + H_m \bar{\epsilon}_m^p) \quad (3)$$

where $\bar{\sigma}_m$ and $\bar{\epsilon}_m^p$ are the equivalent stress and equivalent plastic strain of martensite, respectively, and Y_m and H_m are the material constants. By assuming the von Mises yield criteria and associative flow rule, one can have the constitutive relationship of martensite as the following equation.

$$\dot{\sigma}_m = \left[C_m^e - \frac{C_m^e \frac{\partial F_m}{\partial \sigma_m} \otimes \frac{\partial F_m}{\partial \sigma_m} C_m^e}{\frac{\partial F_m}{\partial \sigma_m} C_m^e \frac{\partial F_m}{\partial \sigma_m} + H_m} \right] \dot{\epsilon} \quad (4)$$

On the other hand, we assumed Yoshida-Uemori kinematic hardening rule [3] for austenite phase since the strong Bauschinger effect was observed in cyclic test results.

$$\text{(Yield function)} \quad F_a = \phi(\sigma_a, \alpha) - Y_a \quad (5)$$

$$\text{(Kinematic hardening)} \quad \alpha = \alpha_* + \beta \quad (6)$$

$$\dot{\alpha}_* = C \left\{ \frac{a}{Y_a} (\sigma_a - \alpha) - \sqrt{\frac{a}{\alpha_*}} \alpha_* \right\} \dot{\epsilon}_a^p \quad (7)$$

$$\dot{\beta} = m \left\{ \frac{b}{Y_a} (\sigma_a - \alpha) - \beta \right\} \dot{\epsilon}_a^p \quad (8)$$

$$a = a_0 + R \quad (9)$$

$$\dot{R} = m(R_{sat} - R) \dot{\epsilon}_a^p \quad (10)$$

Similar to the case of martensite phase, von Mises yield criteria and associative flow rule were assumed then constitutive equation of austenite phase was derived as the following equation.

$$\dot{\sigma}_a = \left[\frac{C_a^e \frac{\partial F_a}{\partial \sigma_a} \otimes \frac{\partial F_a}{\partial \sigma_a} C_a^e}{\frac{\partial F_a}{\partial \sigma_a} C_a^e \frac{\partial F_a}{\partial \sigma_a} + \frac{Ca + mb}{Y_a} \frac{\partial F_a}{\partial \sigma_a} (\sigma_a - \alpha) - \frac{\partial F_a}{\partial \sigma_a} \left(C \sqrt{\frac{a}{\alpha_*}} \alpha_* + m\beta \right)} \right] \dot{\epsilon} \quad (9)$$

From the experimental observation, it was found that the martensitic transformation was induced by the maximum stress imposed in austenite phase. Hence the martensite volume fraction was given by the following form here;

$$f_m = 1 - \exp \left[-\beta_{oc} \left\{ 1 - \exp \left(-\alpha_{oc} \bar{\sigma}_{a, \max} \right)^{n_{oc}} \right\} \right] \quad (10)$$

where α_{oc} , β_{oc} and n_{oc} are material constants. It should be mentioned that the equation (10) is the empirical equation just to approximate the relationship between the martensite volume fraction and austenite stress obtained by the experiment. For an accurate model applicable to multiaxial stress state, further investigation such as biaxial tension with variety of stress ratio are essential. In addition to that, it was observed from the experiments that parameters in equation (10) could be different in tension and compression, therefore, α_{oc} , β_{oc} and n_{oc} were determined from monotonic tension and compression tests separately, and the following assumptions were used for the subsequent calculations:

- i) when starting from tension, parameters for tension were used throughout calculation
- ii) when starting from compression, parameters for compression were used throughout calculation
- iii) for cyclic test with $\pm 5\%$ of strain, parameters for tension were used throughout calculation

Material parameters used for the calculation are shown in Table 1 and 2.

Table 1. Parameters for martensitic evolution.

| | α_{oc} | β_{oc} | n_{oc} |
|-------------|---------------|--------------|----------|
| Tension | 0.0010 | 19.2 | 8.2 |
| Compression | 0.0012 | 4.1 | 6.1 |

Table 2. Parameters for hardening model.

| Ya /MPa | a_0 /MPa | C_1 | C_2 | b /MPa | m | R_{sat} /MPa | h | Y_m /MPa | H_m /MPa |
|---------|------------|-------|-------|----------|-----|----------------|------|------------|------------|
| 200 | 150 | 100 | 150 | 4.0 | 2.1 | 950 | 0.25 | 1750 | 10 |

4. Results

Figure 2(a) and (b) are the experimentally obtained stress-strain curves and f_m vs. plastic strain curves for each temperatures. The martensitic transformation becomes moderate with increase of test temperature. Since stress are almost the same below 8% of strain at any temperature, stress was not affected by temperature up to 353K. Therefore, one can conclude that the decrease in stress at large strain as the increase of temperature was caused by less precipitation of martensite which supposed to be harder than the austenite phase.

Figure 3(a) and (b) are the comparisons of stress-strain and f_m vs. plastic strain curves at 293K between experiment and simulation results, respectively. It is clear that the proposed model successfully predicted both stress-strain curve and martensite volume fraction, especially stagnation of martensitic transformation, were well predicted.

5. Conclusions

From the cyclic tension-compression tests for an austenitic stainless steel, we obtained the following findings:

- (i) deformation induced martensitic transformation would be minor at higher temperature,

- (ii) martensitic transformation stagnates due to the Bauschinger effect even if plastic strain accumulated.

Based on the experimental observations, constitutive model for austenitic stainless steel was proposed. The calculated results well predicted both cyclic stress-strain curves and fm vs. plastic strain curves obtained from experiments.

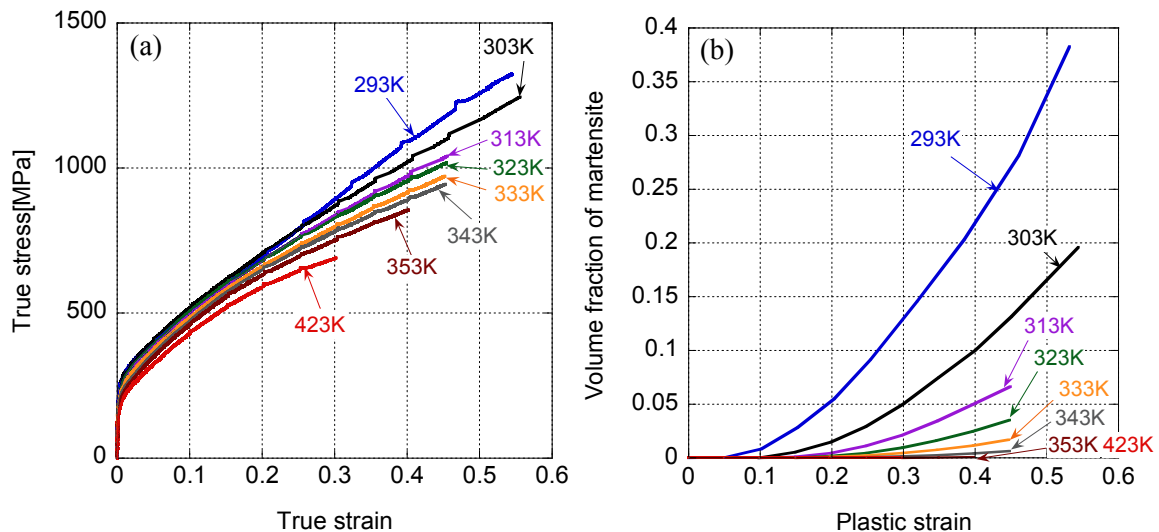


Figure 2. (a) Stress-strain curves and (b) volume fraction of martensite vs. plastic strain curves obtained from experiments at various temperature

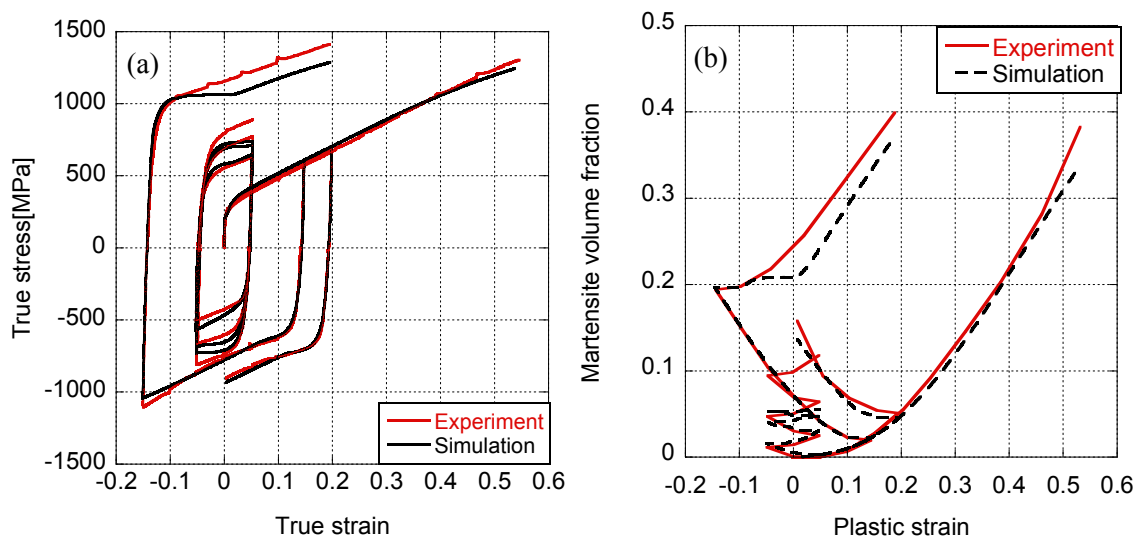


Figure 3. Comparisons of (a) stress-strain and (b) fraction of martensite vs. plastic strain curves between experiments and calculation results using the proposed model.

References

- [1] Stringfellow R G, Parks D M and Olson G B 1992 *Acta Metall. Mater.* **40** 1703.
- [2] Geijselaers H J M, Hilkhuijsen P, Bor T C and van den Boogaard 2015 *Mater. Sci. Eng. A* **631** 166.
- [3] Yoshida F and Uemori T *Int. J. Plast.* **18** 661.