Plastic Behavior of SUS 304 Subsequent to Creep * Prestrain at Various Temperatures

by Yasushi NIITSU ** and Kozo IKEGAMI ***

Plasticity-creep interaction effect was experimentally investigated at various temperatures. Combined stress tests were performed on thin-wall tubular specimens of austenite stainless steel SUS 304 at various temperatures in the range of 27~600°C. Plastic behavior at 600°C subsequent to creep prestrain produced at room temperature and those at room temperature subsequent to creep prestrain produced at 600°C was experimentally determined under various loading conditions. The stress-strain relations obtained by these experiments were compared with the results calculated by the equi-plastic strain surfaces. The influence of creep prestrain at room temperature on subsequent plastic behavior at higher temperature was nearly equal to that of plastic prestrain, but the influence of creep prestrain at high temperature on plastic behavior at room temperature was weaker than that of plastic prestrain.

Key Words: Plasticity, Creep, Stainless Steel, High Temperature, Combined Stress, Subsequent Behavior, Plasticity-Creep Interaction.

1. Introduction

Plastic deformation and creep deformation of the metallic materials have been independently investigated by many researchers. However, there are a few works on the interactions between plastic and creep deformations. For example, Brown⁽¹⁾ experimentally investigated the interactions between creep deformation and plastic deformation of aluminium alloy at high temperature; Kujawski et al.⁽²⁾ studied the time dependence of inelastic deformation of Type 304 stainless steel at room temperature; Greenstreet⁽³⁾ and Cho et al.⁽⁴⁾ examined the relations between creep deformation and plastic deformation of Type 304 stainless steel at high temperature; Ishizaki et al.⁽⁵⁾ investigated the yield surfaces subsequent to creep prestrain for carbon steel; Ohashi et al.⁽⁶⁾ researched the plastic behavior subsequent to creep prestrain under combined stress states at high temperature for SUS 316 stainless steel; and we⁽⁷⁾⁽⁸⁾⁽⁹⁾⁽¹⁰⁾ experimentally investigated the interactions between plastic and creep deformation at room temperature and at high temperature as well as the influence of temperature variations on plastic behavior for SUS 304 stainless steel.

In this paper, the effects of prior

creep strain at one temperature on plastic behavior at another temperature were experimentally investigated under combined stress states. The thin-wall tubular specimens of austenite stainless steel SUS 304 were used in these experiments. Temperature was changed from room temperature to 600°C or from 600°C to room temperature. These experimental results were compared with the stress-strain relations at constant temperature.

2. Experimental Method

The material used in the experiments was an austenite stainless steel SUS 304. The specimens were machined into thin-wall tubes with enlarged ends. They were heat treated in a vacuum at 1050°C for half an hour.

The combined tension and torsion stress testing machine⁽¹¹⁾ was used for the experiments. With this machine, axial load and torque were applied to the thin-wall tubular specimen at room temperature and 600°C. To obtain the axial and torsional strains on the specimen, two lever type measuring devices⁽¹²⁾ were used. The specimen was heated by a high frequency induction heating apparatus, and the temperature was raised at a rate of 2°C/sec. Loading of the specimen was started in about 5 minutes after the temperature reached the prescribed value. The stress rate on the loading paths in stress space was kept constant at 0.654 MPa/sec. The specimens were controlled to be in true stress state by a computer. Room temperature was kept at 27°C.

In this paper, inelastic strain induced by an increase or decrease of

* Received 30th September, 1983,
** Research Associate,
*** Professor, Research Laboratory of
Precision Machinery and Electronics,
Tokyo Institute of Technology,
(4259 Nagatsuta, Midori-Ku, Yokohama)

stress was defined as plastic strain, and one induced by a constant stress was defined as creep strain.

3. Experimental Results and Discussions

3-1: Plastic behavior at constant temperature

The tensile stress tests were performed at various temperatures in the range of 27°C ~ 600°C. The stress-strain curve showed a number of discontinuous steps at 600°C, which were caused by serration.

The stress-strain relations at constant temperature are approximated by the following smooth curves,

$$\sigma_F = \sigma_y + H\rho^a$$

$$\rho = \sqrt{(d\varepsilon^p)^2 + (d\gamma^p)^2/3} \quad \dots\dots\dots(1)$$

where σ_F and ρ are the equivalent stress and the accumulation of equivalent Mises type plastic strain, respectively. The notations $d\varepsilon^p$ and $d\gamma^p$ are the incremental values of axial and torsional plastic strains. The notations σ_y , H and α denote the material constants shown in Table.1, which are obtained by the tensile stress tests.

The combined stress-strain relation is discussed in terms of the equi-plastic strain surface in this paper. The shape of this surface in the combined stress space after tensile preloading is shown in Fig.1. In this figure, the dotted curve is a circle with radius σ_F , which corresponds to the isotropic hardening plastic potential. The stress σ_F is a flow stress for the total plastic strain in tensile loading. The stress σ_B is a decrease of the flow stress in opposite

Table.1 Parameters of the stress strain relation

Temp.	σ_y MPa	H MPa	α
27°C	189.8	48.7	0.69
200°C	112.8	34.9	0.80
400°C	93.3	36.5	0.78
600°C	72.1	37.1	0.76

Fig.1 Illustration of the equi-plastic strain surface

direction to the preloading, σ_C is a decrease of the flow stress in perpendicular direction to the preloading and σ_* is a shift of the center of this surface.

Using these parameters, the equi-plastic strain surface is described by the following equation, (ρ, ρ^p)

$$\left. \begin{aligned} \frac{(\sigma - \sigma_*)^2}{\xi + \eta \operatorname{sgn}(\sigma - \sigma_*)} + \frac{3\tau^2}{\sigma_F - \sigma_C} - 1 &= 0 \\ \xi &= [(\sigma_F - \sigma_*)^2 + (\sigma_* + \sigma_F - \sigma_B)^2]/2 \\ \eta &= [(\sigma_F - \sigma_*)^2 - (\sigma_* + \sigma_F - \sigma_B)^2]/2 \end{aligned} \right\} \dots\dots\dots(2)$$

where $\operatorname{sgn}(x)$ denotes the sign of the argument x . The flow stress σ_F is formulated by Eq.(1), and σ_B , σ_C and σ_* are approximated by the following equations used in the previous papers,

$$\left. \begin{aligned} \sigma_B(R.T.) &= \sigma_{B0} + \Delta\sigma_B \\ \sigma_{B0} &= 0.11\sigma_1[1 - \exp(-0.39\rho_1)] \\ \Delta\sigma_B &= 1.8(\sigma_1 - \sigma_{B0})\exp(-g\sqrt{\rho_1^2}) \\ g &= 3.09 + 2.32\exp(-0.61\rho_1) \\ \sigma_B(600^\circ\text{C}) &= \sigma_1[1.61\exp(-6.18\sqrt{\rho_1^2}) + 0.0711] \\ \sigma_C &= 0.499\sigma_B\exp(-2.1\sqrt{\rho_1^2}) \\ \sigma_* &= 0.499\sigma_B\exp(-0.802\sqrt{\rho_1^2}) \\ \sigma_1 &= \sigma_F(\rho = \rho_1) \end{aligned} \right\} \dots\dots\dots(3)$$

where ρ_1 and ρ_2^p are the equivalent plastic prestrain and the subsequent plastic strain, respectively.

3-2: Plastic behavior at various temperatures

To investigate the effects of both the temperature history and the plastic prestrain on the subsequent plastic behavior, the reloading tests after plastic prestrains were performed at various temperatures in the range of 27°C ~ 600°C. The testing temperature was changed at a rate of about 2.0°C/sec in partial unloaded stress state and held before reloading for 5 minutes. The experimental results together with the loading

Fig.2 Stress strain relations at various temperatures

and temperature conditions are shown in Fig.2. In this figure, the ordinate is the tensile true stress and the abscissa is the plastic strain subtracted by the thermal strain. The marks $\circ$ and Δ indicate the experimental results and the chain curves do the stress-strain relations at constant temperature which are calculated by Eq.(1). The experimental result coincides with the chain curve at each temperature. Therefore, the flow stress depends not on the temperature history but on the accumulated plastic strain in the case of monotonic loading process. The yield phenomenon like mild steel is observed clearly at 200°C and 400°C. Many steps in the stress-strain curve are observed at 600°C, which may be caused by dynamic strain aging.

In the former paper, we had investigated Bauschinger's effect after temperature change in the same material as one in the present tests. According to the results, in the case of reverse loading at high temperature, Bauschinger's effect did not depend on the prestraining temperature and Bauschinger's curve coincided with the curve of reverse loading at same temperature. However, in the case of reverse loading at room temperature, Bauschinger's effect depended on the prestraining temperature. The plastic prestrains at the temperatures in 600°C caused the same Bauschinger's effect at 600°C as the case of giving the plastic prestrain at 600°C. But, the plastic prestrains at higher temperature than room temperature gave weaker Bauschinger's effect than in the case of the room temperature prestrain.

3-3: Plastic behavior at 600°C subsequent to creep prestrain at room temperature

(A); Uniaxial stress state

The hardening effect of creep strain at room temperature was nearly equal to that of plastic strain at room temperature.^(P) To investigate the effect of creep strain at room temperature on the subsequent plastic behavior at high temperature, the tensile and compressive stress tests were performed with the specimens subjected to both plastic and creep prestrains. The loading conditions of the experiments are shown in Figs.3 (a) and (b). The creep stress is 200 MPa. At this stress, a plastic strain of 0.2%

Fig.3 Loading conditions of tensile and compressive stress tests at room temperature to 600°C

occurred, and a creep strain of 1.0% was produced in the specimen by applying the stress for 12 to 18 hours.

Figs.4 (a) and (b) show the experimental results at 600°C. In these figures, the ordinate is the equivalent stress and the abscissa is the subsequent plastic strain value. The marks $\circ$ indicate the experimental results subsequent to the plastic strain of 0.2% and the creep strain of 1.0% at room temperature, while the marks $\bullet$ do those subsequent to only the plastic strain of 0.2%. Therefore, the difference between these two results shows the effect of creep strain at room temperature on plastic behavior at 600°C. The solid and dotted curves in Fig.4 (a) are the stress-strain relations after the plastic strains of 0.2% and 1.2% at 600°C, respectively, which are calculated by equation (1). Those curves in Fig.4 (b) are the experimental results of Bauschinger's curves subsequent to plastic prestrains of 0.2% and 1.2% at 600°C. The marks $\circ$ coincide with the dotted curve and the marks $\bullet$ correspond to the solid curve, respectively. According to these results, this material at 600°C is hardened by creep strain at room temperature and the influence of the creep prestrain at room temperature on subsequent plastic behavior at 600°C is almost equal to that of the plastic prestrain at 600°C. This property

Fig.4 Stress strain curves at 600°C subsequent to plastic and creep prestrain at room temperature (a): Tensile curves (b): Compressive curves

is observed not only in the uni-directional stress-strain relation but also in Bauschinger's effect.

(B); Combined stress state

Similar experiments were performed in combined stress states. The loading condition in the stress space is shown in Fig.5 (a). The stress path was bent at the tensile stress of 75 MPa at 600°C subsequent to creep prestrain at room temperature. The experiment was conducted with five angles of θ_{σ} . Figs.6 (a) and (b) show the experimental results. In Fig.6 (a), the marks indicate the stress states at which the subsequent plastic strains reach the prescribed values, and the curves do the calculated equi-plastic strain surfaces subsequent to the plastic prestrain of 1.2% at 600°C. These curves are equivalent to the dotted curves in Figs.4 (a) and (b). The experimental results coincide with the calculated equi-plastic strain surfaces. A similar tendency is observed under combined stress state as well as uniaxial stress state. But, a characteristic hardening behavior is observed in this experiment. It is

Fig.5 Stress paths used in the experiment (a) and the calculation (b)

Fig.6 Results of equi-plastic strain surfaces (a) and strain trajectories (b) at 600°C subsequent to prestrain at room temperature

found that the equivalent flow stress for the case of $\theta_{\sigma} = 90^\circ$ or 135° is higher than that of $\theta_{\sigma} = 0^\circ$.

The arrows on the experimental points are plastic incremental vectors in stress space. The directions of these vectors are approximately normal to the equi-plastic strain surfaces.

Fig.6 (b) shows subsequent plastic strain trajectories. The curves in this figure are the results subsequent to 1.2% plastic prestrain at 600°C calculated by using the equi-plastic strain surface method. In this calculation, the flow rule of the plastic strain subsequent to prestrain is assumed such that the plastic strain incremental vector is normal to the equi-plastic strain surface. The experimental results coincide with the calculated curves.

3-4: Plastic behavior at room temperature subsequent to creep prestrain at 600°C

(A); Uniaxial stress state

To investigate the effect of creep prestrain at high temperature on the subsequent plastic behavior at room temperature, the tensile and compressive stress tests shown in Figs.7 (a) and (b) were performed. The creep stress at 600°C is 125 MPa. At this stress level, the instantaneous plastic strain was 1.6% and a creep strain of 1.4% was produced for 75 85 hours. Figs.8 (a) and (b) show the stress-strain curves at room temperature. The marks $\circ$, $\bullet$ and Δ indicate the experimental results subsequent to both the plastic prestrain of 1.6% and the creep prestrain of 1.4%, only the plastic prestrain of 1.6%, and only the plastic prestrain of 3.0%, respectively. The solid and dotted curves in Fig.8 (a) are the stress-strain relations subsequent to the plastic strains of 1.6% and 3.0% at room temperature, which are calculated by Eq.(1). The solid and dotted curves in Fig.8 (b) are the calculated Bauschinger's curves subsequent to the prestrains of 1.6% and 3.0% at room temperature by Eqs.(1) and (3). The flow stress is increased by the creep strain at high temperature, but it is lower than that subsequent to the plastic prestrain of 3.0%. Therefore, the hardening effect of creep strain at 600°C on plastic behavior at room temperature is slightly weaker than that of same value of plastic strain.

Fig.7 Loading conditions of tensile and compressive stress tests at 600°C to room temperature

(B); Combined stress state

Similar experiments were performed in combined stress states. The stress condition used in this experiment is shown in Fig.9 (a). The stress path was bent at 240 MPa at room temperature subsequent to both the plastic and creep prestrains at 600°C. The experimental results of the equi-plastic strain surfaces and subsequent plastic strain trajectories are shown in Figs.10 (a) and (b), respectively. The equivalent stress subsequent to the plastic prestrain of 1.6% and the creep prestrain of 1.4% is higher than that subsequent to only the plastic prestrain of 1.6%, but lower than that subsequent to the plastic prestrain of 3.0%. This material is hardened by the creep strain at high temperature and the equi-plastic strain surfaces at room temperature are slightly expanded in all directions by the creep strain at 600°C. In Fig.10 (a), the solid and dotted curves are the equi-plastic strain surfaces after the plastic prestrain at room temperature which were calculated by Eqs.(1), (2) and (3). Comparing the equi-plastic strain surfaces represented by solid and dotted lines and the corresponding experimental results, it is seen that the prestrain at room temperature gives an effect of distorting the equi-plastic strain surface but the plastic prestrain at 600°C causes

an approximately isotropic expansion of the equi-plastic strain surface at room temperature. The creep prestrain at 600°C produces a weaker hardening effect at room temperature than the plastic prestrain at 600°C. Fig.10 (b) shows comparisons between the calculated and experimental strain trajectories corresponding to the experiment of Fig.10 (a). In the experimental results, a difference between the case of plastic prestrain only and the case of both plastic and creep prestrains is recognized in the loading direction of $\theta_\sigma = 90^\circ$. In this direction, the strain trajectory is sensitive to the creep prestrain.

4: Conclusions

Combined stress tests to investigate plasticity-creep interactions were performed on thin-walled tubes of 304 stainless steel in the temperature range of

Fig.9 Stress paths used in the experiment (a) and the calculation (b)

Fig.8 Stress strain curves at room temperature subsequent to plastic and creep prestrains at 600°C (a): Tensile curves (b): Compressive curves

Fig.10 Results of equi-plastic strain surfaces (a) and strain trajectories (b) at room temperature subsequent to prestrain at 600°C

27~600°C. Plastic behaviors subsequent to plastic and creep prestrains under variable temperatures were examined experimentally. The stress-strain relations obtained in these experiments were compared with the results calculated by the equi-plastic strain surface. The following results were obtained.

(1) The influence of creep prestrain at room temperature on the subsequent plastic behavior at 600°C is almost equal to that of the plastic prestrain at 600°C.

(2) The equi-plastic strain surfaces at room temperature slightly expanded in all directions by the creep prestrain produced at 600°C. But, this hardening effect on plastic behavior at room temperature is weaker than that of the same value of plastic prestrain at 600°C.

(3) The characteristic hardening behavior is observed in the experiment, and the equivalent flow stress for the case of $\theta_{\sigma} = 90^{\circ}$ or 135° is found higher than that of $\theta_{\sigma} = 0^{\circ}$.

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