Plastic and Creep Deformations of Stainless Steel SUS 304 under Combined Stress States at Room Temperature *

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To investigate the plasticity-creep interaction effects, the combined stress tests for plastic behavior subsequent to creep pre-strain and creep behavior subsequent to pre-strain were performed at room temperature. In the experiments, the thin wall tubular specimens of SUS 304 stainless steel were used.

The stress-strain relations were obtained in these experiments and the plasticity-creep interaction effects were discussed on the basis of the experimental results. An attempt to predict subsequent behaviors to plastic and creep pre-strain was made using an equi-plastic strain surface and an imaginary hardening value of creep strain.

Key words : Plasticity, Creep, Stainless Steel, Room Temperature, Combined stress, Plasticity-Creep Interaction

1. Introduction

Recently, the structural components are used in severe conditions combining high temperature and complex loading. The materials of these components suffer not only elastic deformation but also inelastic deformations such as plastic and creep strains.

Plastic and creep behaviors of the metallic materials have been independently investigated by many researchers. However, there are a few works investigating the interaction between plastic deformation and creep one. For example, Brown⁽¹⁾ investigated the interactions between high temperature creep and plastic deformation of aluminum alloy, Tanaka et al.⁽²⁾ studied the yield surface subsequent to creep pre-strain at high temperature of carbon steel and aluminum alloy, and authors⁽³⁾ experimentally investigated the plasticity-creep interaction effect with SUS 304 at high temperature. Krempf⁽⁴⁾, Liu⁽⁵⁾ and Kujawski et al.⁽⁶⁾ investigated the time dependence of inelastic deformation of stainless steel of type 304.

In this paper, the inelastic behaviors of SUS 304 stainless steel are experimentally investigated under combined stress states at room temperature. Plastic behaviors subsequent to creep pre-strain and creep behaviors subsequent to plastic pre-strain are obtained under various loading conditions. The interaction effects of these deformations are discussed on the basis of the experimental results. An attempt to predict subsequent behaviors to plastic or creep pre-strain is made using the equi-plastic strain surfaces.

2. Nomenclature

- σ, τ : Axial stress, torsional stress
- $|\sigma|$: Equivalent stress (Mises type)
- $|\sigma| = \sqrt{\sigma^2 + 3\tau^2}$
- σ_0 : Axial pre-stress
- σ_H, τ_H : Axial hold stress, torsional hold stress
- ϵ^i, γ^i : Axial inelastic strain, torsional inelastic strain
- ϵ^p, γ^p : Axial plastic strain, torsional plastic strain
- ρ : Equivalent inelastic strain
- $\rho = \sqrt{(\epsilon^i)^2 + (\gamma^i)^2} / 3$
- ρ^p : Equivalent plastic pre-strain
- ρ^c : Equivalent creep pre-strain
- ρ^p : Subsequent plastic strain
- $\sigma_F, \sigma_B, \sigma_C, \sigma_s$: Material parameters determining the equi-plastic strain surface

3. Experimental method

The material used in the experiments is an austenite stainless steel, SUS 304. The chemical component of this material in weight percent is shown in Table.1. The specimens shown in Fig.1 are machined from 3.0 cm dia rods into thin wall tubes with enlarged ends. Before testing, the machined specimens are heat treated in vacuum at 1050°C for half an hour and then they are cooled in air out of chamber.

The experiments are performed using a combined tension-torsion testing machine⁽⁷⁾. The axial load and torque are applied to the thin wall tubular specimens. The axial and torsional strains of the specimen are measured with three strain gages on the surface of specimen. The values of true stresses are controlled by a micro-computer. In the experiment, the stress rate on the loading path is kept constant at 0.653MPa/sec.

Inelastic strain produced by an increasing stress is defined as plastic

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strain, and that by a constant stress is defined as creep strain.

4. Experimental results and discussions

4-1 The effect of creep pre-strain on plastic behaviors

(a) Uniaxial stress states

For investigating the effects of creep pre-strain on plastic deformations, the step up creep tests are performed by pure tension and pure torsion at room temperature. The results obtained as equivalent stress and equivalent inelastic strain curves are shown in Fig.2. The solid curves are stress-strain curves at constant stress rate of 0.653 MPa/sec. The marks $\circ$ and $\bullet$ are the experimental results obtained as subsequent plastic stress-strain curves after creep tests at 200MPa and 250MPa. The plastic strain subsequent to creep strain is not produced until the increasing stress approaches the solid curve. After the stress reaches the solid curve, the plastic strain is produced again. The flow stress coincides with the solid curve. This property is shown in both tensile and torsional stress states. A similar result was obtained in the experiment by Kujawski et al.⁽⁶⁾

According to these experimental results, this material is hardened in the

preloading direction not only by plastic strain but also by creep strain. The hardening value by creep strain is nearly equal to that by same value of plastic strain.

The creep curves in the step up creep tests are shown in Fig.3. Here, the horizontal axis shows creep time and the vertical axis shows the creep strain which is produced after stress is held. The initial creep rate coincides with the plastic strain rate just before stress is held, and the creep rate decreases rapidly.

To investigate the effect of creep pre-strain on Bauschinger's effect, compression tests are performed with the specimens which have been given tensile plastic and creep pre-strains. The relations between equivalent stress and subsequent plastic strain after pre-strain are shown in Fig.4. In Fig.4 (a), Bauschinger's effect subsequent to only 0.12% plastic pre-strain ($\bullet$ marks) appears to be very small, whereas that effect subsequent to 0.1% plastic pre-strain and 1.0% creep pre-strain ($\circ$ marks) is observed clearly. The curve marked with $\circ$ almost coincides with the stress strain curve subsequent to only 1.4% plastic pre-strain (Δ marks). In Fig.4 (b), the stress-strain curve subsequent to both 1.44% plastic pre-strain and 1.6% creep pre-strain coincides with that subsequent to only 3.0% plastic pre-strain. In Fig.4 (c), Bauschinger's curve subsequent to 4.0% plastic strain and 2.1% creep strain coincides with that subsequent to only 6.0% plastic pre-strain.

According to these results, the effect of creep pre-strain upon Bauschinger's effect is almost equal to that of the same

Table.1 Chemical composition of the test material

C	Si	Mn	P	S	Ni	Cr	Fe
0.07	0.62	1.23	0.27	0.03	8.74	18.2	70.8

Fig.1 Shape and dimensions of test specimen

Fig.2 The influence of creep pre-strain on subsequent plastic behaviors

Fig.3 Creep curves at room temperature

Fig.4 The influence of creep pre-strain on Bauschinger's effect

value of plastic pre-strain at room temperature, too. Plastic behaviors subsequent to plastic and creep pre-strains can be estimated from the following total pre-strain ρ_1 .

$$\rho_1 = \rho^p + \rho^c \dots \dots \dots (1)$$

(b) Combined stress states

To investigate the effect of creep pre-strain on plastic behaviors in combined stress states, experiments for loading along the stress paths shown in Fig.5 are performed. First, the specimen is loaded in a tensile direction until the stress reaches σ_0 and the stress is held for t_H hours. Then, the direction of the stress path is bent to the angle θ_σ and the specimen is reloaded at a constant stress rate until the equivalent stress reaches $(\sigma_0 + 50)$ MPa. The experiments are performed for two holding stresses (200MPa and 250MPa) and five bending angles (0° , 90° , 135° , 158° and 180°).

The experimental results are discussed using the equi-plastic strain surface. The equi-plastic strain surface is defined by the collections of stress points in the stress space at which the equivalent plastic strain subsequent to preloading reaches a certain value. One of the equi-plastic strain surfaces is defined by the case of one equivalent plastic strain subsequent to one preloading condition. The shape of this surface in the combined stress space by tensile preloading is shown in Fig.6. In this figure, the dotted curve is a circle with radius σ_F , which coincides with the isotropic hardening plastic potential. The stress σ_F is a flow stress for the total plastic strain in tensile loading. σ_B is a decrease in the flow stress in the opposite direction to the preloading, σ_C a decrease in the flow stress in the perpendicular direction to the preloading and σ_* a shift in the center of this surface.

With those parameters σ_F , σ_B , σ_C and σ_* , the equi-plastic strain surface is formulated by the following equation.

$$f = \frac{(\sigma - \sigma_*)^2}{\xi + \eta \operatorname{sgn}(\sigma - \sigma_*)} + \frac{3\tau^2}{(\sigma_F - \sigma_c)^2} - 1 = 0$$

$$\xi = \frac{1}{2} \{ (\sigma_F - \sigma_*)^2 + (\sigma_* + \sigma_F - \sigma_B)^2 \}$$

$$\eta = \frac{1}{2} \{ (\sigma_F - \sigma_*)^2 - (\sigma_* + \sigma_F - \sigma_B)^2 \}$$

Fig.5 Stress paths used in the combined stress tests

$$\operatorname{sgn}(x) = \begin{cases} 1 & \dots x > 0 \\ 0 & \dots x = 0 \\ -1 & \dots x < 0 \end{cases} \dots \dots \dots (2)$$

The flow stress σ_F is obtained by the tensile stress test and formulated as follows,

$$\sigma_F = 188 + 50.3\rho^{0.59} \dots \dots \dots (3)$$

The other parameters in Eqs.(2) are related with plastic strain as follows,

$$\left. \begin{aligned} \sigma_B &= \sigma_{B0} + \Delta\sigma_B \\ \sigma_{B0} &= 0.11\sigma_1 \{1 - \exp(-0.39\rho_1)\} \\ \Delta\sigma_B &= 1.8(\sigma_1 - \sigma_{B0}) \exp(-g\sqrt{\rho_1^2}) \\ g &= 3.09 + 2.32 \exp(-0.61\rho_1) \\ \sigma_C &= 0.499\sigma_B \exp(-2.1\sqrt{\rho_1^2}) \\ \sigma_* &= 0.499\sigma_B \exp(-0.802\sqrt{\rho_1^2}) \\ \sigma_1 &= \sigma_F(\rho = \rho_1) \end{aligned} \right\} \dots \dots \dots (4)$$

The numerical values in Eqs.(4) have been determined from the experimental results for loading along the straight stress paths with a corner.

The experimental results and the equi-plastic strain surfaces are shown in Fig.7. The solid curves indicate the results calculated by substituting $\rho_1^p + \rho_1^c$ of the experiments into ρ_1 in Eqs.(2), (3) and (4). The marks in Figs.7 (a) and (b) indicate the stress points where the subsequent plastic strain reaches a certain value in the experiments. The experimental results of $\theta_\sigma = 90^\circ$ are inside the calculated equi-plastic strain surfaces and those of $\theta_\sigma = 135^\circ$ are outside the solid curves. But, the others coincide with the solid curves.

The arrows on the marks indicate the plastic strain incremental directions in the strain space. These directions are approximately normal to the calculated equi-plastic strain surfaces. Then the flow rule of the plastic strain subsequent to pre-strain is assumed such that the plastic strain incremental vector is normal to the equi-plastic strain surface. So, the relation between the function f and the plastic strain incremental vector $d\epsilon^p = (d\epsilon^p, d\gamma^p/\sqrt{3})$ is as follows,

$$d\epsilon^p = \operatorname{grad} f d\lambda, \quad d\lambda = \frac{d\rho^p}{|\operatorname{grad} f|} \dots \dots \dots (5)$$

Fig.6 The illustration of the equi-plastic strain surface

where $d\lambda$ is a positive incremental value which depends on the stress, the strain in the loading path.

Figs.8 (a) and (b) show the results of the strain trajectories after pre-straining in the experiments shown in Figs.7 (a) and (b). The solid lines are the calculated results obtained by using Eq.5. The experimental trajectories agree well with the calculated results.

4-2 Creep behaviors at room temperature

The experimental results of the relations between creep strain and holding time are shown in Fig.9. The specimens are loaded at a constant stress rate and then the stress is held. The relations between the creep rate and the creep strain on a log scale are shown in Fig.10. The experimental result at each holding stress level falls on straight line. To predict this creep behavior, a creep hardening value denoted by $\Delta\sigma$ is introduced. This value is schematically shown in Fig.11 (a) for uniaxial stress state, where the dotted curve is a stress strain curve at a constant stress rate. The value $\Delta\sigma$ denotes the hardening value by plastic strain whose magnitude is equal to the creep strain. $\Delta\sigma$ in the combined stress state is schematically shown in Fig.11 (b). This value is defined as the minimum distance between the stress vector

$\sigma_f(\rho_1 + \rho^c)$ on the equi-plastic strain surface $f(\rho_1 + \rho^c)$ and the holding stress σ_H ,

$$\Delta\sigma = \min\{|\sigma_f(\rho_1 + \rho^c) - \sigma_H|\} \quad \text{.....(6)}$$

and the flow rule for this creep strain is assumed as follows,

$$\frac{\dot{\epsilon}^c}{|\dot{\epsilon}^c|} = \frac{\min\{|\sigma_f(\rho_1 + \rho^c) - \sigma_H|\}}{\min\{|\sigma_f(\rho_1 + \rho^c) - \sigma_H|\}} \quad \text{.....(7)}$$

$$\dot{\epsilon}^c = (\dot{\epsilon}^c, \dot{\gamma}^c/\sqrt{3})$$

where $\dot{\epsilon}^c$, $\dot{\gamma}^c$ are axial creep strain rate and torsional creep strain rate, respectively. The numerator on the right side of Eq.(7) is a vector which satisfies Eq.(6). Using

Fig.7 The equi-plastic strain surfaces subsequent to plastic and creep pre-strain

Fig.8 Plastic strain trajectories subsequent to preloading

Fig.9 Creep curves at various tensile stress levels at room temperature

the value $\Delta\sigma$, the creep behavior at room temperature is formulated by the following equation,

$$\ln \dot{\rho}^c = \alpha - k \Delta\sigma \dots \dots \dots (8)$$

The notation α is a logarithmic initial creep rate which coincides with the plastic strain rate just before stress is held. Therefore, the value of α is calculated by combining Eq.(3) and the following equation,

$$\alpha = \ln \left(\frac{d\rho^p}{dt} \right) \sigma = \sigma_n, \sigma = (\sigma, \sqrt{3} \tau) \dots \dots \dots (9)$$

The notation k in Eq.(8) denotes a value depending on the holding stress. The values of k obtained from the experimental results are shown in Table.2.

The curves in Fig.9 and 10 represent the calculated results obtained by using Eqs.(3), (8) and (9). The calculated curves almost agree with the experimental results. Now this treatment of the uniaxial creep behavior is applied to the case of the combined stress state with the hardening value $\Delta\sigma$ shown in Fig.11 (b) and Eq.(7). The creep strain trajectories subsequent to pre-strain are shown in Fig.12. The horizontal axis in the figure is the subsequent axial creep strain and the vertical axis is the subsequent torsional creep strain divided by $\sqrt{3}$. In this experiment, the specimens are loaded in a tensile direction and are subjected to a creep deformation for six hours at 250MPa. Next, the stress path is bent and the stress is held at the points (1) and (2) shown in Fig.12. The solid and dotted curves in Fig.12 are calculated results obtained by using Eqs.(1) to (9). The calculated creep strain is larger than the experimental result. Figs.13 (a) and (b) show the creep curves subsequent to pre-strain. These experimental results are obtained when the stress is held again after the equivalent stress reaches $(\sigma_0 + 50)$ MPa in the experiments shown in Fig.5. The curves in Fig.13 are calculated results by using Eqs.(1) to (9). In these experiments, the

equivalent holding stress is larger than pre-stress σ_0 , so the direction of the creep strain rate coincides with that of the holding stress vector. The calculated curve in the case of $\theta_\sigma = 0^\circ$ coincides with that of $\theta_\sigma = 180^\circ$. The calculated results almost equal to the experimental curves in the cases of $\theta_\sigma = 0^\circ$ and 180° . But, in the cases of other angles, the calculated creep strain is larger than the experimental results. These differences are due to an under estimate of the initial creep rate.

4-3 Cyclic stress strain relations ⁽⁸⁾

The softening effect of creep behavior was observed in the opposite direction to preloading like Bauschinger's effect.

Cyclic creep test, whose stress condition is shown in Fig.14, are performed. First, the specimen is loaded in tensile direction and the stress is held for 12 hours at 300MPa. Second, the specimen is reloaded in compressive direction and the stress is held for 12 hours at -300MPa. Afterward, these procedures are repeated cyclically.

The stress-strain relations while the specimen is being reloaded from tension to compression, or from compression to tension, are shown in Fig.15. The horizontal axis in the figure is the produced plastic strain

Table.2 Calculated value of the parameter k

σ MPa	200	250	300
k MPa ⁻¹	0.180	0.232	0.256

Fig.10 The relation between creep rate and creep strain at room temperature

Fig.11 Hardening value $\Delta\sigma$ in uniaxial and combined stress states

Fig.12 Creep strain trajectories after stress is held at the points (1) and (2)

during the reloading process and the vertical axis is the equivalent stress. Three curves are calculated results obtained by using Eqs.(3) and (4). In this computation, the accumulated total strain is substituted for ρ_1 in Eqs.(3) and (4).

$$\rho_1 = \sum \rho^p + \sum \rho^c \quad \text{.....(10)}$$

The experimental stress-strain curves agree well with the calculated results.

Four creep curves in this experiment are shown in Fig.16. Four curves in the figure are obtained by using the calculated

(a)

(b)

Fig.13 Creep curves in combined stress state

Fig.14 Loading condition of tension and compression test

stress-strain curves shown in Fig.15 and Eqs.(6), (8) and (9). The creep strains decrease in every loading cycle. The calculated results agree fairly well with the experimental creep curves.

5. Conclusions

To investigate the plasticity-creep interaction effects experimentally, the combined stress tests for plastic behavior subsequent to creep pre-strain and creep behavior subsequent to pre-strain are performed at room temperature. In the experiments, the thin wall tubular specimens of SUS 304 stainless steel are used.

The stress-strain relations in these experiments are obtained and the plasticity-creep interaction effects are discussed on the basis of the experimental results. An attempt to predict subsequent behaviors to plastic or creep pre-strain is made by using the equi-plastic strain surfaces. The following results are obtained.

(1) The influence of tensile creep pre-strain on subsequent tensile stress strain curve is almost equal to that of same value of plastic strain, and this property is observed in torsional stress strain curve and Bauschinger's curve.

(2) In combined stress states, the influence of tensile creep pre-strain on the equi-plastic strain surfaces possesses simi-

Fig.15 Stress-strain curves while the specimen is reloaded in the opposite direction

Fig.16 Creep curves of tension and compression test shown in Fig.14

lar properties of uniaxial stress state.

(3) The tensile creep rate is predicted from the hardening value $\Delta\sigma$. This is a hardening value by creep strain which is equal to that by same value of plastic strain.

(4) Creep behaviors in combined stress state subsequent to pre-strain are experimentally investigated. The calculated results obtained by using the hardening value $\Delta\sigma$ and the equi-plastic strain surface show the same tendency as the experimental results.

(5) Stress-strain relation and creep behavior of the cyclic stress test can be estimated from the hardening value $\Delta\sigma$.

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