Experimental Observation on Viscoplastic Behavior of SUS 304*

(Creep and Ratchetting Behavior)

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A unified constitutive model which can predict cyclic plasticity, uniaxial and biaxial ratchetting, creep, and stress relaxation is required by designers of aeronautic equipment, nuclear reactors and so on. Detailed experimental observation of considering viscoplastic behavior of materials must be carried out to construct a unified constitutive model. In this paper, uniaxial and biaxial ratchetting tests and creep tests were carried out at room temperature and at 550°C using SUS 304 stainless steel. As a result, it is clarified that uniaxial ratchetting behavior is affected by the viscous deformation of the material, and that biaxial ratchetting behavior is affected by both the viscous deformation of the material and the deformation caused by nonproportional loading.

Key Words : Unified Constitutive Model, Uniaxial Ratchetting, Biaxial Ratchetting, Creep, Viscoplasticity, Nonproportional Cyclic Plasticity

1. Introduction

Many parts of spacecraft, airplanes and nuclear systems are subject to complex load histories combining cyclic plasticity, creep and ratchetting. Constitutive models are required for the design of these parts and many models have been proposed⁽¹⁾⁻⁽⁶⁾. However, these models cannot predict uniaxial ratchetting, biaxial ratchetting, creep, and especially, the interaction between creep and ratchetting.

Experimental observation is very important for construction of a constitutive model for cyclic plasticity. Kujawski et al.⁽⁷⁾ observed interaction between cyclic plasticity, creep and stress relaxation during cyclic loading. Murakami et al.⁽⁸⁾ observed the effect of temperature on nonproportional cyclic loading using SUS 316 stainless steel. Moreover, Krempl and Ruggles⁽⁹⁾ simulated uniaxial ratchetting and creep using a theory based on the concept of overstress.

However, detailed experimental research on viscosity of materials subjected to cyclic loading has not been performed.

The authors have already observed the variations of the subsequent yield surface, such as distortion, translation and rotation, during cyclic loading using SUS 304 stainless steel⁽¹⁰⁾, and have found that both creep and biaxial ratchetting after cyclic loading could be expressed by a formula considering the movement of the center of the yield surface during loading⁽¹¹⁾.

In this study, a series of tests that supports to construct a unified constitutive equation for cyclic plasticity, creep and ratchetting was carried out. Namely, cyclic proportional loading, creep, uniaxial ratchetting and biaxial ratchetting tests were conducted at room temperature and at 550°C using SUS 304 stainless steel to study the viscoplastic behavior of the material in detail. Moreover, tests of creep combined with uniaxial ratchetting were also conducted to study the interaction between creep and uniaxial ratchetting.

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2. Experimental Apparatus and Procedure

2.1 Specimens and testing system

Figure 1 shows the geometry of the specimen used in this work. The specimen had the gauge length of 50 mm, and the inner and outer diameter of 20 mm and 23 mm, respectively. The specimen was made of SUS 304 stainless steel subjected to a solution heat treatment at 1070°C. Table 1 shows the chemical composition of the specimen. Table 2 shows the Young's modulus, the shearing modulus, and the yield stress (σ_y) with a 50 $\mu\text{m/m}$ offset strain of the specimen at room temperature and at 550°C.

The servo-controlled axial-torsional testing machine (Shimadzu EHF-EB 10), with a Shimadzu 4825 controller and a computer (NEC PC-9801 DX), was used for computerized testing and data acquisition, accomplished by a program written in Machine Word⁽¹²⁾.

Strain was measured using two strain gauges (Kyowa KFG-2-C1-16, KFG-2-D17-16) on diametrically opposite sides of the specimen at room temperature, while using the uniaxial extensometer (Shimadzu 344-15350) and strain gauges (Kyowa KHC-20-G7-16 L 200) at 550°C.

2.2 Test program

The following six kinds of tests were conducted in this study:

(1) Cyclic tension-compression test with a constant strain amplitude under a constant strain rate: A constant strain amplitude of $\Delta\epsilon=1\%$ was chosen at room temperature and at 550°C. Three constant

strain rates of $\dot{\epsilon}=0.5, 0.05$ and 0.005% /s were chosen at room temperature, whereas two constant strain rates of $\dot{\epsilon}=0.5$ and 0.05% /s were chosen at 550°C.

(2) Creep test during pure tension: Intermittent creep tests at four stress levels were conducted during pure tension tests at room temperature and at 550°C. Time period for the creep tests was 300 seconds. Stress levels of 300, 350, 400 and 450 MPa were chosen at room temperature, whereas those of 150, 200, 250 and 300 MPa were chosen at 550°C.

(3) Uniaxial ratchetting test: After a stress-strain loop of cyclic tension-compression preloading was stabilized, repeated loading between the terminal tensile stress at the stabilized loop of the preloading and zero stress was conducted as a uniaxial ratchetting test at room temperature and at 550°C. A constant strain amplitude of 1% was chosen for the preloading. Three constant stress rates of $\dot{\sigma}=5, 10$ and 20 MPa/s were chosen for the uniaxial ratchetting tests at room temperature, whereas a constant stress rate of 10 MPa/s was chosen at 550°C.

(4) Uniaxial ratchetting test after creep test: After a creep test of time period of 300 seconds at a tensile stress level of 280 MPa, repeated loading between the tensile stress of 280 MPa and the zero stress under a constant stress rate of 10 MPa/s was conducted at room temperature.

(5) Creep test after uniaxial ratchetting test: After repeated loading between a tensile stress of 280 MPa and zero stress under a constant stress rate of 10 MPa/s, a creep test of time period of 300 seconds at the tensile stress level of 280 MPa was conducted at room temperature.

(6) Biaxial ratchetting test: Two types of biaxial ratchetting tests were conducted: (i) A secondary cyclic torsion with a constant strain amplitude of $\Delta\gamma/\sqrt{3}=1\%$, which was superposed on a primary tension stress of $\sigma_s=0.61\sigma_y$, was conducted at room temperature. Four constant strain rates of $\dot{\gamma}/\sqrt{3}=1, 0.1, 0.01$ and 0.001% /s were chosen for the secondary cyclic torsion. (ii) A secondary cyclic tension-compression with a constant strain amplitude of $\Delta\epsilon=1\%$, which was superposed on a primary torsion stress of $\sqrt{3}\tau_s=0.61\sigma_y$, was conducted at room temperature

Table 1 Chemical composition of specimen

C	Si	Mn	Ni	P	S	Cr
0.06	0.51	1.06	8.81	0.028	0.012	18.38

Table 2 Young's modulus, shearing modulus and yield stress of specimens

	Young's modulus (GPa)	Shearing modulus (GPa)	Yield stress (MPa)
Room Temp.	198	74	165
550°C	159	68	66

Fig. 1 Geometry of specimen

and at 550°C. A constant strain rate of $\dot{\epsilon}=0.01\%/s$ was chosen for the secondary cyclic tension-compression.

3. Results and Discussions

3.1 Cyclic tension-compression loading with a constant strain amplitude

Figure 2 shows the stress-strain relation obtained from the cyclic tension-compression test with a constant strain amplitude of $\Delta\epsilon=1.0\%$ under a constant strain rate of $\dot{\epsilon}=0.05\%/s$ at room temperature. The stress-strain relation of the test was stabilized at the 12th cycle after stress hardening occurred.

Figure 3 shows the stress-strain relation obtained from the cyclic tension-compression test at 550°C, which was conducted under the same loading condition as the test at room temperature. The stress-strain relation of the test was stabilized at the 15th cycle after stress hardening occurred.

Figure 4 shows the relation between stress amplitude ($\Delta\sigma/2$) and cycle, which was obtained from the cyclic tension-compression tests with a constant strain amplitude of $\Delta\epsilon=1.0\%$ under several constant strain rates. The symbols $\circ$, $\triangle$ and $\square$ show the results of the constant strain rates of $\dot{\epsilon}=0.5$, 0.05 and $0.005\%/s$ respectively, at room temperature, while the symbols $\bullet$ and $\blacksquare$ show those of the constant strain rates of $\dot{\epsilon}=0.5$ and $0.05\%/s$ respectively, at 550°C. Comparing the result of the strain rate of $\dot{\epsilon}=0.05\%/s$

at room temperature with that at 550°C, it was found that the stress amplitude at room temperature was 33% higher than that at 550°C. However, the stress increment during loading (i.e., from the 1st cycle to the stabilized cycle) at 550°C was 100 MPa, while that at room temperature was 30 MPa. Therefore, larger stress hardening occurred at 550°C than at room temperature.

At room temperature, the stress amplitudes increased with increasing in the strain rates as shown in Fig. 4. Namely, there was a strain rate-effect at room temperature in the case of SUS 304 stainless steel. On the other hand, at 550°C, the stress amplitudes at the stabilized loop of the two strain rates of $\dot{\epsilon}=0.05$ and

Fig. 2 Cyclic tension-compression loading ($\Delta\epsilon=1\%$, $\dot{\epsilon}=0.05\%/s$, room temperature)

Fig. 3 Cyclic tension-compression loading ($\Delta\epsilon=1\%$, $\dot{\epsilon}=0.05\%/s$, 550°C)

Fig. 4 Stress amplitude versus number of cycles during cyclic tension-compression loading

0.5%/s were almost the same, while the stress amplitudes during the earlier stage of loading were very different. The difference was greatest around the 5th cycle, and the difference was more than 10%. Moreover, the stress amplitude of the lower strain rate ($\dot{\epsilon}=0.05\%/s$) was larger than that of the higher strain rate ($\dot{\epsilon}=0.5\%/s$) until the stress-strain relations stabilized. Murakami et al.⁽¹³⁾ reported that the so-called Portevin-LeChatelier effect, in which the atmospheres of the solution elements enhance the drag resistance of dislocation motion, is observed at around 500°C in the case of SUS 316 stainless steel. The zig zag line of the stress-strain relation shown in Fig. 3 might be caused by the Portevin-LeChatelier effect. The Portevin-LeChatelier effect might also cause the difference of the strain-rate effects at room temperature and at 550°C.

3.2 Creep test during pure tension

The stress-total strain curves of two specimens at room temperature and at 550°C, which were subjected to a set-up creep in 300 seconds, are shown by the solid lines in Fig. 5. The stress levels (A, B, C, D, a, b, c, d) conducted the creep tests were A=300 MPa, B=350 MPa, C=400 MPa, D=450 MPa, a=150 MPa, b=200 MPa, c=250 MPa and d=300 MPa. Stress rates of the two specimens during loading were the same, i.e., $\dot{\sigma}=10$ MPa/s. The dash-dot line shows the stress-strain curve under stress-controlled uniaxial loading at $\dot{\sigma}=10$ MPa/s without intermittent creep. The portions of the solid curve with increasing stress could be connected to the pure tension curve shown by the dash-dot line. This result shows that periods of creep do not appear to influence pure tension, and that stress levels of creep have a significant influence on creep strains.

Comparing the curve at room temperature with that at 500°C in Fig. 5, most surprisingly the test at 550°C did not show significant creep strain. Namely,

Fig. 5 Creep during pure tension

SUS 304 stainless steel at 550°C is not influenced by viscous parts of deformations since the viscosity of materials should lead to creep strain.

3.3 Uniaxial ratchetting test

After the stress-strain curve of the cyclic tension-compression preloading with a constant strain amplitude of $\Delta\epsilon=1\%$ under a constant stress rate of $\dot{\sigma}=10$ MPa/s was stabilized, repeated loading between zero stress and the terminal stress in the tensile direction on the stabilized loop of preloading was conducted as a uniaxial ratchetting test. The terminal stresses in the tensile direction on the stabilized loops at room temperature and that at 550°C were 320 MPa and 280 MPa, respectively.

Figure 6 shows the stress-strain relation obtained from the uniaxial ratchetting test conducted with a stress rate of $\dot{\sigma}=10$ MPa/s at room temperature. The stabilized loop of the preloading is also shown. Uniaxial ratchetting strain was observed during repeated loading. However, the strain increment decreased with increasing cycle number, and finally the strain increment at the 80th cycle became small.

Figure 7 shows the relation between uniaxial ratchetting strain and number of cycles at room temperature. The symbols $\circ$, $\triangle$ and $\square$ show the test results under the stress rates of $\dot{\sigma}=20$, 10 and 5 MPa/s, respectively. It is clear that uniaxial ratchetting strain under higher stress rate is smaller than that under lower stress rate. Comparing uniaxial ratchetting strain at the 80th cycle under the stress rate of $\dot{\sigma}$

Fig. 6 Uniaxial ratchetting
($\dot{\sigma}=10$ MPa/s, room temperature)

$\dot{\sigma}=5$ MPa/s with that under the stress rate of $\dot{\sigma}=20$ MPa/s, for example, uniaxial ratchetting strain under the stress rate of $\dot{\sigma}=5$ MPa/s was three times larger than that under the stress rate of $\dot{\sigma}=20$ MPa/s. Namely, stress rates affect uniaxial ratchetting behavior of SUS 304 stainless steel at room temperature.

Figure 8 shows the stress-strain relation of the uniaxial ratchetting test under a stress rate of $\dot{\sigma}=10$ MPa/s at 550°C. Comparing the result at room temperature shown in Fig. 6 with that at 550°C in Fig. 8, uniaxial ratchetting strain at 550°C was much smaller than that at room temperature, and there was no noticeable uniaxial ratchetting strain at 550°C.

Considering that uniaxial ratchetting strain and

Fig. 7 Uniaxial ratchetting strain versus number of cycles at room temperature

Fig. 8 Uniaxial ratchetting ($\dot{\sigma}=10$ MPa/s, 550°C)

creep strain are not appreciable at 550°C, and remembering that creep strain is caused by the viscosity of a material, uniaxial ratchetting strain also seems to be caused by the viscosity of a material as well as creep strain. Observation of interactions between creep and uniaxial ratchetting strain are given in the next section.

3.4 Combined test of creep with uniaxial ratchetting

Two types of tests of creep combined with uniaxial ratchetting were conducted at room temperature. One was a uniaxial ratchetting test after creep as shown in Fig. 9, which was conducted by the following procedure: After the specimen was loaded to point A (280 MPa) under a stress rate of $\dot{\sigma}=10$ MPa/s, an intermittent creep test of time period of 300 seconds was conducted at a stress of 280 MPa. After the creep test, a uniaxial ratchetting test with 20 cycles of stress oscillation between the stress of 280 MPa and zero stress was conducted under a stress rate of $\dot{\sigma}=10$ MPa/s. Creep strain of 0.9% was observed during the creep test, while uniaxial ratchetting strain was not observed as shown in Fig. 9. The reason why uniaxial ratchetting strain does not appear after the creep test is that the viscous parts of deformations have already progressed sufficiently during the creep test.

The other test was a creep test after uniaxial ratchetting as shown in Fig. 10, which was conducted as follows: After the specimen was loaded to point A (280 MPa) under a stress rate of $\dot{\sigma}=10$ MPa/s, a uniaxial ratchetting test with 20 cycles of stress oscillation between the stress of 280 MPa and the zero stress was conducted under a stress rate of $\dot{\sigma}=10$ MPa/s. After the uniaxial ratchetting test, an intermittent creep test of time period of 300 seconds was conducted at the stress of 280 MPa. Both uniaxial ratchetting strain of 0.35% and creep strain of 0.53% were observed as shown in Fig. 10. Comparing creep strain shown in Fig. 10 with that shown in Fig. 9, creep

Fig. 9 Uniaxial ratchetting after creep

strain after the uniaxial ratchetting test was smaller than that without the uniaxial ratchetting test although the creep tests were conducted for the same time period of 300 seconds at the same stress level of 280 MPa.

Figure 11 shows the relation between axial strain and time obtained by the tests shown in Figs. 9 and 10. Solid lines in Fig. 11 show creep strain, and solid lines with open circles show uniaxial ratchetting strain. It was interesting to note that the total strain at 1500 seconds of the two tests was almost the same. This result suggests that an equivalent relationship between creep strain and uniaxial ratchetting strain may exist.

3.5 Biaxial ratchetting test

Figure 12 shows the relation between tensile strain (biaxial ratchetting strain) and shear strain, which was obtained from the biaxial ratchetting test superposing cyclic shear strain with constant shear strain amplitude of $\Delta\gamma/\sqrt{3}=1\%$ under a constant shear strain rate of $\dot{\gamma}/\sqrt{3}=0.01\%/s$ on a primary

Fig. 10 Creep after uniaxial ratchetting

Fig. 11 Total strain versus time during test of creep combined with uniaxial ratchetting

tensile stress of $\sigma_s=0.61\sigma_y$ (100 MPa) at room temperature. It was found that inelastic strain (biaxial ratchetting strain) in the tensile direction occurs due to the cyclic shear strain. However, biaxial ratchetting strain decreased with increasing number of cycles, and finally biaxial ratchetting strain became a small value.

Figure 13 shows the relation between biaxial ratchetting strain and number of cycles. The solid line, broken line, dash-dot line and two dash-dot line show the results under shear strain rates of $\dot{\gamma}/\sqrt{3}=0.001, 0.01, 0.1$ and $1\%/s$, respectively. It was found that the strain rate effect is observed under the strain rates between $\dot{\gamma}/\sqrt{3}=0.01\%/s$ and $0.1\%/s$. On the

Fig. 12 Biaxial ratchetting strain versus shear strain ($\Delta\gamma/\sqrt{3}=1\%$, $\dot{\gamma}/\sqrt{3}=0.01\%/s$, $\sigma_s=0.61\sigma_y$, room temperature)

Fig. 13 Biaxial ratchetting strain versus number of cycles at room temperature

other hand, there was no strain-rate effect under strain rates between $\dot{\gamma}/\sqrt{3}=0.001$ and $0.01\%/s$, or between $\dot{\gamma}/\sqrt{3}=0.1\%/s$ and $1\%/s$. Namely, the strain-rate effect on biaxial ratchetting strain can be observed between particular strain rates, i.e., between $\dot{\gamma}/\sqrt{3}=0.01\%/s$ and $0.1\%/s$ at room temperature in the case of SUS 304 stainless steel.

Figure 14 shows the relation between shear strain (biaxial ratchetting strain) and axial strain, which was obtained from the biaxial ratchetting tests superposing a cyclic tension-compression with a strain

amplitude of $\Delta\epsilon=1\%$ under a strain rate of $\dot{\epsilon}=0.01\%/s$ on a primary shear stress of $\sqrt{3}\tau_s=0.61\sigma_y$ at room temperature and at 550°C . Figures 14(a) and (b) show the relations at room temperature and at 550°C , respectively. Comparing Fig. 14(a) with Fig. 14(b), biaxial ratchetting strain at 550°C was much smaller than that at room temperature in spite of the same stress ratio, 0.61, of the primary stress to the yield stress. However, there was noticeable biaxial ratchetting strain at 550°C . Namely, biaxial ratchetting strain is caused by strains due to both viscosity of materials and nonproportionality of loading path, because viscosity of the material disappears at 550°C as shown in section 3. 2.

4. Conclusions

This paper treated basic experimental observations on viscoplastic behavior using SUS 304 stainless steel, which might support to construct a unified constitutive model for cyclic viscoplasticity. Namely, cyclic tension-compression tests, creep tests during uniaxial loading, uniaxial ratchetting tests, tests of uniaxial ratchetting combined with creep, and biaxial ratchetting tests were conducted using SUS 304 stainless steel at room temperature and at 550°C . As a result, the following conclusions were obtained.

(1) The strain-rate effect on cyclic tension-compression with constant strain amplitude was observed at both room temperature and 550°C . Moreover, the Portevin-LeChatelier effect was observed at 550°C .

(2) Creep strain appeared at room temperature, but not at 550°C . Therefore, the deformations of SUS 304 stainless steel at 550°C is not be caused by the viscosity of the material.

(3) Uniaxial ratchetting strain was observed at room temperature, while that did not at 550°C . Therefore, considering the conclusion (2) uniaxial ratchetting strain is caused by the viscosity of materials.

(4) Uniaxial ratchetting strain did not occur after the creep test. Creep strain after the uniaxial ratchetting test was much smaller than that without the uniaxial ratchetting test. Therefore, there may be an equivalent relation between creep strain and uniaxial ratchetting strain.

(5) The strain-rate effect could be observed in the biaxial ratchetting test at room temperature between particular strain rates.

(6) Biaxial ratchetting strain at 550°C was much smaller than that at room temperature in spite of the same ratio, 0.61, of the primary stress to the yield stress. However, there was noticeable biaxial ratchetting strain at 550°C . Namely, biaxial ratchetting strain is caused by strain due to both the viscosity of

Fig. 14 Biaxial ratchetting strain versus axial strain ($\Delta\epsilon=1\%$, $\dot{\epsilon}=0.01\%/s$, $\sqrt{3}\tau_s=0.61\sigma_y$)

materials and the nonproportionality of loading path.

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