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Development of Tension-Torsion Multiaxial Creep Testing Apparatus for Heat Resisting Steel

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Abstract. This paper describes development of a combined tension-torsion multiaxial creep testing apparatus for heat resisting steel. It is essential for high temperature component designing to investigate creep rupture life and creep properties of heat resisting steel. Although high temperature structural components undergo multiaxial stress damage due to complex loading situation or shape discontinuity of the actual structure, there is no commercial testing apparatus which can conduct a creep testing under multiaxial stress conditions. In this study, we developed a combined tension-torsion multiaxial creep testing apparatus which can apply multiaxial stress to a hollow cylinder type testing specimen with 6 kN axial load and 12 Nm torsional load at high temperatures. Since the testing apparatus also has measuring devices for axial and shear displacements of the specimen, relationship curve between testing time and equivalent strain under multiaxial stress conditions of type 304 stainless steel is also discussed.

1 Introduction

High temperature structural components undergo not only cyclic loading damage but also multiaxial creep stress damage due to complex loading of actual service condition. Although it is essential for safety high temperature structure designing to make clear the creep rupture time and the creep properties under multiaxial stress conditions, there is little experimental research paper on multiaxial creep [1-3]. The reason for the small number of experimental study on multiaxial creep may be there is no commercial creep testing apparatus which can conduct experiments under multiaxial stress condition.

There are several methods for multiaxial creep testing. One is using notched bar type specimen with conventional uniaxial tensile creep testing apparatus. Other one is loading bi-axial stress to a cruciform type specimen. In this study, we tried to develop a new type multiaxial creep testing apparatus which can load combined tension-torsion stress to a hollow cylinder type specimen. By comparing the experimental data obtained by using

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tension-torsion method with the data obtained by using bi-axial tension method, safety designing for the high temperature structure can be improved.

2 Combined Tension-Torsion Creep Testing Apparatus

Table 1 summarizes a specification of a combined tension-torsion multiaxial creep testing apparatus developed in this study. Figures 1 and 2 show schematic figure and general view photo of the apparatus, respectively. Axial tensile stress and shear stress are generated by deadweight separately. The apparatus has a capacity of 6 kN axial load and 12 Nm torsional load. Load of the deadweight for axial loading is increased tenfold by lever. Torque for torsional loading is generated by deadweight for torsional loading with a pulley which has 184 mm in diameter.

A hollow cylinder type specimen for multiaxial loading was also designed. Figure 3 shows shape and dimensions and general view photo of the specimen. The specimen has 8 mm outer dimeter, 5 mm inner diameter and 8 mm gage length. The shape and dimensions are designed by using finite elements analysis calculation. The specimen is heated with electric resistance furnace of 900 W and the maximum temperature of the furnace is 973 K.

The multiaxial creep testing apparatus is also designed to have measuring sensors for displacement of the specimen in order to investigate multiaxial creep properties. A pair of linear variable differential transformer sensor is used for the axial loading shaft displacement measuring. A rotary encoder and a pair of eddy current sensor are used for the loading shaft twist angle measuring and the specimen shear displacement measuring, respectively.

Table 1. Specification of the developed multiaxial creep testing apparatus.

Maximum axial load	6 kN
Maximum torsional load	12 Nm
Maximum temperature	973 K (700 C)
Axial displacement measuring	Linear variable differential transformer
Shear displacement measuring	Encoder and Eddy current sensor

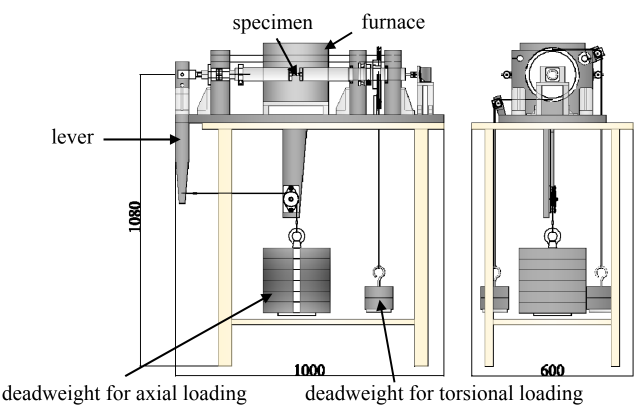

Fig. 1. Schematic figure of the combined tension-torsion multiaxial creep testing apparatus.

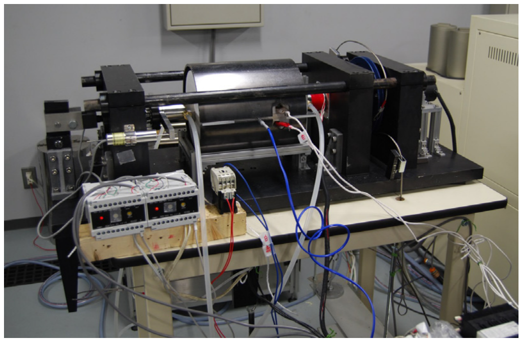

Fig. 2. General view photo of the combined tension-torsion multiaxial creep testing apparatus.

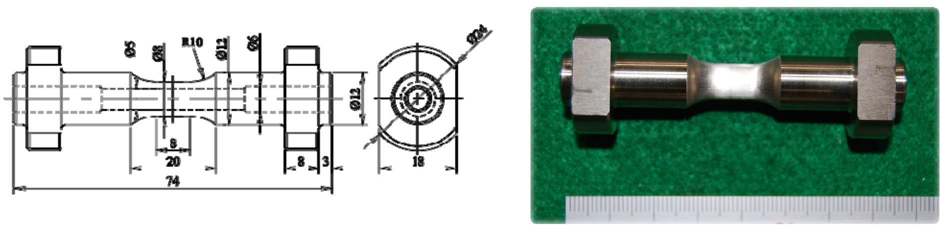

Fig. 3. Shape and dimensions and view photo of the specimen.

3 Experimental Procedure

A combined tension-torsion loading test was conducted at 923 K in order to inspect an ability of the creep testing apparatus and investigate the multiaxial creep properties of heat resisting steel. The material tested in this study was type 304 stainless steel. The chemical composition and heat treatment of the material are listed in Table 2. Mechanical properties of the material at room temperature is listed in Table 3.

Table 2. Chemical composition and heat treatment condition of the tested material (mass%).

C	Si	Mn	P	S	Ni	Cr
0.05	0.32	1.76	0.37	0.27	8.27	18.7

Heat treatment at 1353 K for 11min.

Table 3. Mechanical properties of the tested material at room temperature.

Tensile strength σ_B, MPa	607
Proof stress $\sigma_{0.2\%}$, MPa	280
Elongation δ, %	60
Reduction of area ϕ, %	75
Hardness, HBW	170

In this study, a principal stress ratio λ is used for expressing the stress multiaxiality and is calculated as follows,

$$\lambda = \frac{\sigma_2}{\sigma_1} \tag{1}$$

where σ_1 and σ_2 are maximum principal stress and minimum principal stress, respectively. According to this definition, pure axial tensile loading test is expressed as λ=0 and pure torsional loading test is expressed as λ=–1. λ of combined tension-torsion loading tests are in the range of $-1<\lambda<0$. A combined tension-torsion multiaxial creep test with λ=–0.5 and σ_{eq}=170 MPa was conducted at 923 K, where σ_{eq} is von Mises equivalent stress and is calculated as follows for combined tension-torsion stress,

$$\sigma_{eq} = \sqrt{\sigma^2 + 3\tau^2} \quad (\sigma\text{: axial stress, } \tau\text{: shear stress}) \qquad (2)$$

4 Results and Discussion

Figure 4 shows time versus creep strain curves of the multiaxial creep testing for type 304 stainless steel at 923 K. Symbol in red color and blue color are axial and shear strain, respectively. As axial strain and shear strain are plotted clearly in Fig. 4, these results indicate that strain measuring methods adopted in this study are suitable for the tension-torsion multiaxial creep testing.

Green coloured line in Fig. 4 shows von Mises equivalent strain and is calculated as follows,

$$\varepsilon_{eq} = \sqrt{\varepsilon^2 + \frac{1}{3}\gamma^2} \qquad (\varepsilon\text{: axial strain, } \gamma\text{: shear strain}) \qquad (3)$$

Primary transient stage, secondary steady stage and tertiary acceleration stage of the equivalent strain are observed clearly in Fig. 4. Strain rate curve calculated with the equivalent strain data is shown in Fig. 5. Since minimum creep strain rate which is essential material data for safety products designing can be obtained in Fig. 5, use of the equivalent strain may be available for the tension-torsion multiaxial creep testing.

Figure 6 correlates the multiaxial creep rupture time with the principal stress ratio in order to discuss about influence of stress multiaxiality on creep fracture properties. Average data of uniaxial creep testing with solid bar type specimen, which were provided by National Institute for Materials Science, is also plotted in the same figure as reference data. The creep rupture time with σ_{eq}=170 MPa are 2552 h and 194 h for λ=–0.5 and λ=0, respectively and the creep rupture time decrease with the principal stress ratio. We need more sufficient experimental data collection and data analysis in order to make clear the influence of the stress multiaxiality on creep rupture time.

Figure 7 is general view photo of the ruptured specimen. Fracture surface direction was perpendicular direction to the specimen axis for λ=–0.5. Figure 8 shows optical microscope observation results of the fracture surface. Many rubbed marks were observed clearly but there is little axial elongated deformation in Fig. 8. These results imply that torsional loading may give more damage to the specimen than axial loading. We also need more sufficient observation in order to make clear the fracture mechanism under multiaxial loading.

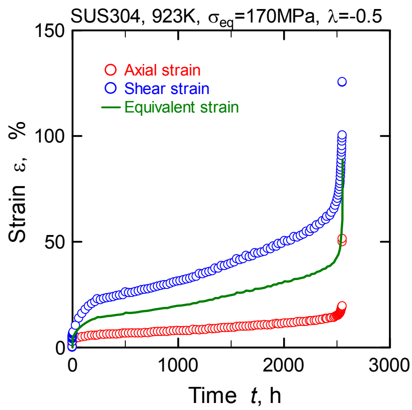

Fig. 4. Creep curves of type 304 stainless steel at 923 K under λ=–0.5.

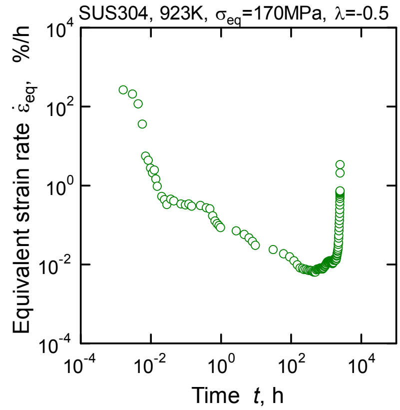

Fig. 5. Equivalent strain rate curve of type 304 stainless steel at 923 K under λ=–0.5.

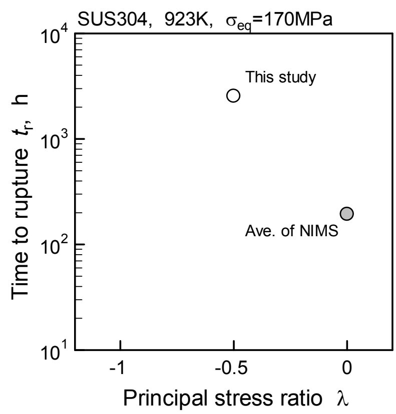

Fig. 6. Correlation of creep rupture time with principal stress ratio.

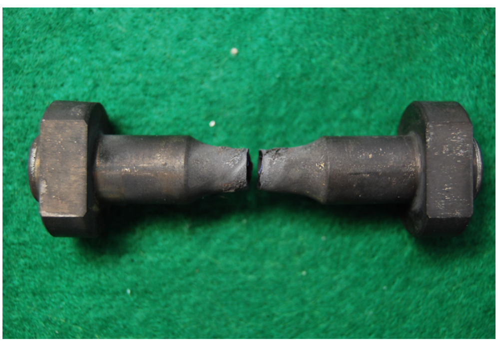

Fig. 7. Specimen surface observation after the test.

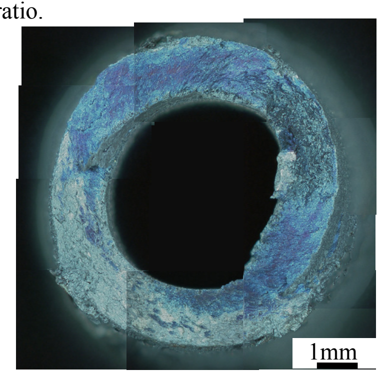

Fig. 8. Fracture surface observation results with optical microscope.

5 Conclusions

Experimental research work on multiaxial creep for heat resisting steel was conducted in this study.

(1) Combined tension-torsion multiaxial creep testing apparatus which has 6 kN axial loading and 12 Nm torsional loading capacity was developed.

(2) Hollow cylinder type specimen for multiaxial creep testing was also designed.

(3) Creep rupture time under $\lambda=-0.5$ was longer than $\lambda=0$ uniaxial stress conditions. There are influence of stress multiaxiality on creep rupture time.

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