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Effect of cold work on the irradiation creep of SUS 316L

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Abstract

The network dislocation density in structural materials is one of the important factors of radiation-induced deformation. Hence creep deformation under 17 MeV proton irradiation was examined for SUS 316L with 5% and 25% cold work at ∼300 °C. At relatively low stresses, irradiation creep of 5%CW specimen was larger than that of the 25%CW specimen, and the measured creep rates of both specimens were close to the results of computer simulation. The stress dependencies of the two specimens are roughly similar, and their stress exponents appear to correspond well with the simulation results. At relatively high stresses, the dependence of creep rate on the applied stress was stronger for both cold-worked specimens. Acceleration of thermal creep mechanism due to irradiation might be one of the causes for the increase.

1. Introduction

Structural materials for fusion reactors suffer from radiation damage induced by energetic particles like neutrons, and their mechanical properties will be altered. Under irradiation, continuously produced point defects move around and interact with externally applied stress. As a result, characteristic behaviors such as irradiation creep will be induced only during irradiation, resulting in a very significant plastic deformation. Irradiation creep is one of the most important problems for fusion reactors because materials are expected simultaneously to experience high fluxes of energetic neutrons and external thermal stresses.

Many experimental studies of irradiation creep have been carried out at rather high temperatures around 500 °C. However, the accumulation of experimental data is not adequate at temperatures below 400 °C, while the structural materials of International Thermonuclear Experimental Reactor (ITER) are designed to be used in the temperature range of 100–400 °C, centered at ∼300 °C. SUS 316L stainless steel is the major structural material for the commercial and prototype fission reactors and will also be used in ITER. Although the material will be mainly provided in annealed condition at the beginning of fabrication, cold-working and consequent introduction of network dislocations would be involved at various parts of the structure during construction or operation. Recently, a rather complicated dependence of irradiation creep on dislocation density has been predicted for SUS 316L stainless steel in a computer simulation [1]. The simulation calculation is based on the kinetic equations of point defects under externally applied stress and on the major mechanisms of radiation-induced deformations [2,3].

The objective of the present study is to investigate the effect of cold work on the irradiation creep of SUS 316L stainless steel. Irradiation creep behavior was examined at ∼300 °C using small size specimens with two levels of cold work (5% and 25%). Experiments were carried out using a newly made in-beam irradiation creep apparatus. The results were compared with those of the computer simulation reported separately [1].

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2. Experimental procedure

Irradiation creep tests were performed for the two cold-worked materials (5% and 25%) of SUS 316L austenitic stainless steel (Cr: 17.66, Ni: 12.19, Mn: 0.86, Mo: 2.12, C: 0.017, Si: 0.61, P: 0.024, S: 0.001, in wt%). Fig. 1 shows the network dislocation density as a function of cold work, which was obtained by TEM for the present material. The density in 5% cold-worked material was 3.1×10^{14} m^{-2}, and that in 25% was 1.0×10^{15} m^{-2}. The 5% and 25% cold-worked sheets were punched out into the specimen geometry shown in Fig. 2. The gauge size of the specimen was $2.0\times10\times0.15$ mm. Average grain size after the final annealing was 15 μm. Yield stresses of the cold-worked materials measured by tensile testing at 288 °C were 320 MPa for the 5%CW specimen and 630 MPa for the 25%CW specimen. The irradiation experiments were carried out with 17 MeV protons from the compact cyclotron at National Institute for Materials Science. Fig. 3 shows the depth dependence of displacement damage rate calculated by TRIM 91 code for SUS 316 stainless steel under 17 MeV proton irradiation. The average damage rate calculated was 2×10^{-7} dpa/s.

Fig. 4 shows the tensile irradiation creep apparatus with novel loading and strain-measurement systems. Control of the load is enabled by adjusting the vacuum in a drum with diaphragm through precise back feed control of the PIEZO valve opening. The strain-measurement system consists of a high-resolution laser interferometer with a resolution of 0.0097 μm. During the experiment, the specimen temperature was held at 288 °C with an accuracy of ±0.15 °C by controlling Joule heating using back feed from the thermocouple attached to the specimen. In addition, the specimen was

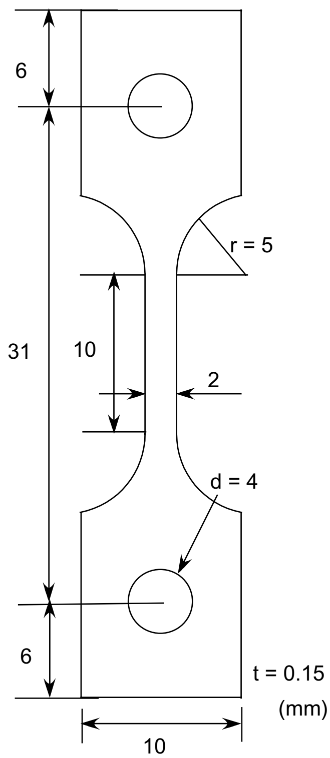

Fig. 2. Specimen geometry.

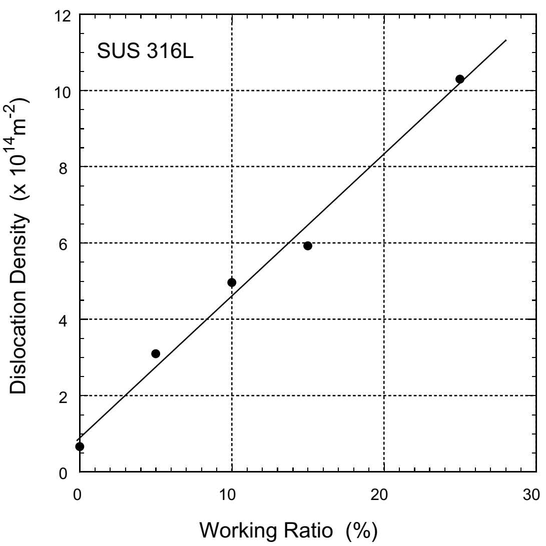

Fig. 1. Change in dislocation density with cold work in SUS 316L.

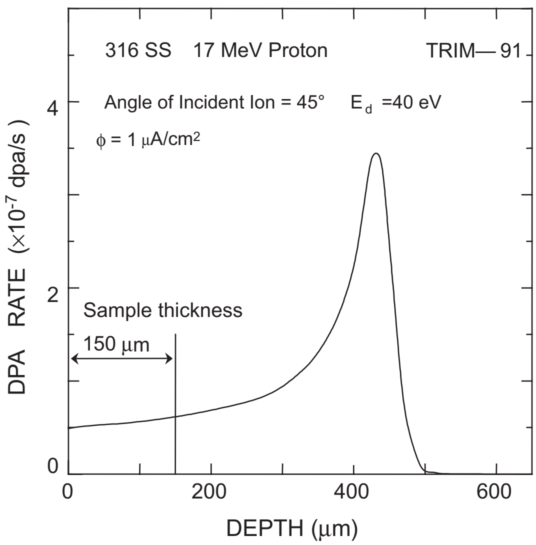

Fig. 3. Depth dependence of displacement damage rate in 316SS with 17 MeV protons.

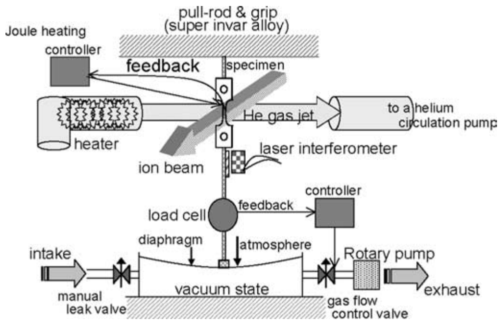

Fig. 4. Irradiation creep apparatus with novel loading and strain-measurement system.

cooled by a temperature-controlled He gas jet to partially remove the beam heating. The specimen temperature was also monitored by infrared pyrometer through a quartz window of the chamber. Irradiation experiments were carried out with applied stresses from 50 to 200 MPa for the 5%CW specimen, and from 150 to 600 MPa for the 25%CW specimen. The environment during experiments, such as the beam characteristics and temperature of both atmosphere and apparatus, reached steady state in about three hours after the start of irradiation. All the data shown in this paper were obtained after this preparatory period.

3. Results and discussion

Fig. 5 shows the measured creep strain under irradiation for the 25%CW specimen. Creep rates without irradiation in the examined stress range are extremely low, far below the resolution of creep apparatus ($\sim 5\times10^{-11}$ s^{-1}), at this temperature. However, creep deformation was accelerated under irradiation and showed a stress dependence in both 5%CW and 25%CW specimens as can be seen in Fig. 5. Fig. 6 shows the stress dependence of the measured irradiation creep rate and that of simulation calculation in 5%CW specimen. At lower stresses below about 100 MPa, measured creep rates in 5%CW specimen were close to the simulation results. Fig. 7 presents the measured irradiation creep rate and the calculated result of 25%CW specimen. In the lower stress region below ~400 MPa, the measured creep rates were rather close to the calculated line. Comparison of the experimental results of the 5%CW and the 25%CW specimens indicates that the measured creep rates of 5%CW specimen were larger than those of the 25%CW specimen at the examined stress range. In

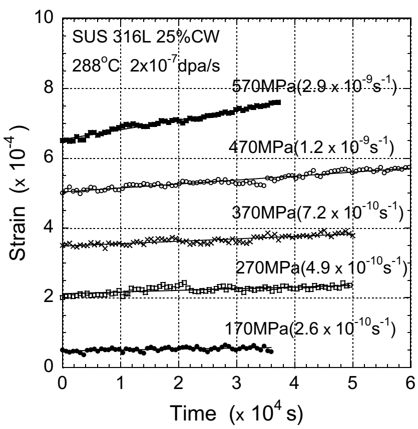

Fig. 5. Creep curve of 25%CW specimen at 288 °C during irradiation.

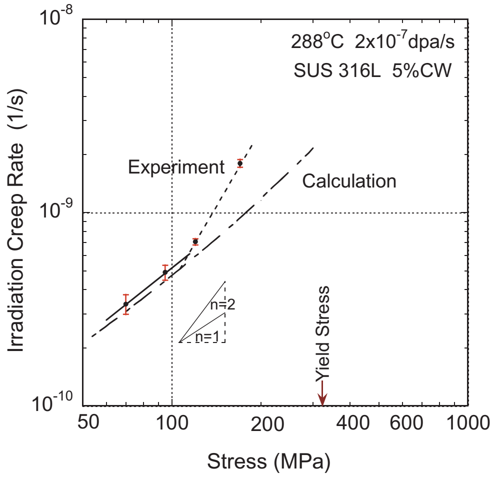

Fig. 6. Stress dependence of irradiation creep rate in 5%CW specimens.

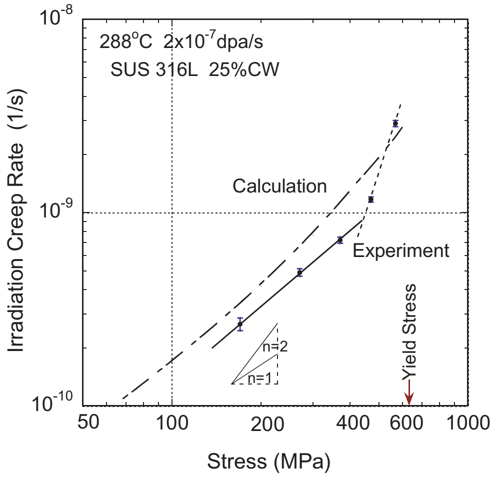

Fig. 7. Stress dependence of irradiation creep rate in 25%CW specimens.

the lower stress region, well below the yield stresses for 5%CW and 25%CW specimens, the measured creep rates in both specimens were almost in proportion to the stress, and the measured exponent was about 1.2 that corresponds well with the calculation results. At higher stresses, above ~100 MPa for the 5%CW specimen and above ~500 MPa for the 25%CW specimen, stress dependence of the obtained creep rate appears to increase significantly in both specimens. The stress exponents were much larger than those predicted by our calculation in such higher stresses. One of the causes for such a discrepancy between experimental and calculated result would be associated with the irradiation enhanced thermal creep. Another possibility may be the contribution from the glide of un-faulted dislocation loops under higher stresses [4]. We should therefore compare these experimental data with the calculation results only at low stresses, because the calculation has considered only radiation-induced creep mechanisms. Detail of the calculation is reported in a separated paper [1]. Fig. 8 shows the calculated dislocation density dependence of irradiation creep rate. The creep rate at 100 MPa estimated for 5%CW and 25%CW specimens is shown by point A and B, respectively.

Although the data points are limited, the results support the calculated dependence of irradiation creep rate on dislocation density. As shown in Fig. 8, the calculation predicts that the dislocation density of creep rate has a peak at the density of about 1.0×10^{14} m^{-2}. This peak could be explained as follows [1]. At lower dislocation density, the production of dislocation loops and hence the contribution by stress-induced preferred nucleation (SIPN) of point defect [2,3,5,6] decreases because of the enhanced loss of point defects by recombination. Contributions from stress induced preferred absorption (SIPA) of interstitial atoms [2,3,6] and PAG (glide enabled by SIPA) [2,3,7] also decrease with decreasing dislocation density. PAG is a dislocation glide enabled after the network dislocation climbs over obstacles by SIPA. At higher dislocation density, the SIPN contribution decreases because more interstitials flow into network dislocations with increasing dislocation density. On the other hand, contributions from PA (SIPA climb), i.e. a climb of network dislocations enabled by SIPA, and PAG mechanisms increase with increasing dislocation density and consequently the decrease of a total creep rate stopped.

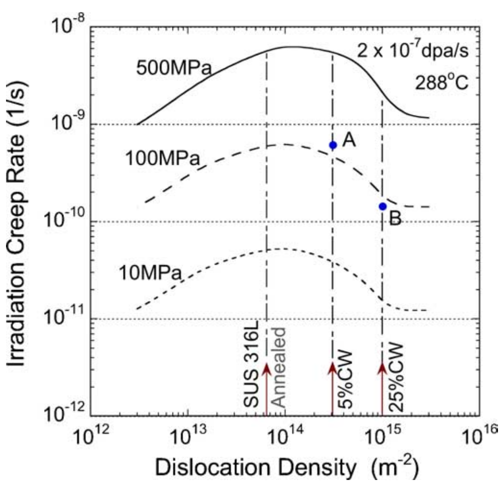

Fig. 8. Calculated dislocation dependence of irradiation creep rates in SUS 316L.

A negative creep, i.e. a deformation in the direction opposite to the applied stress was sometimes detected for the 5%CW specimen for a certain period of time after the irradiation started. Negative creep of SUS 316 has also been reported in annealed condition [8,9], and not observed in the CW specimen. In these reports, radiation-induced segregation and precipitation of Ni and Si and the consequent precipitation have been suggested to induce shrinkage and/or increase of elasticity and the resultant deformation against the externally applied stress [8,9]. The dislocation density of SUS 316L 5%CW material used in present experiments is 3.1×10^{14} m^{-2} that is higher than that of annealed material (6.5×10^{13} m^{-2}), but the observed negative creep rate might be due to the same mechanism.

4. Conclusion

The effect of network dislocation density on the irradiation creep behavior of SUS 316L stainless steel has been investigated at ~300 °C under 17 MeV proton irradiation (damage rate: 2×10^{-7} dpa/s), and the results were compared with simulation calculation.

(1) Acceleration of creep deformation was detected for both 5%CW and 25%CW materials at all the stresses examined. The irradiation creep rate of the 5%CW material was larger than that of 25%CW material, and both creep rates were close to the results of simulation calculation.
(2) At lower stresses, the stress exponent of measured irradiation creep rate was about the same between 5%CW and 25%CW material and it correspond was well with the simulation calculation.
(3) At higher stresses, the stress exponent increased in both materials and became much larger than those of the calculation. Enhancement of thermal creep mechanism by irradiation might be one of the causes for the observed increase of stress exponent at high stresses.
(4) Negative creep, i.e., contraction, was observed during the earlier stage of irradiation for 5%CW material.

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