**3.3 NEUTRON-IRRADIATION CREEP OF SILICON CARBIDE MATERIALS BEYOND THE INITIAL TRANSIENT—**T. Koyanagi, Y. Katoh (Oak Ridge National Laboratory), K. Ozawa (Japan Atomic Energy Agency), K. Shimoda, T. Hinoki (Kyoto University), L.L. Snead (Massachusetts Institute of Technology)

## OBJECTIVE

The objective of this work is to evaluate the irradiation creep behavior of silicon carbide (SiC) materials to aid in the understanding of the performance of SiC composite as fusion reactor structural components.

## SUMMARY

Irradiation creep beyond the transient regime was investigated for various SiC materials. The materials examined included polycrystalline or monocrystalline high-purity SiC, nanopowder sintered SiC, highly crystalline and near-stoichiometric SiC fibers, and a Tyranno SA3 SiC fiber reinforced SiC matrix composite fabricated through a nano-infiltration transient eutectic phase process. Findings are 1) the stress exponent of the post-transient creep was near unity, 2) the small apparent steady-state creep rate was ~1 × $10^{-7}$ [$dpa^{-1}MPa^{-1}$] at ~300 to ~800°C for most polycrystalline SiC materials, and 3) the effect of material quality on the creep rate, including structure of grain boundaries and crystal orientation, increased with increasing irradiation temperature. The results have been published in J. Nucl. Mater. [1] and a condensed version is given here.

## PROGRESS AND STATUS

### Introduction

Irradiation creep is an important phenomenon for nuclear materials because of its potential impact on the design stresses and service lifetimes of thermo-structural components. For SiC and SiC fiber reinforced SiC matrix (SiC/SiC) composites, irradiation creep is also known to be a key property in defining design limits. In short, and especially for materials such as SiC and its composites that possess very limited strain tolerance, irradiation creep provides an important stress mitigating function. This study shows high dose irradiation creep behavior of various SiC materials including monolithic ceramics, fibers, and a SiC/SiC composite. The experimental method can be found elsewhere [1].

### Results

The creep coefficient, which is normalized creep strain with respect to stress and neutron fluence, is used to indicate creep rate and to compare the creep behavior of different materials [2]. The instantaneous creep coefficient (*K*) is defined by

$$K \cong \frac{\varepsilon_2 - \varepsilon_1}{\sigma(\gamma_2 - \gamma_1)} \ , \qquad (1)$$

where $\gamma_1$ and $\gamma_2$ ($\gamma_1 < \gamma_2$) are neutron fluences, $\sigma$ is average stress during irradiation, and $\varepsilon_1$ and $\varepsilon_2$ are irradiation creep strains following irradiation to fluences of $\gamma_1$ and $\gamma_2$, respectively. Figure 1 shows the fluence dependence of the instantaneous creep coefficient of the SiC materials. The vertical error bars indicate one standard deviation. The highest and lowest horizontal error bars indicate the fluence of and for each data point, respectively. Figure 1 also shows the curves giving the creep behavior calculated by mechanistic models. The transient creep of chemical vapor deposited (CVD) SiC and sintered SiC materials is described using swelling-coupled creep and logarithmic creep, respectively [3]. The swelling-creep coupling values were expressed as products of the swelling coupling coefficient, applied

stress, and swelling rate. Logarithmic creep is commonly observed in metals and ceramics in the transient stage of thermal creep. The behaviors of simultaneous transient creep (swelling coupling or logarithmic creep) and secondary creep with a constant creep coefficient of K = $1\times10^{-7}$ or $2\times10^{-7}$ [dpa MPa]$^{-1}$ are also shown in the graph.

The creep coefficients of CVD SiC decreased rapidly with increasing fluence in the transient creep regime up to ~1 dpa, and then the creep coefficients appeared to be constant at ~$1\times10^{-7}$ [MPa$^{-1}$ dpa$^{-1}$] or to become very small, depending on the material type and irradiation temperature (Figure 1a). The swelling-creep coupling model is a good description of the initial transient creep behavior of CVD SiC materials up to ~1 dpa, as reported in [3]. However, this model cannot explain the creep behavior at higher fluence, which indicates the presence of secondary creep. Additional creep with a constant creep rate of $1\times10^{-7}$ [MPa$^{-1}$ dpa$^{-1}$] reasonably describes the overall creep behavior. The fluence dependence of the creep coefficients of the nano-powder sintered SiC (NT1 and NT2) is similar to that of CVD SiC: a significant reduction with increasing fluence up to ~1 dpa and an apparent steady state value of ~$2\times10^{-7}$ [MPa$^{-1}$ dpa$^{-1}$] at higher fluence. The creep coefficients are slightly larger than for CVD SiC but are within the same order under both low- and high-dose irradiations, as shown in Figure 1b. The transient creep may be explained as logarithmic creep, as previously discussed [4]. Although the logarithmic creep cannot describe the creep behavior up to 30 dpa, simultaneous transient creep (logarithmic creep) and secondary creep at $2\times10^{-7}$ [MPa$^{-1}$ dpa$^{-1}$] reasonably fit the creep behavior up to 30 dpa. The creep coefficient of SiC fibers (HNS, SYL, SYL-iBN, and SA3) follows the trend of the nano-powder sintered materials rather than CVD SiC. No significant difference in fluence-dependent creep coefficient was observed between them. In summary, the radiation creep behavior of various SiC materials can be explained using simultaneous transient and secondary creep, and the creep coefficients are on the order of ~$10^{-7}$ [MPa$^{-1}$ dpa$^{-1}$] or less at 380–790°C above 1 dpa.

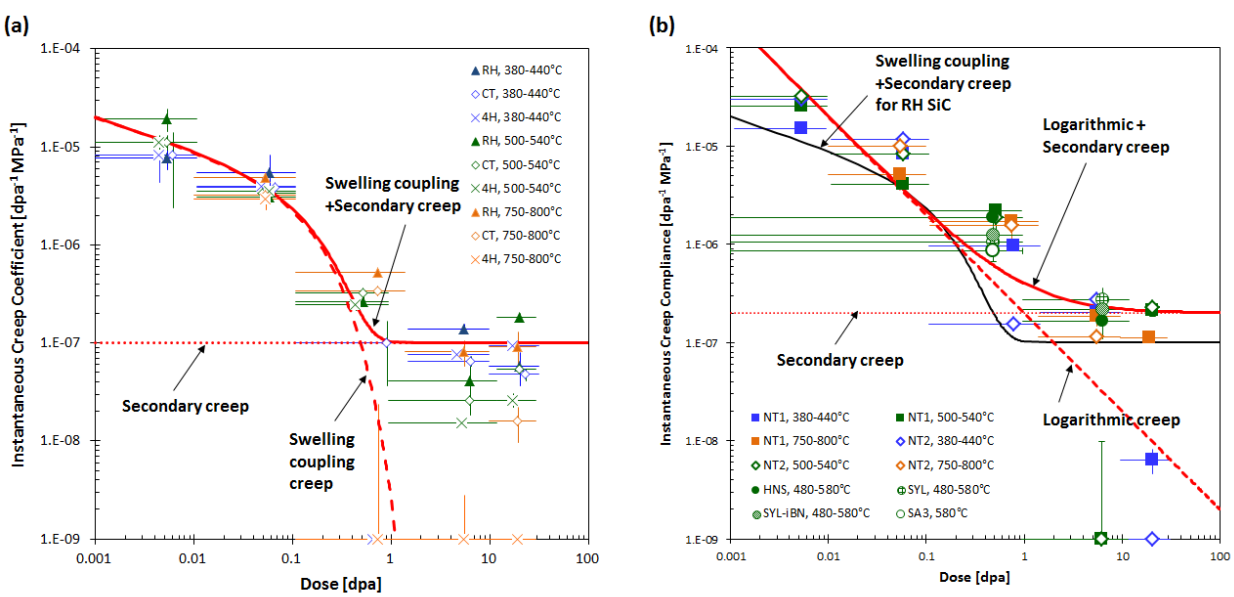


**Figure 1.** Neutron dose dependence of instantaneous creep coefficients of CVD SiC materials (a) and nanopowder sintered SiC and SiC fibers (b). Behavior based on creep models such as transient creep (swelling-coupled creep or logarithmic creep) and simultaneous transient and secondary creep is also shown. The data points on $1\times10^{-9}$ [dpa MPa]$^{-1}$ in (a) are actually below that number.

The differential creep behavior among various SiC materials in Figure 1 indicates that the starting microstructure affected creep behavior in the post-transient regime. Microstructural differences among CVD SiC, sintered SiC, and SiC fibers included grain size and impurity phases located mainly between

grains. Therefore, differential creep behavior is suspected to be caused by grain boundary–related mechanisms. Figure 2 shows instantaneous creep coefficients plotted against grain size for CVD SiC, sintered SiC, and SiC fibers. The grain size of single-crystal 4H SiC is assumed to be 40 mm, which is the length of the creep specimen. Irradiation temperature affected the grain-size dependence of the creep coefficient as follows. The creep was independent of grain size at ~400°C. Above this temperature, the SiC with smaller grains exhibited a larger creep coefficient, which was more significant at higher irradiation temperatures. Although the structures of grain boundaries are different depending on the material, the smaller grains led to the greater contribution of grain boundaries to irradiation creep.

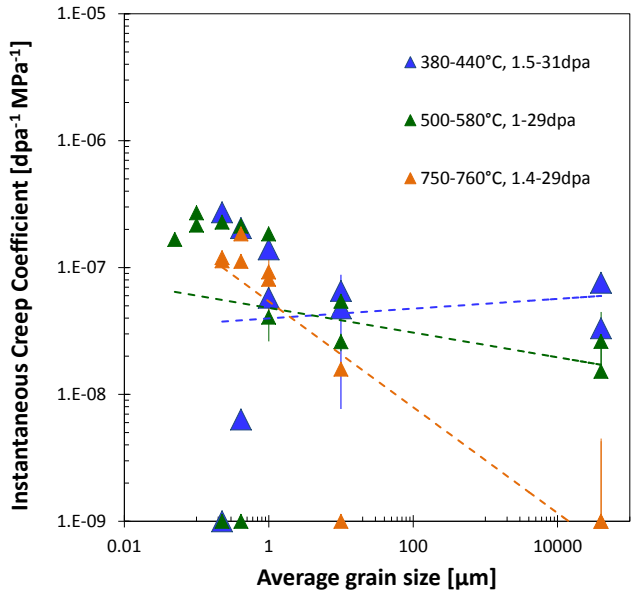


**Figure 2.** Grain-size dependence of instantaneous creep coefficient for various SiC materials. Trend lines fitted using a power law distribution are also shown. The data points on $1\times10^{-9}$ [dpa MPa]$^{-1}$ are actually below that number.

We found that the instantaneous creep coefficient was ~$1\times10^{-7}$ [MPa dpa]$^{-1}$ at ~400 to ~750°C to ~1–30 dpa for all the SiC materials except for the SiC with coarse grains at ~750°C (Figure 2). That creep coefficient is compared with those of the metals in Figure 3. The post-transient irradiation creep was investigated for zirconium alloys, vanadium alloy (V-4Cr-4Ti), austenitic stainless steels including 316 and 304, oxide-dispersion-strengthened (ODS) ferritic steels (MA957 and HT9), and ferritic/martensitic steels (F82H and JLF-1). Those irradiation temperatures ranged from ~300 to ~700°C. The irradiation creep was investigated using a pressurized tube method for all the materials other than SiC. The stress exponents of those materials are reported to be between one and two. Although the test method, irradiation conditions, and stress exponents were different, the significant differences in the creep coefficient between SiC and the other materials can be discussed. The creep coefficient of the zirconium alloys was ~$1\times10^{-5}$ [MPa dpa]$^{-1}$. A slightly smaller creep coefficient of ~$5 \times 10^{-6}$ [MPa dpa]$^{-1}$ was obtained for the specific vanadium alloy. A much smaller creep coefficient of ~$1\times10^{-6}$ [MPa dpa]$^{-1}$ was typical for the austenitic stainless, ODS, and ferritic/martensitic steels. The creep coefficients of the SiC materials were approximately one order smaller than the coefficients for those steels. Therefore, the creep coefficients of the SiC materials are extremely small compared with those of the other nuclear materials. Although the smaller creep coefficient does not necessarily indicate a longer creep lifetime, it can be concluded that the smaller creep coefficient contributes to higher dimensional stability. In the case of the high-purity CVD SiC, the saturation of swelling above ~1 dpa in addition to the small creep coefficient makes the material more dimensionally stable in the irradiation environment than the metals.

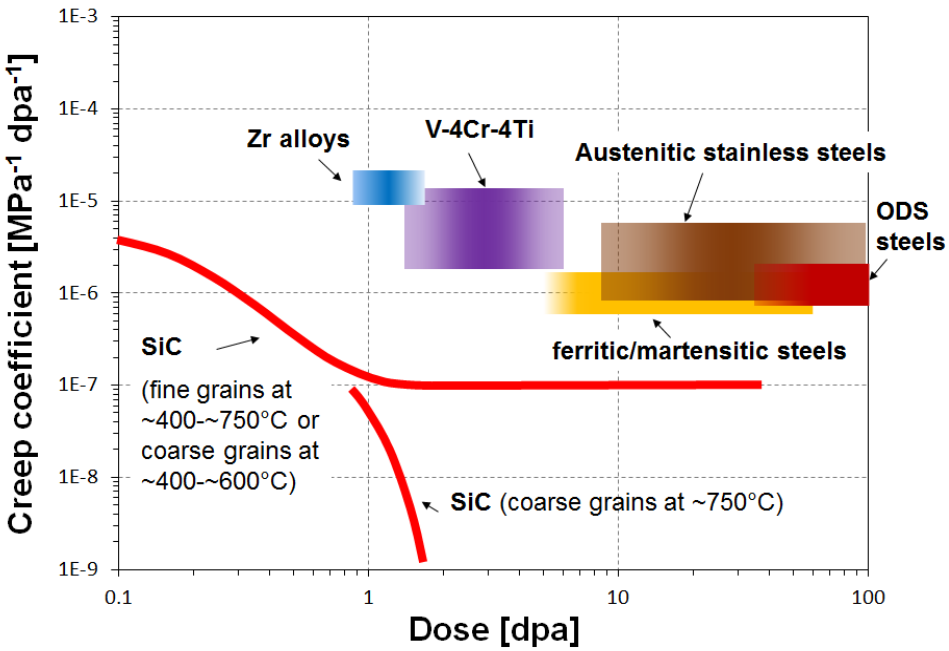


**Figure 3.** Comparison of typical creep coefficients among different nuclear materials. The data for the metals were reported in elsewhere [2, 5-13].

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