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STEADY STATE CREEP OF ZIRCONIUM AT HIGH AND INTERMEDIATE TEMPERATURES

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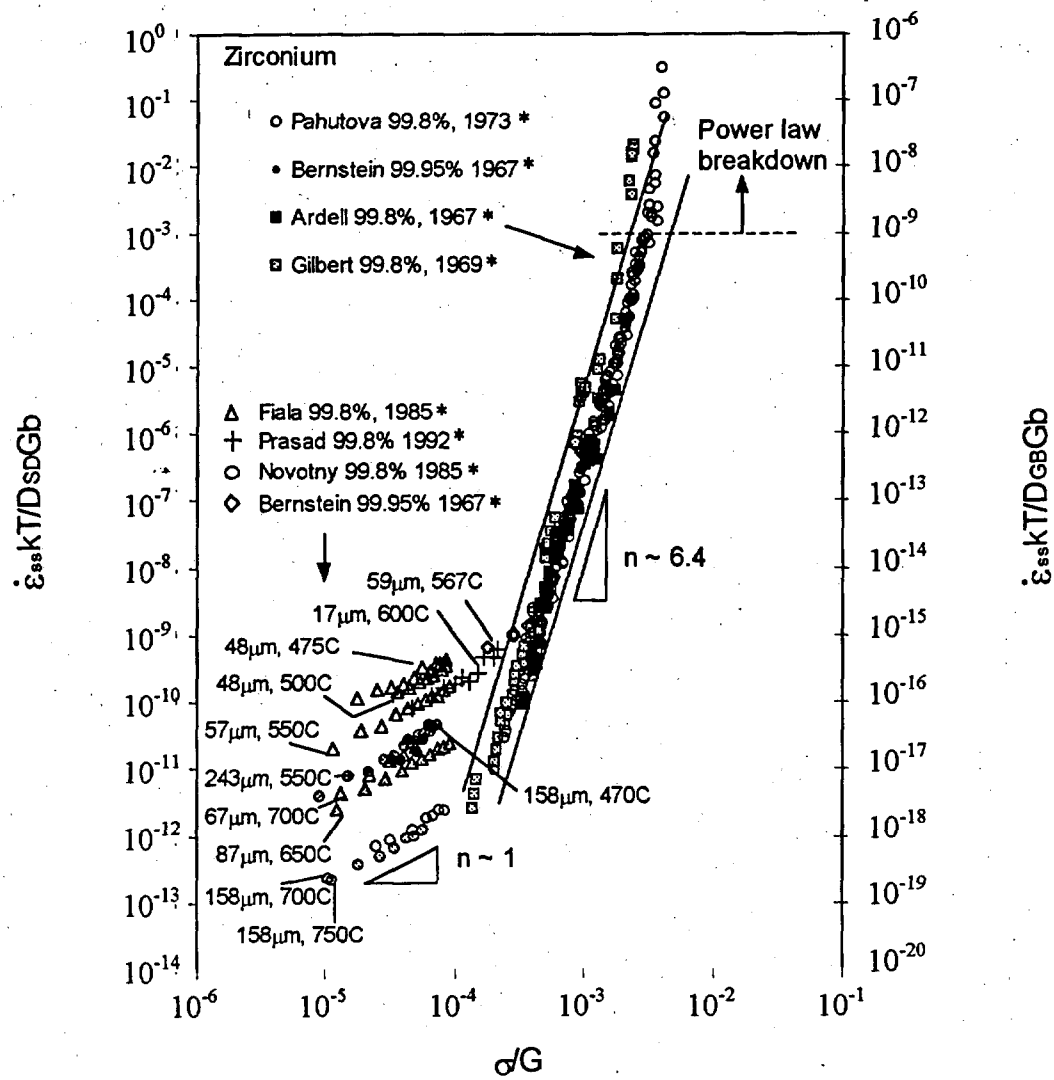
ABSTRACT- Creep of zirconium and zirconium alloys has been labeled "anomalous." Researchers often report that zirconium and its alloys never reach true steady state creep and have stress exponents that continuously change with stress and temperature. Many varied interpretations have been offered explaining the creep behavior of zirconium. Some have suggested that creep is diffusion controlled, while others maintain that creep is dislocation glide controlled. Cumulative zirconium creep data will be presented based on an extensive literature review. An interpretation of results will be presented and compared to previous interpretations.

INTRODUCTION: Zirconium alloys are commonly used as a cladding material to contain nuclear fuel. After the fuel is removed from reactor, the cladding must serve as a containment barrier for the spent nuclear fuel for long periods of time. Spent fuel rods experience stresses and temperatures up to approximately 100 MPa and 400°C. Knowledge of the creep properties of zirconium and zirconium alloys is therefore very important. Creep of zirconium and zirconium alloys has been labeled "anomalous" (see Hayes et al. [1999] for a detailed discussion). Researchers often report that zirconium and its alloys never reach true steady state creep and have continuously changing stress exponents. Many varied interpretations have been offered explaining the creep behavior of zirconium. Some have suggested that creep is diffusion controlled, while others maintain that creep is dislocation glide controlled.

RESULTS AND DISCUSSION: Data from various past studies are presented below in Fig. 1, which is a plot of the diffusion coefficient compensated steady-state strain (creep) rate versus the modulus compensated (σ/G) creep stress. The data in the moderate σ/G (power-law) and high σ/G (power-law breakdown) regimes are normalized by the zirconium self-diffusion coefficient (with Q_{SD} ~270kJ/mol), while the data in the low σ/G regime is normalized by the grain boundary diffusion coefficient (with $Q_{GB} \sim 0.6Q_{SD} = 162$kJ/mol). It is apparent from Fig. 1 that when all past data are viewed on a single plot, zirconium appears to obey typical creep behavior. At low σ/G, the data in Fig. 1 have a constant slope (stress exponent, n) of 1 indicative of Harper-Dorn or possibly diffusional creep. At intermediate values of σ/G, the data has a constant stress exponent of approximately 6.4, which is typical for so-called 'five-power-law' creep. At values for σ/G above approximately 2×10^{-3}, zirconium reaches power-law breakdown, where the stress-exponent then increases with σ/G.

Moderate σ/G (power-law) regime: The activation energy for creep in the power law regime is approximately 270 kJ/mol and appears constant with respect to stress and temperature. This value falls within the range of self-diffusion activation energies reported in the literature (which range from approximately 92 - 315 kJ/mol – see Hayes et al. [1999]) and is fairly close to what is considered to be the 'intrinsic' self diffusion activation energy (reported by Hood [1988] to be approximately 315 kJ/mol). Thus, it appears that creep is self-diffusion controlled, rather than dislocation glide controlled.



* Pahutova [1973] is referenced below. See Hayes et al. [1999] for full citations of other references in Fig. 1.

Figure 1 Diffusion coefficient-compensated steady-state strain rate versus modulus-compensated stress from various sources.

When examined individually, the data reported by Ardell et al. [1967] appear to indicate a non-constant stress exponent over the power-law regime (data appear slightly curved in Fig. 1). It is not clear what caused this behavior, however the data fit well within the

scatter of data reported by other investigators. Other investigators did not observe such behavior. Such 'undulation' has also been observed in other, well-behaved, systems such as high purity aluminum (see Kassner et al. [2000]). This is possibly due to some solute effect.

Low σ/G regime: The data in this regime were normalized by the grain boundary diffusion coefficient because it condensed the data from a range of 4 orders of magnitude to 2 orders of magnitude when compared to using the self-diffusion coefficient. The large variation (still about 2 orders of magnitude) in reported data below the transition from the six power-law regime to the one power-law regime (n~1) warrants further investigation. The creep mechanism(s) in this region are not well known. Some argue that creep in this regime is grain boundary diffusion controlled (Coble or Ashby-Verall creep) for small grain sizes (<125μm) and Harper-Dorn controlled for large grain sizes (>125μm). Those who support Harper-Dorn creep suggest using an activation energy for dislocation-pipe diffusion of 124 kJ/mol, which is a little unusual when considering the relatively low dislocation densities. Others believe that a grain boundary sliding mechanism is rate controlling. It is possible that some combination of these mechanisms may be controlling creep. The Fiala et al. data (see Fig. 1) may be condensed onto a single line by normalizing by the cube of the grain size, which would indicate Coble creep, however there are still significant discrepancies when comparing data from the multiple investigations presented in Fig. 1, even with similar grain sizes. The current authors plan to investigate this issue in detail in the future.

CONCLUSIONS: Zirconium obeys traditional power-law creep with a stress exponent of approximately 6.4 over the power-law regime. Power-law breakdown occurs at values of σ/G greater than approximately 2×10^{-3}. The creep rate of zirconium at low values of σ/G varies proportional to the stress. It is not clear which mechanism(s) control creep in this regime.

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