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Creep Behaviour of a Zr–1 wt% Nb Alloy at Elevated Temperatures

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This paper presents experimental data regarding creep behaviour of a Zr–1 wt% Nb alloy at elevated (623 K) and at high temperatures (873–1123 K) corresponding to loss-of-cooling situation of fuel cladding tubes for nuclear reactors. For an elaboration of methodological procedure and comparison purposes, the tensile creep tests were conducted using both constant stress and constant load over a wide range of applied stress. The substantial differences in the acquired creep data between constant stress and constant load creep testing were found especially at high stresses and large creep strain levels.

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1. Introduction

The zirconium alloys have served as one of the key structural materials for fuel claddings used in fuel assemblies of both pressurized water reactor (PWR) and boiling water reactors (BWR). Cladding tubes as a separator between fuel and coolant and a container of fuel in nuclear reactors are exposed to oxidation and/or corrosion, creep and irradiation. The oxidation of zirconium based claddings has extensively been studied by many different methods worldwide with the aim to improve the cladding corrosion performance for extended fuel burn ups [1, 2]. However, despite the intensive efforts spent in improving the corrosion resistance of claddings, the mechanisms responsible for improved corrosion resistance are not known in detail.

The creep behaviour of zirconium and its alloys has been investigated over four decades [3, 4] and continuously reviewed [e.g. 5–7]. An understanding of the creep behaviour and operating mechanisms of the cladding material in a wide range of applied stresses and temperatures is essential to execute mitigating plans in the event of an untoward incident such as a loss-of-coolant accident (LOCA situation). Unfortunately, there are still considerable differences of opinion as to controlling creep mechanisms of zirconium alloys. Further, it is frequently argued that a better understanding of creep behaviour of cladding tubes and creep testing for its prediction are required for the relevant operating conditions. In spite of these demands, the creep testing should be carried out on the test pieces machined from the real cladding tube. However, at present there appears to be insufficient quantitative creep data in the literature demonstrating the creep behaviour and stress rupture life of the zirconium cladding tubes [e.g. 1, 3, 8, 9]. Further, it is essential to keep the inevitable scatter associated with the uniaxial creep data as small as possible; this requires close control over the loading devices and straining the test piece by means of a constant tensile force (constant load) or constant tensile stress applied along its longitudinal axis [10]. Constant stress means that the ratio of the force to the instantaneous cross-section of the creep specimen remains constant throughout the test.

From a more detailed evaluation of a situation in the recent experimental investigations of creep in zirconium based cladding materials follows that the agreement between the results of various investigations cannot be considered quite satisfactory due to various testing techniques used. This should justify a further development and assessment of the creep testing methodology. Despite the apparent success associated with various procedures, there has been no attempt yet to meaningfully compare basic creep characteristics of some zirconium alloys and/or cladding tubes as obtained by constant load and constant stress creep testing. This was the main reason to undertaking the present work to provide relevant information on the influence of the different testing approaches on the creep behaviour and obtained characteristics of a selected zirconium cladding tube. Thus the present paper reports the results of constant load and constant stress creep tests carried out on the same Zr1Nb fuel cladding tube at elevated temperatures, in order to make possible a direct comparison between constant load and constant stress creep data.

2. Material and experimental procedures

The fuel cladding tube made out of a Zr–1 wt% Nb alloy was provided with an outer diameter of 9.12 mm and an inner diameter 7.74 mm in as-received state. Its chemical composition was Zr, 1.0wt%Nb, 0.05wt%O

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and 0.01wt%Fe. The alloy was recrystallized with equiaxed grains of a mean size of $\approx$5 μm.

The tube creep specimens were machined directly from cladding tube. Both constant load and constant stress creep tests were conducted in tension using flat samples having gauge lengths of 25 mm and cross-sectional areas of 3.0 mm $\times$ 3.2 mm. All specimens were pulled to the maximum elongation allowed by the constant stress creep testing machines configuration ($\approx$0.35). True strain–time readings were continuously recorded by the PC-based data acquisition system.

3. Experimental results

Representative creep curves shown in Fig. 1 were obtained at an absolute temperature, T, of 623 K, using the applied stress, σ, of 175 MPa. The figures illustrate (a) the variation of the strain, ε, with the time t (Fig. 1a), (b) the variation of the instantaneous strain rate, $\dot{\varepsilon}$, with the time (Fig. 1b), and (c) the variation of the instantaneous strain rate with the strain (Fig. 1c). Similarly, creep curves obtained at temperatures 923 and 1075 K are shown in Figs. 2 and 3.

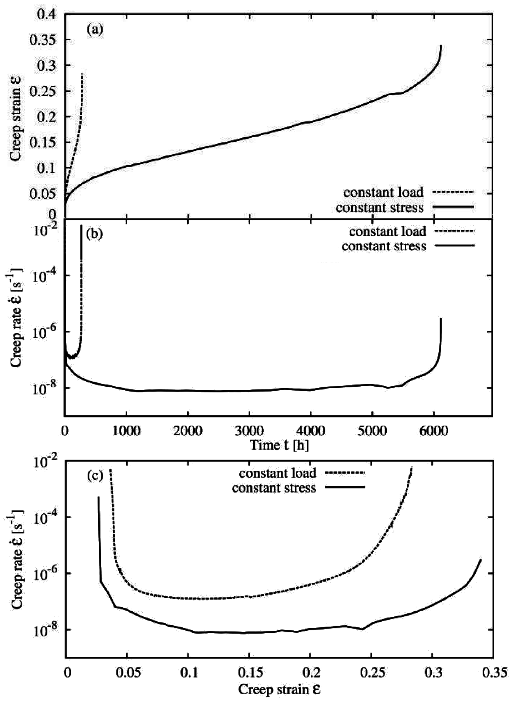

Fig. 1. Creep curves obtained at 623 K and 175 MPa showing (a) strain vs. time, (b) strain rate vs. time, and (c) strain rate vs. strain.

Several important conclusions may be reached from inspection of these plots. First, it is important to note that under the same loading conditions there is a significant difference in the time to achieve the strain $\approx$0.35 for constant load and constant stress testing. In general, the constant stress creep tests exhibit markedly longer creep

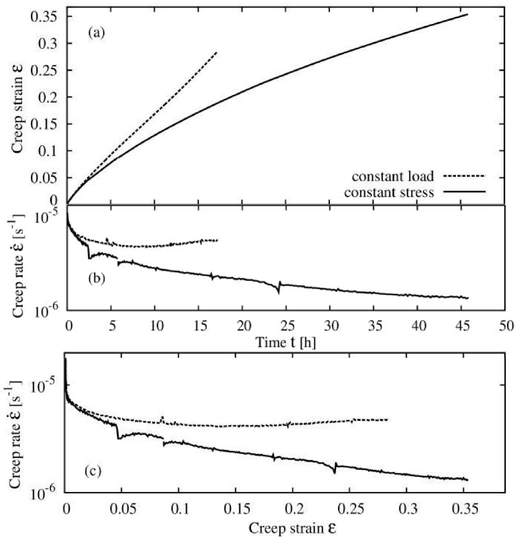

Fig. 2. As in Fig. 1, but for 923 K and 20 MPa.

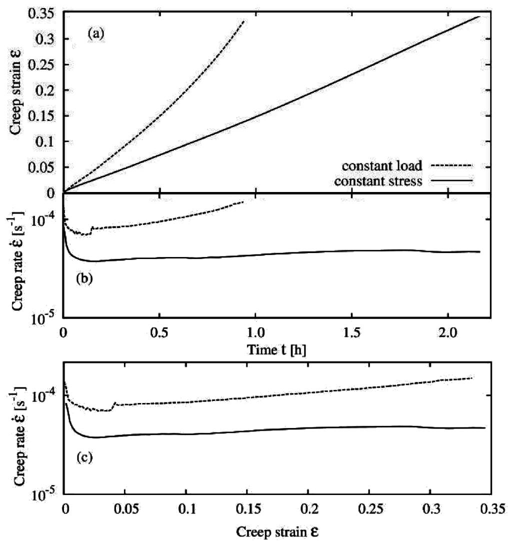

Fig. 3. As in Fig. 1, but for 1073 K and 10 MPa.

exposures than constant load creep tests. Second, the creep testing methods result in a difference in the shape of the creep curve (Figs. 1–3). In particular, under constant load, primary stage is followed by a minimum creep rate range, rather than by a well defined secondary region. Then, an early onset of tertiary (accelerated) stage is observed. When the steady-state disappears, it is still possible to define the minimum creep rate $\dot{\varepsilon}_{\rm min}$. Usually, it is assumed that the minimum creep rate is equivalent to the steady-state creep rate, as the steady-state creep stage has been reduced to an inflection point of the $\dot{\varepsilon}$ versus t curve [11]. Additional information can be obtained by logarithmically plotting the minimum creep rate, $\dot{\varepsilon}_{\rm min}$, against stress, σ. However, both methods exhibit similar trends in these plots: the values of the stress exponent, n, defined as $n = (\partial \ln(\dot{\varepsilon}_{\rm min})/\partial \ln(\sigma))_T$ gradually increase with increasing applied stress.

4. Discussion

From previous results (at the constant stress experiments) is clearly seen that the Zr–1 wt% Nb alloy exhibits very large creep ductility, mainly at elevated temperatures. There is no strong acceleration of the creep rate, caused by rapid grow and coalescence of the cavities and other creep damage at temperatures higher than 873 K and strains up to 0.4. This behaviour exposes the accelerating effect of growing stress with the constant load creep test clearly, thus the differences of the creep testing methodology and its consequences must be addressed.

4.1. Minimum creep rate

The minimum creep rate used to be considered as one of main creep characteristics, since it represents the instant in the microstructural development when the accelerating processes represented mainly by creep damage development start to overweight work hardening. This holds for constant stress experiments, but with constant load the growing stress is an additional accelerating factor which can change the minimum creep rate considerably.

This is clearly visible from Fig. 2b and c, where no minimum creep rate is observed with constant stress test, while constant load test shows clear minimum. The creep rate minimum obtained with constant load creep test then refers to completely different microstructural state than that of constant stress test.

One can conclude that the minimum creep rate obtained from constant load creep test must not be compared to that obtained from constant stress one. Moreover, only the minimum creep rate obtained from constant stress test can be interpreted in terms of creep damage development.

4.2. Stress sensitivity of the creep rate

The stress exponent n, defined in the previous section need not be necessarily derived exclusively from the minimum creep rate. It is also possible to derive it comparing creep rate at some defined instant, for instance at the given time of the creep test or at the same creep strain reached. Since both strain controlled and stress assisted time controlled processes are involved, the choice depends on which process is dominating. Thus, the stress exponents n could be defined as:

$$n_t = \frac{\ln\left(\frac{\dot{\varepsilon}_a}{\dot{\varepsilon}_b}\right)_t}{\ln\left(\frac{\dot{\sigma}_a}{\dot{\sigma}_b}\right)_t} \text{ and } n_\varepsilon = \frac{\ln\left(\frac{\dot{\varepsilon}_a}{\dot{\varepsilon}_b}\right)_\varepsilon}{\ln\left(\frac{\dot{\sigma}_a}{\dot{\sigma}_b}\right)_t}. \quad (1)$$

The values of corresponding n then could be derived comparing constant load and constant stress experiments at the same initial applied stress. Taking into account that for constant load test $\sigma = \sigma_0 \exp(\varepsilon)$ holds, we can get

$$n_t = \frac{1}{\varepsilon_{\rm cl}} \ln\left(\frac{\dot{\varepsilon}_{\rm cl}}{\dot{\varepsilon}_{\rm cs}}\right)_t \text{ and } n_\varepsilon = \frac{1}{\varepsilon_{\rm cl}} \ln\left(\frac{\dot{\varepsilon}_{\rm cl}}{\dot{\varepsilon}_{\rm cs}}\right)_\varepsilon, \quad (2)$$

where cl and cs subscripts refer to constant load and constant stress test results, respectively.

Results of such analysis for various testing conditions are shown in Fig. 4a and b. The scatter is large for small strains, but for large strains the values are almost constant. It is clear that the stress sensitivity of the creep rate increases with growing stress and reaches very different values. Actually, it was experimentally found that while $n \approx 65$ at 623 K and 200 MPa, almost viscous behaviour with $n \approx 1.5$ can be found at 1023 K and 10 MPa. These results indicate changes in the creep deformation mechanisms.

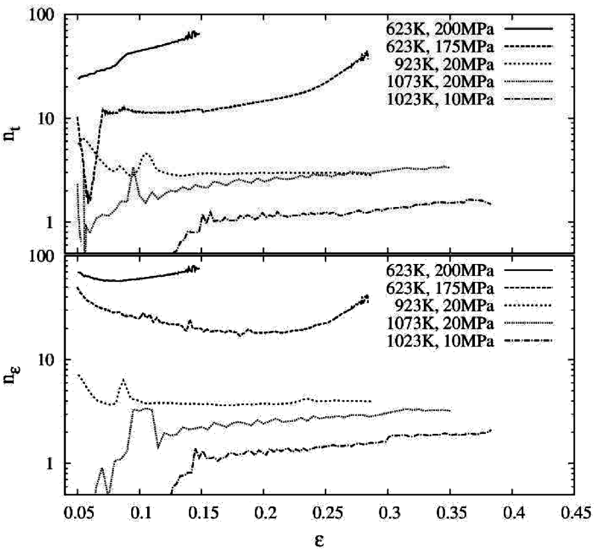

Fig. 4. Stress exponents derived from constant load and constant stress creep data according to Eq. (2) for (a) the same time, and (b) and the same strain.

5. Conclusions

The present investigation of the creep behaviour of a Zr–1 wt% Nb alloy at elevated temperatures led to the following results:

- A Zr–1 wt% Nb alloy for cladding tubes of nuclear fuel exhibits extraordinary creep ductility, mainly at temperatures corresponding to LOCA condition.
- Differences between constant load and constant stress test results are huge and point out the importance of the used creep testing methodology. Constant load tests can provide false minima on the creep rate dependences, which cannot be interpreted in terms of creep damage development.
- Stress sensitivity of the creep rate, expressed by the stress exponent, sharply decreases with decreasing stress and increasing temperature, indicating the transition in the creep mechanisms. Creep properties in LOCA conditions cannot be extrapolated from that of operational temperatures and vice versa.

Acknowledgments

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