High Temperature Deformation Characteristics of Zirlo^{TM} Tubing via Ring Creep and Burst Tests

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ABSTRACT

Cladding tubing acting as a barrier between the coolant and the radioactive fuel pellets in light water reactors undergo a combination of mechanical and thermal effects along with corrosive conditions during normal operations as well as accident situations like loss-of-coolant accident (LOCA) etc. Therefore, the mechanical integrity of the cladding tubes is very important. Here high temperature deformation characteristics of a niobium-added zirconium alloy cladding material (Zirlo^{TM}) have been evaluated via both ring-creep and burst-creep tests. Creep-rupture data are presented in terms of Larson-Miller parameters (LMP). Data (creep rate vs. stress) from ring-creep and burst tests are analyzed, and operating creep mechanisms are elucidated. This study demonstrates that the hoop creep data obtained from ring creep and burst tests are equivalent, and one can be replaced with the other if needed in order to evaluate creep life.

INTRODUCTION

Zirconium alloys (mainly Zircaloys) are widely used as the fuel cladding tubes and other core internals in light water reactors (LWR). Recrystallized Zircaloy-2 alloy finds application in boiling water reactors (BWR) whereas cold-worked stress-relieved (CWSR) Zircaloy-4 alloy in pressurized water reactors (PWR). Recently, niobium-modified zirconium alloys (such as, Zirlo$^{TM(1)}$ and M5$^{TM(2)}$) are being considered for applications in the advanced light water reactors [1]. These alloys possess good long-term corrosion resistance along with other favorable mechanical properties that lead to higher burnup characteristics. For instance, a typical PWR core experiences temperatures in the range of 290-350^{o}C, and a system pressure of 15-16 MPa during the normal operation [2]. Stresses may arise from various factors, such as the external coolant pressure, flow-induced vibration, internal pressure due to released fission gases and pellet-cladding interactions, and spacer grid forces due to differential growth. Under accident situations (such as, LOCA) the reactor conditions become more serious. Hence, a careful evaluation of high temperature mechanical properties of these zirconium alloys is of paramount importance for reactor safety and reliability. Burst test and ring tests are thus important mechanical test techniques to evaluate the deformation characteristics of cladding tubes at elevated temperatures.

Burst test is used for evaluating the stress-rupture properties of tubes/pipes under internal gas pressurization [3]. It is basically similar to a biaxial creep test continued until failure having a stress ratio (hoop stress to axial stress) of 2:1. However, it has been recognized that the hoop stress is more important in cladding applications, and burst creep properties are strongly related to the hoop creep properties. On the other hand, ring creep tests [4] can be used for evaluating uniaxial hoop properties.

This study has been undertaken to compare data from both burst and ring creep tests, and comment in terms of Larson-Miller parameters and operative creep mechanisms.

EXPERIMENTAL

Thin-walled Zirlo (nominal composition: Zr-1Sn-1Nb-0.01Fe-0.008Cr-0.01O, in mass%) cladding tubes of ~9.5 mm outer diameter and ~0.56 mm wall thickness were used in this study. Ring creep tests were performed to evaluate the properties in the hoop direction at various temperatures (350-600 ^{o}C). The test involves application of

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[1] Zirlo^{TM} is a trademark of Westinghouse Electric Company, Pittsburgh, PA, USA
[2] M5^{TM} is a trademark of Areva NP, Lynchburg, VA, USA

tensile force in the hoop direction of specially machined ring specimens (Fig. 1a). The details of the test configuration and method have been described elsewhere [4, 5]

Burst tests were performed by internally pressurizing (with compressed argon gas) closed end tubes at various pressures and temperatures (365-570 ^{o}C). The experiments were carried out following the method described in detail elsewhere [3, 6]. The diameter of the tube specimen before and after the burst test was measured every 6.4 mm along the longitudinal direction and used to calculate the uniform circumferential elongation (*UCE*). The burst stresses were calculated using thin-wall approximation:

$$\sigma_\theta = \frac{pD}{2t} \tag{1}$$

where p is the internal pressure, D the mean diameter and t the thickness of the cladding. The strain rate ($\dot{\varepsilon}$) was calculated from the following equation (t_r is the time to rupture):

$$\dot{\varepsilon} = \frac{UCE}{t_r}. \tag{2}$$

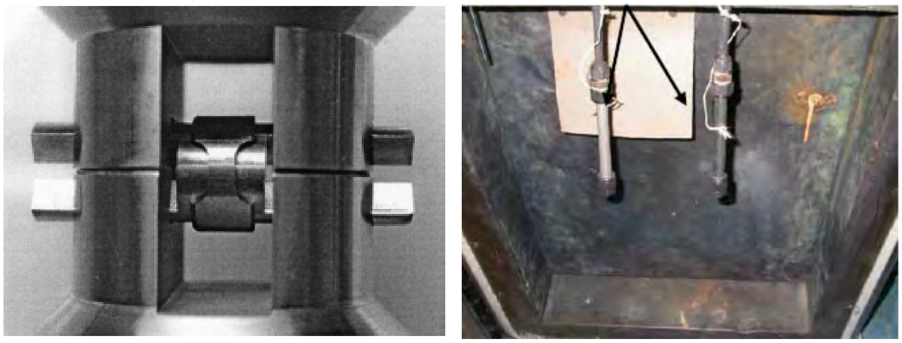

Figure 1. A view of the ring creep test configuration (left) and burst test configuration (right).

RESULTS & DISCUSSION

Two representative ring creep curves of CWSR Zirlo are shown in Fig. 2. It is important to note that the creep curves resemble conventional creep curves with three distinct creep stages, i.e. primary, secondary (steady-state) and tertiary. The minimum creep rates (i.e. steady-state creep rates) were used in the analysis of identifying the operating deformation mechanism under creep conditions. As noted earlier, the burst creep data were obtained from measuring tube diameters before and after the test and the minimum creep rates were determined following Eqn. (2).

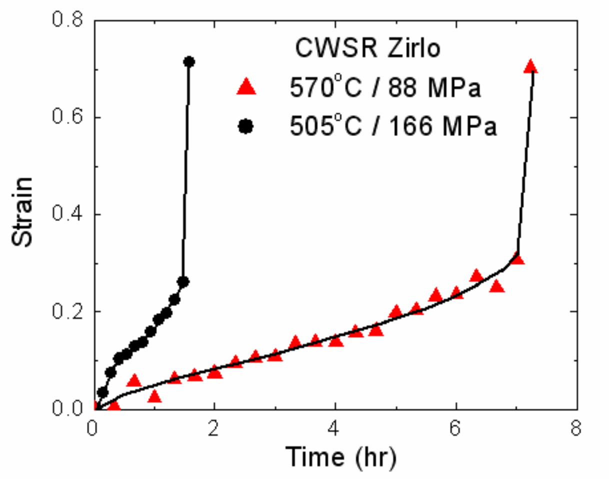

Figure 2. Two representative creep curves of CWSR Zirlo under different conditions (obtained from ring creep tests).

It is well known that Norton's law (Eqn. 3) can be used to evaluate stress exponents (i.e. stress dependence of strain rate):

$$\dot{\varepsilon} = A'\sigma^{n} \tag{3}$$

where σ is the stress, A' is constant dependent on various factors (microstructure, material, temperature etc.) and n is the stress exponent. The stress exponent can be evaluated from the slope of the fitted straight lines of creep rate vs. stress data.

Based on Eqn. (3), hoop creep rate vs. hoop stress data obtained from the burst creep tests are plotted in Figure 3a to evaluate the stress exponents. Stress exponents at higher temperatures are found to be ~ 6. Similarly, test data from the ring creep tests are plotted in Fig. 3b.

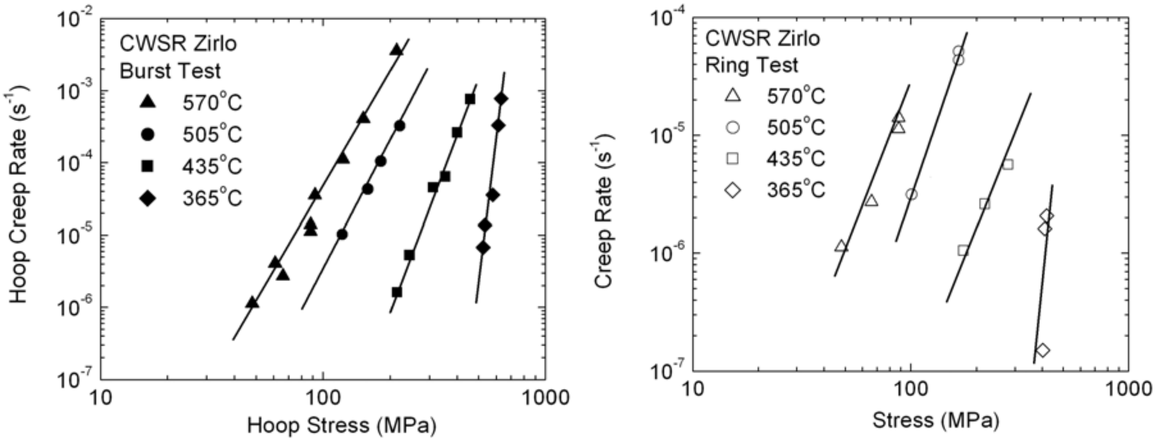

Figure 3. Creep rate vs. stress data obtained from burst tests (left) and ring tests (right) for CWSR Zirlo.

The stress exponent evaluated above is only apparent in nature because there are many other factors (such as temperature dependence of elastic modulus) that can influence the creep behavior. In this regard, the use of Dorn equation is the most appropriate [1]:

$$\dot{\varepsilon} = \frac{ADEb}{kT}\left(\frac{\sigma}{E}\right)^{n} \tag{4}$$

where *A* is a material and microstructure constant, *D* the appropriate diffusivity, *E* the appropriate temperature-dependent elastic modulus, *b* the Burgers vector, k is Boltzmann's constant, *T* the temperature in K, and all other terms have previously been defined. *D* is generally expressed in terms of the following relation:

$$D = D_o \exp\left(-\frac{Q}{RT}\right) \tag{5}$$

where D_o is the frequency factor, Q the activation energy for creep and R the universal gas constant.

Although the burst test is biaxial in nature (a stress ratio of 2:1), the burst hoop data closely relate with the uniaxial creep data obtained from the ring creep tests since both the stress and strain along the tube axis are negligible in the biaxial tests. Normalization of the data was made using appropriate modulus and diffusivity values, and the results are shown in Fig. 4. The following diffusivity equation [7] and temperature-dependent elastic modulus (E) were used for the normalization of creep data:

$$D = 1.26x10^{-3} \exp\left(-\frac{272{,}000J}{RT}\right) m^{2}s^{-1} \tag{6}$$

$$E(T) = (88000 - 61.4T)MPa \tag{7}$$

where T is in K.

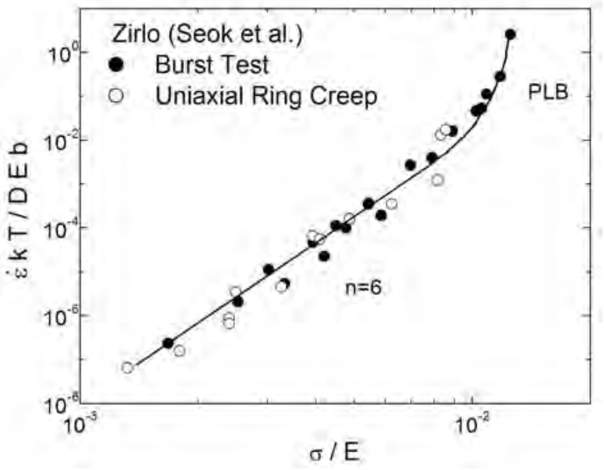

Figure 4. Normalized creep rates vs. normalized stress data (burst and ring creep tests) for CWSR Zirlo.

Fig. 4 clearly shows that there is a transition in the deformation mechanism from a dislocation climb-controlled power law regime (a stress exponent of 6) to a power law breakdown (PLB) regime where the strain rate increases exponentially with stress. The transitional nature of deformation mechanisms may have important implications for the accurate life-estimation of reactor components under reactor service conditions. Fundamental creep data are often obtained at higher temperatures and higher stresses in order to obtain the relevant creep data faster. However, if an extrapolation to lower temperatures/stresses (which is often more representative of the service conditions) is made to predict the life of reactor cladding, it would be grossly inaccurate because of the presence of transitional creep mechanisms. Therefore, there lies a potential danger in *blind extrapolation*, and mitigating plans should be made in order to avoid such situations.

All stress and corresponding time to rupture data (obtained from burst and ring creep tests) for CWSR Zirlo are plotted in Fig. 5. It is clear that the cladding creep life increases with the decrease in the applied hoop stress. Further, there is an excellent correlation between the two types of data (burst and ring tests), implying that the burst test and ring test can generate creep data in the hoop direction that are equivalent to each other.

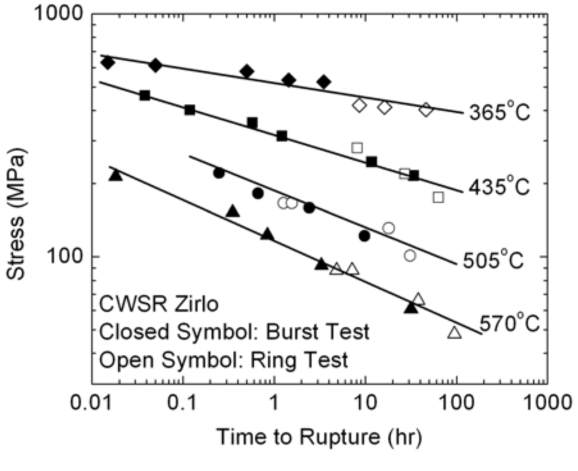

Figure 5. Hoop stress vs. time to rupture for CWSR Zirlo cladding tubes

An empirical design parameter known as Larson-Miller parameter (LMP) is often used and is considered as a useful engineering design parameter for component undergoing creep loading. LMP is defined as $T(\log t_r + C)$ where T is the temperature (in K), t_r is the time to rupture (hr) and C (~20) is a constant [3]. Figure 6 shows the stress vs. LMP plot for CWSR Zirlo. Again, excellent correlation can be seen between the burst and ring creep data. Also, the literature data from recrystallized (Rx) [6] and CWSR Zircaloy-4 [8] are also plotted. Interestingly, on the stress-LMP plots the results of the Rx Zircaloy-4 data show a deviation from those of CWSR Zircaloy-4 as well as CWSR Zirlo data. This indicates that alloying (Nb) addition has negligible effect while the heat treatment strongly affects creep and burst properties. The burst/ring creep data for Rx Zirlo have not been available, and hence it could not be shown in Fig. 6. The deviation can be attributed to the transition in creep mechanism (i.e. from power-law to power law breakdown regime). It appears that PLB starts much earlier (i.e. at lower stresses) in Rx Zircaloy-4 than the CWSR Zircaloy-4 or Zirlo. It will be interesting to study similar behavior in Rx Zirlo.

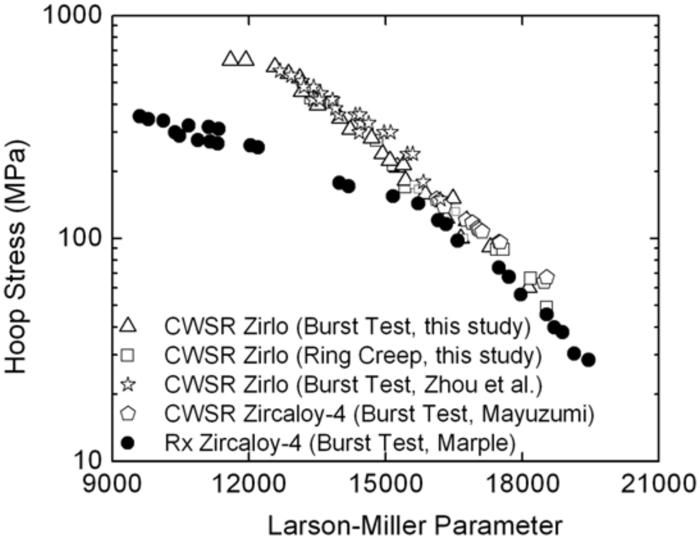

Figure 6. Stress vs. LMP plots for different zirconium alloys.

SUMMARY & CONCLUSIONS

In this work, creep data obtained from burst and ring creep tests of CWSR Zirlo are analyzed. It is found that the two types of data are complementary to each other. A transition in the creep mechanism (from dislocation climb-controlled regime to power law breakdown regime) is noted whereas transition is also noted in stress – LMP plots. Further, the danger in the blind extrapolation of creep data in the prediction of cladding life is highlighted.

ACNKOWLEDGMENT

We (Marple, Srikant, Charit and Murty) acknowledge financial support from National Science Foundation grant # DMR-0412583 and Department of Energy grant #DE-FG07-041D14611. C.S. Seok acknowledges support from Brain Korea 21 project and KESRI (R-2003-B-071) funded by MOCIE (Ministry of Commerce, Industry and Energy), Korea.

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