MASTER

CREEP DAMAGE IN ZIRCALOY-4
AT LWR TEMPERATURES

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or technical of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

R.L. Keusseyan, C.P. Hu and C.Y. Li
Dept. of Materials Science and Engineering
Cornell University, Bard Hall
Ithaca, New York 14853

August 1978

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

1. INTRODUCTION

This letter reports the observation of creep damage in the form of grain boundary cavitation in Zircaloy-4 in the temperature range of interest to Light Water Reactor (LWR) applications. The observed damage is shown to reduce the ductility of Zircaloy-4 in a tensile test at LWR temperatures.

The nucleation and growth of grain boundary cavities during creep in the absence of environmental effects are known to cause intergranular failure and reduction of ductility [1,2,3]. This type of damage process at low stresses is also associated with the increased slope shown in a stress versus logarithmic time to failure plot of creep-to-rupture data. It should be noted that when a specimen with accumulated creep damage is failed in a tensile test at a moderate extension rate, one observes reduced ductility but not necessarily intergranular failure [4].

The nucleation of grain boundary cavity in the absence of environmental effects is generally recognized to be caused by plastic incompatibility at grain boundary steps and corners resulting from grain boundary sliding. These nuclei will grow under an applied tensile stress by a mechanism of stress induced mass transport similar to that for Nabarro-Herring creep, except for the present interest the source of vacancies is the grain boundary, the sink is the cavity and the diffusion path is the grain boundary [5,6]. The stress induced cavity growth at the grain boundary is roughly linearly related to the magnitude of the applied stress. Since the creep rate is usually a power function of the applied stress, one can expect a considerable extent of cavity growth if sufficient time is allowed while the dimension of

the specimen is essentially unchanged by creep.

Grain boundary sliding and the nucleation and growth of grain boundary cavities usually occur at temperatures near one half of the absolute melting temperature of a material. The cladding temperature of a light water reactor is significantly lower than one half of the absolute melting temperature of the Zircalloys. This probably is the reason that the possibility of creep damage during normal operation of a light water reactor has not been explored extensively even though after some fluence tensile stresses in the cladding may result from pellet-clad interactions. Recently the contribution of grain boundary sliding at 350°C and above and at strain rates of interest to LWR applications was identified based on load relaxation data in this laboratory. This result prompted us to search for the existence of grain boundary cavities produced during creep in the Zircalloys at these temperatures.

2. EXPERIMENT

Specimens were prepared from Zircaloy-4 sheets obtained from Westinghouse Corporation. The sheets of 0.76 mm thickness were α -annealed at 700°C for 3 hours resulting in an average grain diameter of 12 microns. Tensile specimens were prepared by spark cutting according to ASTM standards with a gauge length of 2.54 cm and a width range from 1 mm to 1.78 mm. They were chemically polished and washed thoroughly before creep tests.

Creep tests were performed in an atmosphere of high purity argon (research grade tank argon purified by an "Inert Gas Purifier" with a titanium element operating at 900°C; R.D. Mathis Company, model GP100). The gas system was made of stainless steel parts

and was well flushed before creep tests. The specimen, the data for which is included in this letter, was creep tested at 375°C (temperature controlled to within $\pm 3^\circ\text{C}$) with an initial stress of 132 MN/m^2 for 240 hours and accumulated a strain of 3%. For each creep specimen, a duplicate specimen is placed in the system to experience the same thermal and environmental history in the unstressed condition. The experimental results showed that there is no significant difference between longitudinal and transversal oriented specimens. For direct observations of grain boundary cavities in the Scanning Electron Microscope (SEM) the specimen was notched and fractured intergranularly.

3. RESULTS AND DISCUSSION

Fig. 1 shows the results of tensile tests of the specimens described in the previous section. The specimens were notched by spark cutting prior to the tensile test to a depth of 0.01 mm along the width of the specimen. The tensile test was performed in air at 350°C and at an extension rate of 0.005 cm/min, the strain being determined from crosshead displacement and corrected for machine effects. The uncrept specimen with the same thermal and environmental history, as the crept specimen, was also tensile tested, the latter specimen failed by necking away from the notch. The crept specimen failed at the notch in the transgranular mode with a significant reduction in ductility.

A duplicated crept specimen was fractured intergranularly for SEM examination (without tensile test). The SEM photomicrograph, fig. 2, clearly reveals the existence of grain boundary cavities. Apparently the size and number of the cavities shown are sufficient

to cause the observed reduction in ductility. SEM examination of a duplicated uncrept specimen of the same thermal and chemical history showed neither grain boundary cavities nor second phase particles.

The present results are consistent with our previous data [7] on grain boundary sliding in that grain boundary sliding can occur in the Zircalloys at LWR temperatures which are considerably lower than one half of the absolute melting temperature. The α - β phase transformation occurs at 862°C for pure Zirconium. The experimental results on grain boundary sliding [7] and the present result of grain boundary cavitation in Zircaloy-4 suggest that the homologous temperature scale of the Zircalloys is shifted downward because of the low phase transformation temperature.

LWR fuel element failure resulting from pellet-clad interactions during a power ramp is of current technological interest. Stress corrosion cracking has been proposed as a mechanism for failure [8]. The results of this work suggest that at LWR temperatures, after some finite fluence if tensile stresses exist in the cladding during normal operation; creep damage of the type discussed can accumulate as a function of time, while the total deformation of the cladding is limited. The existence of grain boundary cavities could cause a part of the reduction in ductility observed in failures associated with a power ramp depending on the size and number density of cavities. These grain boundary cavities will not always lead to intergranular failure if the strain rate is high during a power ramp. This possibility as well as the kinetics of grain boundary cavitation in the Zircalloys will be explored in our future work.

4. ACKNOWLEDGEMENT

This work is supported by the Department of Energy. The authors wish to thank Westinghouse Corporation for providing the Zircaloy-4 sheets.

REFERENCES

- [1] F. Garofalo, Fundamentals of Creep and Creep-Rupture in Metals (Macmillan Series in Materials Science, 1965).
- [2] C.Y. Li, F.V. Ellis and F.H. Huang, Alloy and Microstructural Design, chapter XI (Academic Press, 1976).
- [3] F.L. Yaggee and C.Y. Li, Failure Mechanisms for Internally Pressurized Thin-Wall Tubes and Their Relationship to Fuel Element Failure Criteria. ANL Rep. No. ANL-1317, Argonne Nat. Lab. (1972).
- [4] J.F. Mancuso, Ph.D. Thesis, Cornell University (1977).
- [5] D. Hull and D.E. Rimmer, Phil. Mag., vol. 4, p. 673 (1959).
- [6] J.F. Mancuso, F.H. Huang and C.Y. Li, Proceedings of the International Conference on Fundamental Aspects of Radiation Damage in Metals, Gatlinburg, Tennessee, CONF-751006-P2, p. 1279 (1975).
- [7] F.H. Huang, G.P. Sabol, S.G. McDonald and C.Y. Li, Load Relaxation Studies of Zircaloy-4, Westinghouse R & D Center, document number 77-1D2-ZIRST-P1 (1977), accepted for publication in the Journal of Nuclear Materials.
- [8] See papers in Proceedings of ANS Topical Meeting on "Water Reactor Fuel Performance", St. Charles, Illinois, May 1977.

FIGURE CAPTIONS

Fig. 1 Engineering stress-strain curves for Zircaloy-4, tensile tested in air at 350°C, both specimens having the same thermal and environmental history.

Fig. 2 Scanning Electron Microscope photomicrograph of the grain boundary of a crept specimen showing cavities (magnification 10,000X).

Fig. 1

Fig. 2