DISCLAIMER

MASTER

UCIA-342177-26
UCIA-ENG-7927

REACTOR STEELS STUDIES

Final Report

for the period of July 1974 - December 1977

K. Ono
A.J. Ardell
A.S. Tetelman

MATERIALS DEPARTMENT
School of Engineering and Applied Science
University of California
Los Angeles

Prepared for the

U.S. Department of Energy
Division of Reactor Development and Technology
Under Contract No. E(04-3)-34, P.A. #177

April 1979

27

Foreword

This program was concerned with three different aspects of high temperature deformation and fracture of LMFBR candidate materials. Results of each three subtasks have been described in the theses of three M.S. and Ph.D. students supported by the program and reported quarterly in "Mechanical Properties Test Data for Structural Materials Quarterly Progress Report", compiled and published by Oak Ridge National Laboratory. Papers and presentations resulting from this project are listed in Part I. We have also participated and described the progress of our project at the ERDA/GE/UGLA Mechanical Properties Review Meeting at GE, San Jose, California, December 1974 and at the National Mechanical Properties Meeting at ORNL, Oak Ridge, Tennessee, November 1975.

J. M.S. and Ph.D. Students supported by the project of O. Ajaja (Ph.D., Dec. 1977)

THE INFLUENCE OF PRIOR COLD WORK ON THE CREEP CHARACTERISTICS
OF AISI TYPE 304 AUSTENITIC STAINLESS STEEL

Abstract

The creep behavior of cold worked type 304 stainless steel was investigated at 69-241.3 MPa² and 677-760°C. Constant stress tensile creep testing was done on annealed specimens and specimens which were prestrained 2, 4, 6, 8 and 10% in tension at room temperature. The microstructures at various creep conditions were investigated using transmission electron microscopy.

Cold work was observed to have significant effect on the primary and secondary creep behavior only at the lowest stresses investigated. The experimental creep data were fitted into the strain (ϵ) - time (t) relation

$$\epsilon = \epsilon_0 + \dot{\epsilon}_s t + \epsilon_t (1 - e^{-rt})$$

where ϵ_0 and ϵ_t are the loading and the total transient creep strains respectively, $\dot{\epsilon}_s$ is the steady-state creep rate and r is a parameter related to the rate of exhaustion of transient creep. All the parameters ϵ_0 , ϵ_t , r , $\dot{\epsilon}_s$ as well as the initial creep rate, $\dot{\epsilon}_i$ were found to decrease with increasing cold work at low stresses. In general, cold work appeared to influence the steady-state creep rate only when the material had been prestrained to a (temperature-compensated) flow stress which is higher than the applied creep stress.

The steady-state creep rate was found to follow the power law stress dependence (σ^n) at low stresses, the value of n increasing with increasing cold work or decreasing temperature. The activation energy for creep was determined to be 312 KJ/mole, in good agreement with the literature data for

stainless steels.

The substructural developments associated with transient creep were investigated with the TEM. It is suggested that subgrain boundaries are not primarily responsible for the decreasing creep rate during normal transient creep. In specimens which exhibit subgrains, prestraining speeds up the rate of subgrain development. This behavior, which generally leads to a shorter period of transient creep in prestrained specimens, is explained in the light of Friedel's theory of network growth.

At low creep stresses, the free dislocation density, ρ_F , at steady-state, was found to increase with increasing cold work. This is true whether or not subgrains were formed. The lower creep rate associated with a prestrained specimen is attributed to the increased internal resistance provided by the stress fields of the free dislocations. An empirical relationship was found to exist between $\dot{\epsilon}_s$, ρ_F and σ of the form:

$$\dot{\epsilon}_s \rho_F^{-m} \sigma^N$$

where $N \approx 8$ and $m \approx 1.7$ at the creep conditions investigated. The results of constant structure tests reported by past investigators are explained with the aid of the above relation.

A brief analysis of the precipitation occurring during creep is presented. The precipitates were identified as $M_{23}C_6$ or M_6C -type carbides and were often observed on the grain boundaries, and, in case of prestrained specimens, on deformation bands which were formed during prestraining. Intragranular precipitation was rarely observed in the annealed specimens.

A new creep model is proposed which takes account of the contribution to creep strain at any time, t , of all the dislocations that have slipped at one instant or another within the time interval $0 < t < \tau$, but have ceased contributing either because they have been annihilated or have moved to a sub-

boundary. This contribution was found to be decreasing creep rate associated with normal transient creep. Very good agreement was found between the strain-time relationship derived from this model and the experimental data at 760°C and 69 MN/m². The new model predicts normal transient creep for high values of r (i.e., at high stresses and/or temperatures) and an inverted transient creep for low values of r (i.e., at low stresses and/or temperatures). It was demonstrated that cold work affects the creep behavior by reducing the parameter $\dot{\epsilon}_0$, which is related to the initial and the steady state dislocation densities. This is used to explain the observed variation of the various transient creep parameters with cold work.

Shuh-Yueh Simon Fan
(N.S., June 1977)

MECHANICAL PROPERTIES OF 2-1/4Cr-1% Si STEELS
WITH VARIOUS TEMPERATURES

Abstract

C creep and tensile properties of 2-1/4Cr-1% Si steels with varied carbon contents (0.12% C to 0.60% C) were studied in the temperature range of 450°C to 560°C. The elevated temperature strengths were found to be correlated to both the microstructures and the effects of dynamic strain aging. The significance of dynamic strain aging varied with such parameters as the carbon content, heat treatment, and testing temperature. The effects of dynamic strain aging were manifested in the high yield hardening rates and serrated stress-strain curves in the tensile testing, and the high creep strength and the strain bursts in the creep testing.

Phillip Hele Jones
(Ph.D.; August 1977)

A STUDY OF THE EFFECT OF CARBON FROM THE HEAVY METALLOIDS
MECHANICAL, FRACTURE AND STATIC LOAD-CARRYING CAPACITY
BEHAVIOR OF AUSTENITE-STEEL

Abstract

Historically, there has been relatively little experimental work performed to quantify the effects of carbonization on the mechanical performance of austenite stainless steels because there are no direct applications for such an alloy. With the recent development of the heavy metal fast breeder reactor, and the potential for corrosion, transport and subsequent diffusion into the piping of the secondary side of the intermediate heat exchanger, corrosion, metal embrittlement, etc., could potentially affect the long term structural integrity of this system. The present study was conducted in order to characterize both the short and elevated temperature mechanical and fracture behavior of the creep and extension behavior of materials under consideration for use in the secondary sodium loop. Particular reference is given to the effect of carbon content and distribution on mechanical properties.

From tensile tests conducted at 700°C, it was determined that both the yield and fracture strength increase in proportion to the depth of the carbon case. The most significant finding in this portion of the research program is the sharp decrease in tensile ductility noted at relatively shallow case depths.

Comparing the observed ultimate tensile strength, taken as a function of the volume fraction of the carbon case, to that predicted using a continuous fibered composite model yielded consistent results, and also indicated that a

transition from a core-controlled to a case-controlled failure mechanism occurs at a volume fraction, $V_f(\text{crit})$, of approximately 0.6%. Based on the load-bearing cross-sectional areas of the core material after cracking of the brittle carbon case, a transition in the fracture controlling process was predicted at a case depth of approximately 4.6×10^{-2} cm. This corresponds to a critical volume fraction of 0.6%, which is close to that predicted using a constant, filtered composite material.

Along with the sharp decrease in tensile ductility observed, a transition from a ductile, transgranular to a brittle, intergranular type fracture was noted as a function of internal case depth. Comparing the observed fracture rate to the critical volume fraction required for a transition in the fracture controlling process indicated that case fracture is core-controlled, the fracture rate is the smallest, and when the fracture is case-controlled, the fracture rate tends to be larger. By considering the effects of matrix hardness, chloride depletion, triaxial constraint, and strain rate, it was determined that an increased load strain rate, acting on the core material at the tip of a crack in the carbon case, is the primary cause of the observed transition in the fracture rate.

Static load crack propagation tests were conducted in both an inert and carburizing gas atmosphere between 650°C and 800°C. From tests conducted in an inert atmosphere it was determined that a power function of the net section stress can be used to empirically correlate creep crack extension rates, independent of the test temperature or specimen geometry. However, correlating crack extension rates with the apparent stress intensity factor yielded results that are highly dependent on the specimen geometry. The apparent activation energy for creep crack growth and the creep crack growth exponents obtained from the net section stress correlation are consistent with

both the stress and temperature dependence of the activation energy and creep exponents for steady state creep reported in the literature.

Crack tip displacements were measured as a function of creep exposure time, and the crack tip displacement rates thus measured were compared to the corresponding crack growth rates. The results indicate a direct correspondence between load displacement rate and crack growth rate, which implies that creep crack extension is a load displacement (strain) rate related phenomenon. A physical model for creep crack extension, based on stress relaxation and on the attainment of a critical strain in a distance ahead of specimen immediately ahead of the crack tip, was developed. This model proposed for austenitic stainless steel reported in the literature, it was shown that this model provides a plausible link between the time dependence of crack dependence of creep crack growth rate on the rate of the preceding crack tip events in a manner that is consistent with both the above mentioned correspondence between the load displacement rate and crack growth rate, as well as with existing theories of steady state creep.

The most significant finding in this portion of the present paper is the effect of carburization on the observed crack extension rates. From the results obtained in tests conducted at 750°C and 850°C in a carburizing atmosphere, it was determined that creep crack growth exponent is identical, and, as in tests conducted in an inert environment, the crack growth rate is controlled by the load displacement rate. However, in a carburizing potential of $C_s = 0.88$ w/o, the observed creep crack extension rates are reduced by approximately 50%. This observed crack growth retardation can be explained in terms of creep strengthening due to carbide-dislocation interactions in the material immediately ahead of the crack tip in a manner that is consistent with the above mentioned physical model proposed for creep crack extension.

11. PUBLICATIONS AND PRESENTATIONS

Published Papers

Ajaja, G. and Ardell, A.J., "The Effect of Prior Cold Work on the Creep Characteristics of AISI Type 304 Stainless Steel, Proceedings of the Fourth International Conference on the Strength of Metals and Alloys, Nancy, France (1977) 2, 171-175.

Ajaja, G. and Ardell, A.J., "Microstructural Parameters and Steady-State Creep," Scripta Metallurgica, (1977) 11, 1089-1093.

Ajaja, G. and Ardell, A.J., "Microstructure and Transient Creep in an Austenitic Stainless Steel," Philosophical Magazine A, (1979) 39, 65-74.

Ajaja, G. and Ardell, A.J., "A Phenomenological Theory of Transient Creep," Philosophical Magazine A, (1979) 39, 75-96.

Technical Reports

Guo, F., Ardell, A.J. and Tetelman, L.C.,
Reactor Studies Studies Quarterly Progress Report (January - June 1974), UCLA-34P177-22, October 1974.

Guo, F.
(July 1974-Jan. 1975), UCLA-34P177-23.

Ajaja, G. and Ardell, A.J., Microstructural Parameters and Steady State Creep (October 1977), UCLA-34P177-24.

Ajaja, G. and Ardell, A.J., The Influence of Prior Cold Work on the Creep Characteristics of AISI Type 304 Austenitic Stainless Steel (October 1977), UCLA-34P177-25.

Presentations at Conferences

Ajaja, G. and Ardell, A.J., "Influence of Prior Cold Work on the Creep Behavior of Austenitic Stainless Steels," presented at the 105th AIME Annual Meeting, Las Vegas, Nevada, February 1976.

Ajaja, G. and Ardell, A.J., "The Effect of Prior Cold Work on the Creep Characteristics of AISI Type 304 Stainless Steel," presented at the Fourth International Conference on the Strength of Metals and Alloys, Nancy, France, September 1976.

Ajaja, G. and Ardell, A.J., "Microstructural Characteristics Associated with Transient Creep in Annealed and Prestrained Type 304 Stainless Steel"; "Microstructural Parameters and Steady-State Creep"; "A Unified Creep Model for Transient and Steady-State Creep," all presented at the 107th AIME Annual Meeting, Denver, Colorado, March 1978.

III. Contributions to "Mechanical Properties Test Data for Structural Materials Quarterly Progress Reports"

1. ORNL - 4963, June 1974, pp. 261-283 (for period ending April 30, 1974).
2. ORNL - 4998, September 1974, pp. 329-409 (for period ending July 31, 1974).
3. ORNL - 5103, December 1974, pp. 343-373, (for period ending October 31, 1974).
4. ORNL - 5105, June 1975, pp. 341-369 (for ending April 30, 1975).
5. ORNL - 5106, September 1975, pp. 287-307 (for period ending July 31, 1975).
6. ORNL - 5107, December 1975, pp. 285-295 (for period ending October 31, 1975).
7. ORNL - 5112, March 1976, pp. 246-275 (for period ending January 31, 1976).
8. ORNL - 5200, September 1976, pp. 381-417 (for period ending July 31, 1976).
9. ORNL - 5237, December 1976, pp. 331-353 (for period ending October 31, 1976).
10. ORNL - 5255, March 1977, pp. 357-367 (for period ending January 31, 1977).