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Stochastic aspects of evolution of creep damage in austenitic stainless steel

N. Roy [a,*], S.C. Bose [b], R.N. Ghosh [c]

[a] Mathematical Modeling and Simulation Division, Burmamines, National Metallurgical Laboratory, Jamshedpur 831007, India
[b] Material Science and Technology Division, Burmamines, National Metallurgical Laboratory, Jamshedpur 831007, India
[c] Metallurgical & Materials Engineering Department, Indian Institute of Technology, Kharagpur 721302, WB, India

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ABSTRACT

A stochastic model for the creep damage evolution and associated scatter in austenitic stainless steel has been developed in terms of a discontinuous Markov process. The magnitude of damage has been described in the form of a probability distribution function whose evolution in time characterizes the nondeterministic nature of the damage accumulation process. The long-term creep behavior on samples obtained from different locations of a thick walled SS304 LN steel pipe are studied under an identical stress and temperature condition so as to observe the scatter in creep deformation and failure data. Also the occurrences of damage and its accumulation due to creep deformation were evaluated through microstructural assessment using light optical microscope and scanning electron microscope. The validity of the model has been established by repeat data of SS304 LN steel and 316 stainless steel [1].

1. Introduction

Creep tests conducted on engineering materials at a given stress and temperature exhibit considerable scatter in creep strain time data. This is often attributed to material variability. It is well known that modest variations in chemical composition, thermo-mechanical processing and heat treatment can lead to substantial variations in mechanical properties [1]. This variation or scatter is primarily responsible for the gap that exists between theoretical predictions of existing continuum damage model and experimental observations.

The homogeneity of microstructure is a prerequisite for homogeneous deformation. Heterogeneities can be present in the material from fabricated state. Alternatively the same heterogeneities can also develop during straining in particular at higher temperatures, as a consequence of microstructural instabilities. The mechanical properties of a component at different locations in a wrought product even from single heat posses some variation because of the presence of localized heterogeneities like segregation of micro-constituents and localized strains in extensively deformed metals and alloys as a result of thermo-mechanical processing or improper heat treatment. The inherent textures (micro-shear/slip bands) present, induces strain localization leading to rapid deterioration of localized microstructure and therefore imparts damage accumulation at a faster rate.

The scatter observed in creep deformation and time to failure is of considerable technological importance because it makes the task of making accurate lifetime predictions of high temperature components quite challenging. The deterministic approach provides a basis for the evolution of damage which is a measure of the loss of load bearing capacity of the material. It is assumed to have an initial value of 0 and reaches a limiting value of 1 when failure occurs. The effects of test variables are incorporated in the material parameters. To account for scatter these are assumed to be random variables. Several studies employing the concept of probability have been developed to predict and characterize the variation in the evolution of creep damage. Most of these are extensions of the existing deterministic models [2–6] with the assumption that the parameters are random variables. These are estimated from test data using statistical parameter estimation procedures.

The Weibull distribution function [7,8] frequently provides a reasonable fit to the probability distributions of life times (time to rupture) obtained from such tests. This explains to some extent the variability in life time. However the probability distribution of damage as it evolves during the test cannot be reasonably represented by Weibull distribution in many cases. This is because it looks only at two limiting states, viz., the initial state when material is virgin and the final state when the material has failed (ruptured). This imposes severe limitations as it cannot predict any intermediate states of damage accumulation. Kozin and Bogdanoff [12] and Ganeson [10] have developed an evolutionary probabilistic model for fatigue life time prediction. This gives the evolution of the probability distribution as a function of number of cycles or time.

* Corresponding author. Tel.: +91 0657 2345091; fax: +91 0657 2345213.
E-mail address: nry@nmlindia.org (N. Roy).

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Table 1
The chemical composition of SS304 LN material.

Design	Elements in weight (%)										
	C	Mn	Si	S	P	N	Fe	Ni	Cr	Cu	Mo
304 LN	0.03	1.78	0.65	0.02	0.034	0.08	Bal	8.17	18.73	0.29	0.26

Table 2
General room and high temperature mechanical properties of SS304 LN thick walled steel pipes.

Material	Test temperature (°C)	0.2% P.S. (MPa)	UTS (MPa)	El (%)	RA (%)	Hardness (Hv30) VPN
304	25	353	671	70	88	220
LN	600	138	385	36	52	–

Austenitic steel is a commonly used material for super-heater and re-heaters of steam generators for power plants when steam temperature is in the range 565–650 °C. Therefore its creep behavior in this temperature range is of considerable interest. Creep data on such steels reported in the literature [1] does exhibit significant scatter. Nucleation of cavities at grain boundaries and precipitate matrix interface and their subsequent growth and coalescence are thought to be the mechanisms for its creep rupture. A suitable methodology of characterizing the creep damage evolution has not so far been developed. The objective of the present work is to study the stochastic aspects of creep damage evolution and its effect on rupture life in austenitic stainless steel.

2. Materials and experimental procedures

Test specimens for this study were prepared from an as received commercial thick walled pipe made of 304 LN grade stainless steel. The chemical composition in weight percentage is shown in Table 1. The material was initially provided with a solution annealing heat treatment at 980 °C for 8 h and cooled in furnace. Room and high temperature (600 °C) tensile tests on as received bulk material were conducted and the results are shown in Table 2.

Creep rupture tests were conducted following isothermal methodology. Tests were carried out in a single point, high precision creep testing machines of 3 ton capacity. Specimens were fabricated from the longitudinal direction of a thick walled pipe. They were of cylindrical type with 8 mm gauge diameter and 50 mm gauge length. Temperature was measured by three numbers of R-type thermocouples fitted along the gauge length and the temperature was controlled within ±2 °C through out the test. Strain was monitored with the help of 2.5 mm stroke LVDTS fixed with an extensometer and output was logged periodically in a data logger.

Creep tests were carried out at a single temperature level i.e. 600 °C and at a flow stress level of 220 MPa. The flow stress was calculated by taking the mean value of yield and ultimate tensile strength from tensile test conducted at 600 °C. A set of four specimens was tested under this identical condition to examine the statistical creep behavior. These four specimens are coded as #1, #2, #3 and #4, which will be followed here after in the text. All creep rupture test results are shown in Table 3. Here it can be noted that specimens #1 and # 2 were allowed to fracture whereas, #3 and #4 were interrupted at different time fractions.

Table 4
Density measurement.

Specimen no.	Condition	Density (mg/mm^3)
Original	Solution annealed at 980 °C and FC	7.96508
1	Creep fracture at 220 MPa/600 °C/7153 h	7.743
2	Creep fracture at 220 MPa/600 °C/5615 h	7.725
3	Creep-interrupted at 220 MPa/600 °C/5633 h	7.8513
4	Creep fracture at 220 MPa/600 °C/3563 h	7.805

The occurrences of damage and its accumulation due to creep deformation were evaluated through microstructural assessment using light optical microscope (LOM) and scanning electron microscope (SEM). For crept specimen the plane of observation was at the mid-section of the specimen diameter and parallel to the loading axis. To reveal microstructural features sample surfaces were mechanically ground and polished and were etched in Aqua regia (1% HNO_3 + 3% HCl) solution. As received microstructural features of SS304 LN steel (#1 and #2) are shown in Figs. 1 and 2. Fracture topography of creep fractured specimens was made in SEM and creep cavitational damage of respective creep fractured specimen is shown in Figs. 3 and 4.

In order to assess the creep damage accumulation due to formation of creep cavities, density measurement technique was used on as received and various creep tested specimens. As for crept specimens, the gauge portion of cylindrical test pieces was included. The density measurement was carried out in high precision equipment (METTLER TOLEDO, Sweden) specially designed for this type of estimation. The average values of densities in each case are shown in Table 4.

Interrupted creep tested specimens viz. #3 and #4 were also found to contain creep cavities at austenite grain boundaries (GB). The population of these cavities was quantified by percentage area fraction measurement with the help of LOM using in built Olympus-Gx51 image analysis software. The cavity distribution at over ten locations was measured and an average value is reported in the present work. Area fraction of creep cavities in interrupted samples, #3 and #4 are found to be 0.382% and 0.674% respectively.

3. Creep as a discrete Markov process

Cavitation is one of the most common forms of creep damage. This has been correlated with creep stain accumulation by

Table 3
Creep rupture properties of SS304 LN material.

Specimen no.	Stress (MPA)	Temperature (°C)	Life (h)	Min. creep rate (h^{-1})	El (%)	RA (%)	Hardness Hv30 (VPN)
1	220	600	7153	7.70×10^{-6}	20	22	220
2	220	600	5615	8.71×10^{-6}	26	24.5	214
3	220	600	5633*	5.61×10^{-6}	7.6*	7.3*	224
4	220	600	3563*	8.22×10^{-6}	7.5*	8.82*	213

* indicates interrupted specimen.