CREEP STRENGTH EVALUATION FOR IN 738 BASED ON STRESS RELAXATION

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Abstract

A new conceptual framework involving an integrated approach to materials development, component design and life prediction for high temperature applications is outlined. Termed "Design for Performance" this provides an alternative to the traditional approach which requires the creep to rupture testing of many specimens over long times. The concept is presented in terms of the development and design needs of nickel-based superalloys for gas turbine blades. Specifically, data generated on the cast alloy IN738 are used to illustrate the approach. The tests described are a refined stress relaxation test from which extensive stress vs. strain-rate data may be generated over a range of temperatures, and a constant displacement rate crack growth test. These tests provide a separation of the creep strength and fracture resistance criteria required in design. It is also shown that calibration with traditional design methods is possible. The new approach is cheaper, faster and, we believe, more rigorous from a technological perspective.

Superalloys 1992
Edited by S.D. Antolovich, R.W. Stusrud, R.A. MacKay,
D.L. Anton, T. Khan, R.D. Kissinger, D.L. Klarstrom
The Minerals, Metals & Materials Society, 1992

Introduction

The industrial gas turbine has advanced considerably in performance and efficiency in the past several decades due in part to advances in alloy composition and processing. However, much of the creep data used to develop design criteria, even for established alloys, is not available in the open literature and, therefore, may not be accessible to the gas turbine user. This makes it very difficult for the user to participate in important decisions regarding remaining life of critical components as they affect repair or replacement. Moreover, the development of new alloys and processes is paced by the necessity at present to generate long time creep and stress rupture data. There are, therefore, strong motivations to seek accelerated test methods as a basis for decision support in remaining life assessment, and also for materials selection and development.

The traditional approach to materials development, design, and life assessment for high temperature components requires extrapolation of experimental measurements of creep strain and fracture lives to times of 50,000 to 100,000 hours for many applications. Design protocol then calls for a safety factor which typically sets the allowable maximum stress at two-thirds of the mean extrapolated value. Thus, the method employs laboratory tests involving extensive creep deformation, under a prescribed deformation path, to identify a stress which is probably below the level at which measurable creep strain occurs. For estimating remaining part life the method of measuring time to fracture of specimens taken from the part, and using an extrapolation procedure similar to that used in the initial design, is even more questionable. Since the material from a broken part has a finite life in a subsequent laboratory test, sometimes close to that of a new part, it is unreasonable to expect to be able quantitatively to predict the remaining life of an unbroken part. This complexity has been called "the Remaining Life Paradox" [1].

Recently, a new framework based on setting separate minimum performance criteria for creep strength, fracture resistance, and other critical properties was proposed. Termed "Design for Performance", [2,3] this approach could, in principle, be applied both to initial design analysis and also to remaining life assessment. Figure 1 summarizes the concept in terms of three limiting performance criteria.

The creep strength criterion may be developed from a series of carefully conducted stress relaxation tests. The stress vs. time response is converted to a stress vs. creep strain-rate response. This is, in effect, a self-programmed variable stress creep test. Typically, a test lasting less than one day may cover five decades in creep rate. The accumulated inelastic strain is usually less than 0.1% so that several relaxation runs at different temperatures and from different stresses can be made on a single specimen. Thus, an enormous amount of creep data can be generated in a short time.

This paper describes the stress relaxation test (SRT) as a basis for creep strength evaluation and also proposes a constant displacement rate (CDR) test (4) as a separate basis to evaluate the fracture resistance. Minimum performance criteria based on these tests are applicable when the part is new and also in a serviced part, and thus can be used in an integrated framework for development, design and life prediction.

Experimental Procedure

Stress Relaxation Testing

Specimens were machined from cast slabs of fully heat treated IN738 (1120°C for 2 hr. plus 840°C for 24 hr.). Tests were performed on an Instron

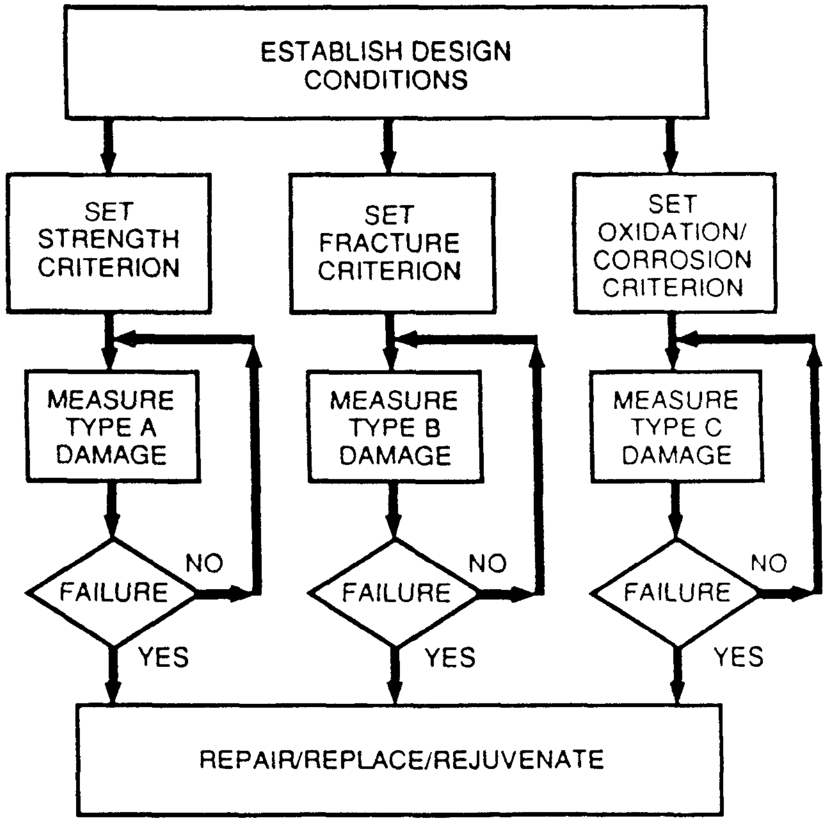

Figure 1. Schematic of the Design for Performance Concept

electromechanical series 8562 test system fitted with self-aligning grips, a 1500C short furnace, and capacitive extensometry. Specimens, designed for use with the grips, were 165mm long and featured a reduced section of 40mm and diameter of 6mm. Temperature calibration along a 25.4mm gage was maintained and controlled to 1C at temperatures to 1000C. The extensometer was sensitive to 10^{-6} strain and, at temperature in the strain control mode, was capable of holding at a total strain to $\pm 5\times10^{-6}$.

Standard procedure involved loading at a fast rate of 10MPa/sec to a prescribed stress and switching to strain control on the specimen and monitoring the relaxation of stress. The inelastic (principally creep) strain-rate is calculated from the following equations:

$$\epsilon_e + \epsilon_I = \epsilon_t = \text{constant}$$

$$\dot{\epsilon}_I = -\dot{\epsilon}_e = -\frac{1}{E}\ \frac{d\sigma}{dt}$$

Where ϵ_e is the elastic strain, ϵ_I is the inelastic strain (principally creep strain), ϵ_t is the total strain, σ is the stress, and E is the elastic modulus measured during loading. Using this procedure stress vs. strain-rate curves were generated covering up to five orders of magnitude in strain-rate in a test lasting less than five hours.

It was found that to avoid transient effects associated with anelastic phenomena it was necessary to exceed a critical stress on loading, roughly corresponding to the proportional limit. This was also reported in previous studies developing this technique for aluminum (5). When this was recognized, self-consistent results were obtained and preliminary experiments involving various high temperature exposures could be evaluated.

In the test series reported, the degree to which microstructural changes might affect the creep strength was examined by preexposing specimens at very high temperature. The treatments included were: as-heat treated, 1050C in air for 50 hr., 1050C in vacuum for 240 hr., and 1050C in vacuum for ten 24 hr. cycles.

Constant Displacement Rate Tests

For the CDR test the standard specimen was used with a shallow notch of radius 6mm machined in the reduced section. This was to ensure that failure occurred at a location between the extensometer arms, but also to allow the crack to initiate naturally rather than force it to start at the root of a sharp notch. The test was run under closed loop displacement control on the extensometer. Once cracking initiated the increased compliance of the specimen caused the machine actuator to slow down in accordance with the control mode. The crack could then propagate under control, and a measure of fracture resistance could be established. The preliminary tests have been run at 700C, a temperature likely to be most sensitive to embrittling phenomena. (6)

Results

Figure 2 is a sequence of five relaxation runs on a single specimen at three temperatures. All runs were planned to start at stresses close to the proportional limit and a set of nearly unique responses was obtained. Thus exposure to temperatures to 1000C had little effect on the response at 800C. The data range was established in about five hours. For reference, 10^{-9} sec^{-1} corresponds to a creep rate of 3% per year.

As an indication of the permanent strains involved, Table 1 gives specific data from these tests. Permanent strain on loading was less than 10^{-4} for all runs. The accumulated strain during relaxation calculated from $\Delta\sigma/E$ was between $5x10^{-4}$ and $1.5x10^{-3}$. This compares well with the values measured on the extensometer after unloading. It is also clear from the table that a small amount of anelastic strain recovery occurs on holding the specimen for 1 hour at temperature after unloading. This was small relative to the total strain, provided the initial stress exceeded the flow stress, as was true in all of these runs. When the proper loading conditions were used, the complexities associated with anelastic phenomena had an insignificant effect on the calculated creep strain rate.

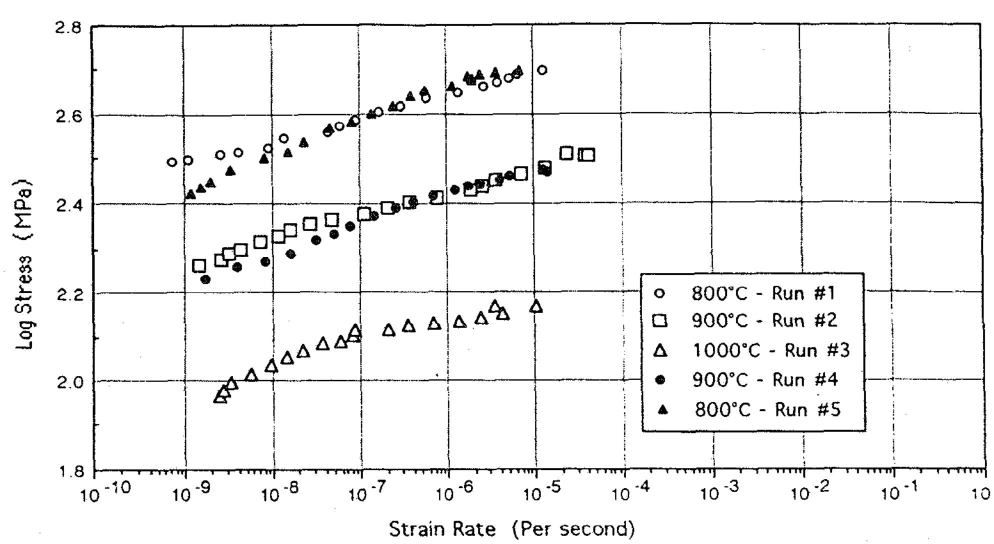

Figure 2. Stress vs. Strain-Rate at Three Temperatures Including Repeat Runs

Table I Summary of Strain Data

	Test Temp. C°	Max Stress MPa	Modulus GPa	Calculated Creep Strain $\frac{\Delta\sigma}{E} \times 10^3$	Measured Strain (Immediate) $\times 10^3$	Measured Strain (After 1 hr.) $\times 10^3$
Run 1	800	500	156	N/A	N/A	N/A
Run 2	900	325	123	1.16	1.3	1.13
Run 3	1000	150	115	0.50	0.55	0.48
Run 4	900	300	139	1.07	1.09	0.98
Run 5	800	500	150	1.57	1.40	1.20

On the basis of these data and several other specimen runs, it was decided to use 850C as an appropriate comparative temperature for the different exposures. Figure 3 shows a relaxation run sequence to demonstrate transient effects at this temperature. The low stress curves are dominated at high strain-rates by anelastic effects but clearly merge at the lowest rates to define unique behavior. All test runs completed at 850C in which the stress was sufficiently high to minimize transient anelastic effects are plotted on an expanded ordinate scale in Figure 4. It is apparent that these severe thermal exposures have had a minimal effect on the creep strength at this temperature.

It is well known that exposure in air at high temperatures can lead to grain boundary oxygen embrittlement (6,7). Indeed, one of the relaxation specimens fractured during loading following a previous test run at 1000C. This is a further indication of the need to monitor separately the fracture resistance. The results of two tests shown in Figure 5 confirm this embrittlement. The heat treated specimen cracked first at the maximum stress and the crack propagated in a controlled manner under the displacement rate control. When unloaded from 100MPa there was about 10% of unbroken intergranular ligament remaining. By contrast, the embrittled specimen first cracked at stresses of 100-200MPa and loaded to maximum stress with a reduced slope reflecting the reduced cross section. At about 50% of the cross section the crack became critical for the reduced fracture toughness in the embrittled condition. The CDR test provides a separate and effective measure of fracture resistance.

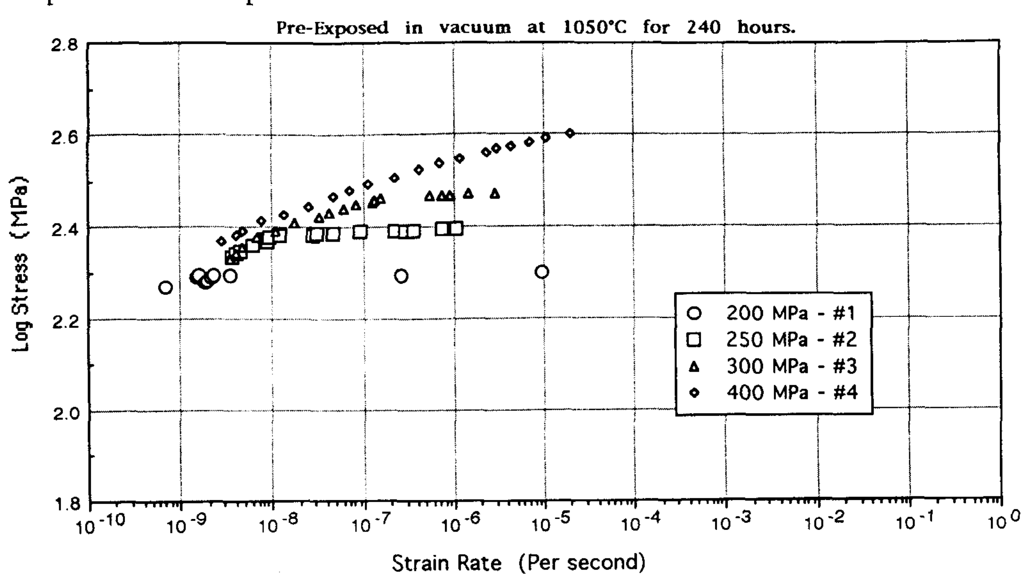

Figure 3. Multiple Relaxation Runs at 850°C Showing Transient Effects for Low Stresses.

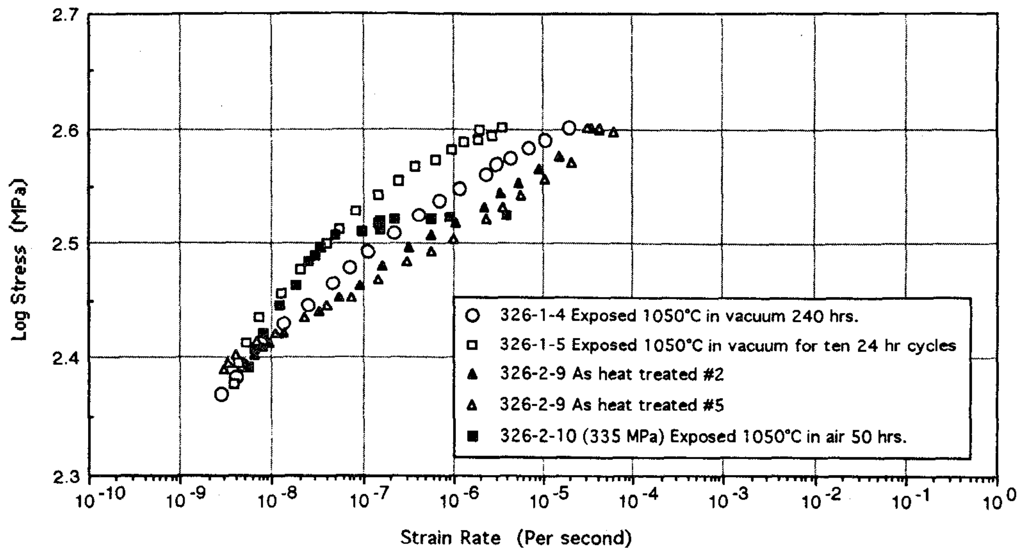

Fig. 4. All Data at 850°C for Various Initial Thermal Treatments.

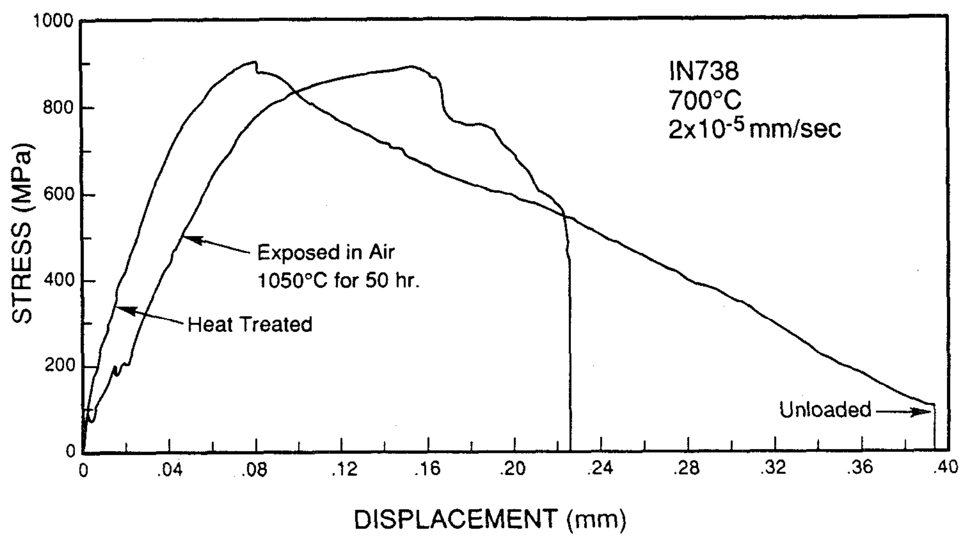

Fig. 5. Constant Displacement Rate Tests Comparing Crack Growth Resistance in Heat Treated and Oxygen Embrittled Specimens.

Discussion

Although the premise is that with a combination of sophisticated test measurements, and recognition of the need to set discreet performance limits on critical properties, there may be no need to run long term creep tests, it is understood that some calibration with current methods is desirable. Although the creep to rupture test does not clearly separate creep strength and fracture resistance, we can consider the rupture life as principally a measure of creep strength, and use it as a basis for comparison with the relaxation data. Figure 6 is a comparison of the 100,000 hour extrapolated stress rupture life for IN738 at various temperatures [8] plotted against the stress for an arbitrary creep rate of 10^{-7} sec^{-1} taken from a single specimen. Using this calibration, a relaxation run at any temperature could be used to estimate the rupture stress at that temperature. Whether this curve is unique for a given class of alloy remains to be determined.

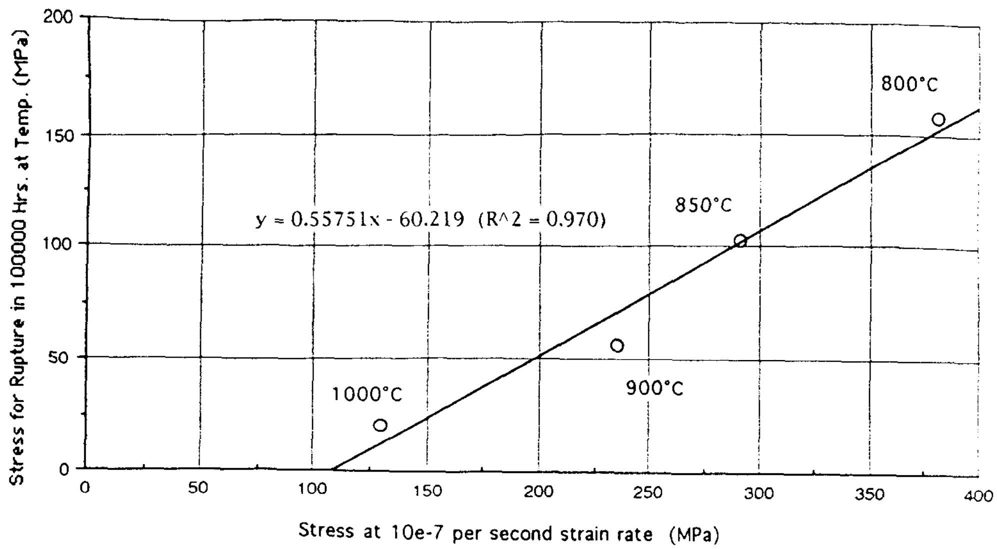

Figure 6. Correlation Between Stress for Rupture in 100,000 hr. and Stress at a Specific Strain Rate from Relaxation Data on a Single Specimen.

One major objection to this framework has been that effects of very long time exposures which could influence stress rupture life will not be accounted for. However, such effects, i.e. precipitation of embrittling phases and grain boundary segregation of harmful elements are expected to influence the fracture resistance rather than the creep strength. Design for Performance, by separating these critical criteria should provide a superior framework to deal with these complexities. Of course, considerable experimentation will initially be needed to induce and evaluate these damaging phenomena in terms of the SRT and CDR tests.

There are three primary needs in the competitive market for manufactured equipment operating at high temperatures:
- The development cycle for new designs must be reduced.
- The designs must be optimized for efficiency and performance.
- Procedures must be developed to allow timely repair or replacement.

The proposed framework and test plan could now by applied to these needs for gas turbines by studying effects of alloy composition, processing, heat treatment, and prior exposures.

Conclusions

1. It is not axiomatic that machines destined for long term service must be designed based on long term testing.
2. A new framework "Design for Performance" is based on measurements of the current state in terms of critical performance criteria and requires short term tests.
3. Two mechanical tests: a well-controlled stress relaxation test (SRT) and a constant displacement rate test (CDR) are suitable to determine the creep strength and fracture resistance respectively.
4. For IN738 a calibration is demonstrated with traditional long term creep rupture tests.
5. There is no a priori reason why time-dependent damaging processes cannot be included in the framework.

References

1). D.A. Woodford, International Conference on Fossil Power Plant Rehabilitation, ASM International, 1989, p. 149.

2). D.A. Woodford, Journal of Materials, 1990, Dec., p. 18.

3). D.A. Woodford, Creep: Characterization, Damage and Life Assessment, ASM International, 1992, p. 23.

4). J.J. Pepe and D.C. Gonyea, International Conference on Fossil Power Plant Rehabilitation, ASM International, 1989, p. 39.

5). E.W. Hart and H.D. Solomon, Acta Met., vol. 21, 1973, p. 295.

6). W.H. Chang, Proceedings Second International Conference on Superalloys, AIME, 1972.

7). D.A. Woodford and R.H. Bricknell, Embrittlement of Engineering Alloys, Academic Press, 1983, p. 157.

8). V.P. Swaminathan, T.R. Sharron and J.M. Allen, Life Assessment and Repair Technology for Combustion Hot Section Components, ASM International, 1990, p. 129.