CREEP STRENGTH AND FRACTURE RESISTANCE OF DIRECTIONALLY SOLIDIFIED GTD111

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Abstract

This work describes the application of a new approach (Design for Performance) to high temperature alloy development, design analysis, and remaining life assessment, based on short time high precision testing. The material tested was a directionally solidified nickel based alloy, GTD111, tested in the longitudinal, transverse and diagonal orientations relative to the growth direction. It was found that the creep strength comparison at 900C was dependent on stress and loading procedure, and was not necessarily enhanced by the preferred alignment of grain boundaries and crystal orientation. By contrast, the fracture resistance at 800C was improved in the longitudinal direction compared with transverse and diagonal orientations in terms of susceptibility to gas phase embrittlement (GPE) by oxygen. The new conceptual framework allows account to be taken of GPE, and other embrittling phenomena, which may develop in service, leading to rational life management decisions for gas turbine users. Additionally, straightforward design analysis procedures may be developed from the test data, which allow separate measurements of creep strength and fracture resistance to be used for performance evaluation.

Introduction

High temperature design of components in energy conversion systems is dependent to a large extent on data generated from creep to rupture testing. The same test is used as a basis for creep strength evaluation (i.e. the resistance to time-dependent deformation) and component life assessment (i.e the resistance to fracture). This leads to a number of conceptual problems. For example, the minimum creep rate and the time to rupture usually show a reciprocal dependence suggesting that they are separate measures of the same property. However, the latter is used as a measure of specimen, and hence component, life. Thus, fracture and life prediction are measured in terms of lapsed time from some arbitrary origin. This leads to fundamental ambiguity when assessing the remaining life after some prior creep exposure (1). And, in the limit, a specimen taken from a failed component invariably will have a finite creep rupture life.

It has been argued that long time creep to rupture tests are necessary to simulate the evolution of microstructure and damage during service. However, to simulate such evolution it must be recognized that there is a hierarchy of increasing test complexity and expense. For most applications there are effects of periodic unloading and temperature changes, multiaxial stresses, superimposed cyclic stresses, environmental attack, and synergism among them all. Clearly, the duration of a creep test is itself of little consequence relative to long term performance in most applications. Taking just one example, a typical jet engine operates with all these factors in complex thermal mechanical cycles of between one and ten hours; a 10,000 hour creep test at a fixed stress and temperature may not be a useful investment in time and money for this application.

Thus, there are flaws in the testing details, in the interpretation of results, and in the conceptual justification of long time testing. What is needed is a testing methodology that not only provides a procedural acceleration, is cheaper and more efficient, but also one that circumvents these flaws. Such a methodology has been termed ***Design for Performance*** (2). This approach decouples the creep strength and fracture resistance. The former is evaluated based on a high precision short time stress relaxation test (SRT), and the latter is determined from a constant displacement rate tensile test (CDR) run at a temperature where the material in service is most vulnerable to fracture.

Rather than attempt to incorporate microstructural evolution and damage development in the test methodology, the new approach measures the consequences of such changes in short time tests. The material in a component is treated as if it has a definable creep strength and fracture resistance at any stage in its service. The creep strength is defined in terms of a stress vs. strain rate relationship, although the analysis may be presented in terms of a predicted stress vs. time curve, as shown in the present paper, for comparison with traditional representations. The fracture resistance is defined in terms of tensile displacement at failure in a smooth or notched specimen at a temperature where the material is most sensitive to embrittlement due to environmental attack or microstructural changes. In practice, this temperature usually corresponds to a ductility minimum, and often to a temperature where maximum strains are developed in components during thermal fatigue(3).

The separation of creep strength and fracture resistance is particularly important in directionally solidified alloys because creep strength (expressed in terms of creep rates or time to specific strains) may be much less sensitive to orientation than fracture resistance (expressed as tensile ductility or crack propagation resistance) (4). The present study reports results on the GE alloy DSGTD111 (a modification of the aircraft engine blade alloy, Rene'80) for various specimen orientations

Experimental

Material and Specimen

Superalloys 1996
Edited by R. D. Kissinger, D. J. Deye, D. L. Anton,
A. D. Cetel, M. V. Nathal, T. M. Pollock, and D. A. Woodford
The Minerals, Metals & Materials Society, 1996

Miniature specimens used in this study were designed to be machined from thin sections of gas turbine blades, and were 41mm long with a reduced section of 32mm by 1.9mm. Six specimens were cut from a new blade shank at each of three orientations: parallel, perpendicular, and at 45° to the growth direction. For the constant displacement rate tests (CDR) the same small specimens were used.

Stress Relaxation Testing (SRT)

The tests reported in the present paper, at a temperature of 900C, were loaded at a strain rate of .01%/sec. to a set strain which was then held constant. With the capacitive extensometer this was maintained to $\pm 5 \times 10^{-6}$ for the test duration which was usually one day.

The stress vs. time response was converted to a stress vs. creep strain-rate response by differentiating and dividing by the modulus measured on loading(2). The accumulated inelastic strain during relaxation was usually less than 0.1%, so that several relaxation runs at different temperatures and from different stresses could be made on a single specimen with minimal change in the mechanical state. Thus, an enormous amount of creep data was generated in a short time. By appropriate cross-plotting, pseudo stress-strain plots were constructed which may then be used to generate strain vs. time or stress vs. time curves.

Constant Displacement Rate Testing (CDR)

This test involved tensile testing to fracture at 800C under closed loop strain control on the specimen. The temperature was chosen to be in the range of greatest susceptibility to gas phase embrittlement (GPE) (4), and the displacement rate was 1%/hour. For the three orientations the susceptibility to GPE by oxygen was evaluated in terms of high temperature prior exposures in air.

Results

Figure 1 shows relaxation results on a transverse specimen of GTD111 at 900C from four total strain levels. The corresponding stress vs. inelastic strain (creep) rate curves are shown in figure 2. This plot may then be used to construct pseudo stress vs. strain curves from vertical intercepts at various strain rates (see figure 3). In practice, the construction is made by fitting polynomial expressions to the stress vs. strain rate curves,

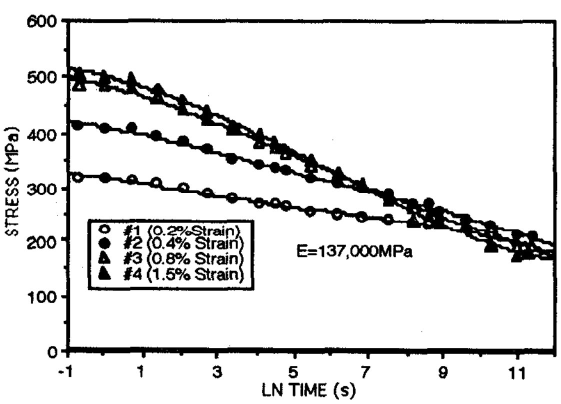

Figure 1 Stress relaxation at 900C from four strain levels for transverse specimen

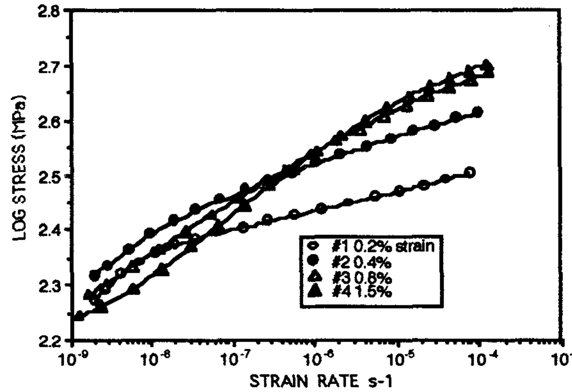

Figure 2 Stress vs. creep rate curves at 900C for transverse specimen

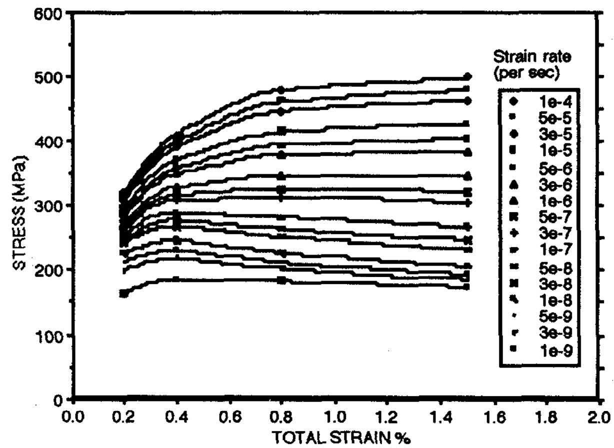

Figure 3 Pseudo stress vs. strain curves as a function of creep strain rate for transverse specimen

and solving at specific strain rates. These curves are similar to isochronous creep curves crossplotted from conventional creep curves and often used in high temperature design. The isostrain rate curves may be used in a slightly different way where the time is estimated by dividing the inelastic strain (total strain less elastic strain) by the inelastic strain rate. This then gives a stress, strain and time representation.

The same testing procedure and analysis for the longitudinal orientation are shown in figures 4-6. In this case the measured modulus was 87,200 MPa compared with 137,000 for the transverse orientation

One approach to analysis for comparison with conventional approaches is to use the actual stress vs. creep rate curve which is closely representative of 0.5% inelastic strain. The test run from 0.8% total strain was chosen as an appropriate standard in terms of the total inelastic strain during loading and relaxation. Also, it should be noted that the pseudo stress vs. strain curves are quite flat at this strain so the actual prestrain level is not especially critical. Once the appropriate curve is chosen, the time is calculated directly from this inelastic strain (0.5%) divided by the creep rate as a function of stress. Of course, other strains could be taken from the pseudo stress vs. strain curves and the stress and strain rate picked from those.

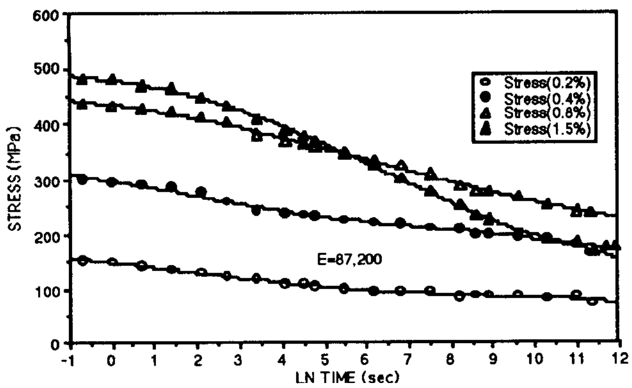

Figure 4 Stress relaxation at 900C from four strain levels for longitudinal specimen

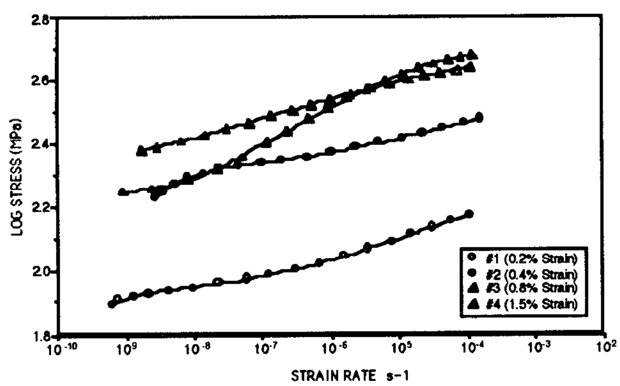

Figure 5 Stress vs. creep rate curves at 900C for longitudinal specimen

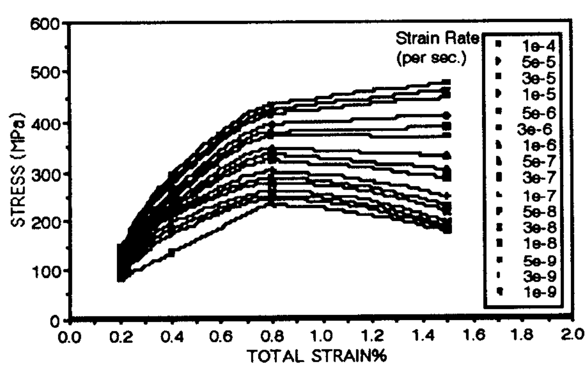

Figure 6 Pseudo stress vs. strain curves as a function of creep strain rate for longitudinal specimen

The data may also be presented in the form of strain vs. time curves using horizontal cuts at fixed stresses. However, using an actual test run allows a small computer program to generate the stress vs. predicted time curve for 0.5% creep from a polynomial curve fit to the actual stress vs. creep rate curve. Of special interest is the ability to extend the curve to several thousand hours from a single run of 20 hours (see figure 7). This stems from the calculation of the longest time for 0.5% creep being based on the lowest creep rate in the relaxation test. For example, a creep rate of 10^{-9}/sec. gives a predicted time of 1,390 hours. This might be thought of as a pseudo time rather than an extrapolated time, since actual creep rate data are used.

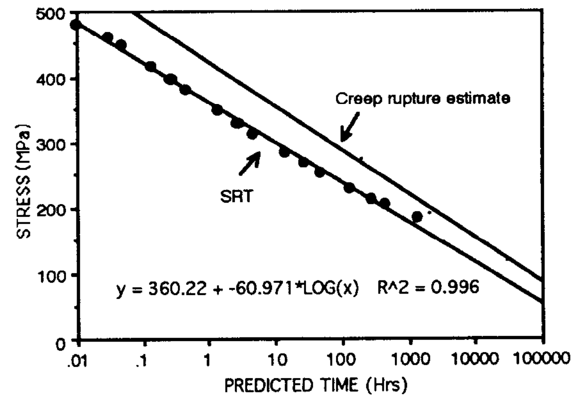

Figure 7 Comparison between creep rupture estimate at 900C and stress vs. predicted time to 0.5% creep from SRT for transverse specimen

Unfortunately there are no published long time creep data on this alloy. However, an estimate is made of the rupture behavior derived from a published Larson-Miller parameter plot of the conventionally cast alloy (6). While recognizing that different specimen sizes were involved, the comparison is good. It shows that the SRT data may be used as a basis for setting design stresses, either directly or with appropriate scaling.

Whether there is good quantitative agreement between the two approaches is dependent on the sensitivity to thermal mechanical history. The high strength cast superalloys are quite insensitive to prior thermal-mechanical history in terms of creep strength(2) and hence agreement is expected to be good.

What is important to recognize is that if these predictions are close to long term data, then they may be used in current design protocol either directly or with an appropriate scaling factor. If that is the case, then it is appropriate to recognize that figure 7 was derived directly from the stress vs. strain rate curves and that the latter should be amenable to direct use. The equivalent creep rate for 0.5% creep strain in 100,000 hours is 1.4×10^{-11}/sec. Thus, a design stress could be taken either from figure 7 in terms of time or directly from figures 2 and 5 in terms of creep rate; 10^6 hours is directly equivalent to 1.4×10^{-11}/sec. As an example, figure 8 compares creep rates for the transverse and longitudinal orientation. The particular representation shown in figure 8 is semi-logarithmic or exponential. It may be that a power function is more appropriate for some alloys. The fit is about as good for the data shown as the exponential fit and yields stress exponents of 17.62 and 11.88 for the longitudinal and transverse orientation specimens, respectively. These are appropriate exponents to be used, for example, in crack tip creep deformation analysis, rather than exponents calculated from minimum creep rate data.

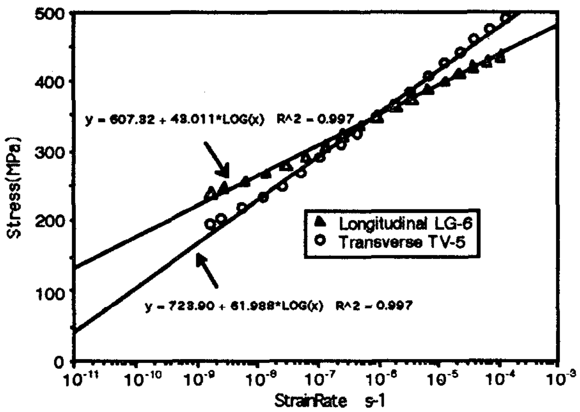

Figure 8 Stress vs. creep rate curves for 0.5% creep strain at 900C for two orientations

Figure 9 shows CDR results at 800C on the three GTD111 orientations compared with data on a widely used cast superalloy, IN738, taken from a test slab casting using the same miniature specimens. All show reasonable ductility at this intermediate test temperature. Although the yielding stresses are higher for GTD111 for all orientations, the pronounced fall in flow stress at higher strains for the transverse and diagonal orientation, below corresponding values for IN738, is interesting but, as yet, unexplained.

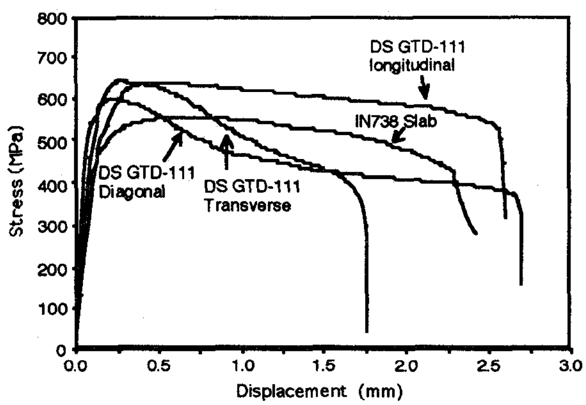

Figure 9 CDR results at 800C and 1%/h. for the three orientations

To compare the effect of orientation on embrittlement by oxygen (GPE), specimens were exposed at 1000C for 24 hours in air. In the longitudinal orientation, with very few grain boundaries intersecting the surface, the ductility was reduced by about 30% (see figure 10). However, the other specimens failed with little or no plasticity. Figure 11 shows that, for the diagonal orientation, even 5 hours exposure at this temperature leads to an appreciable loss in fracture resistance. This figure also shows that a specimen which had previously been exposed at 850C for about a week of SRT testing was unembrittled.

Discussion

It has become increasingly clear that the traditional approach to materials development and design, involving long time creep testing, is not able to explain instances of part failure, especially for nickel based superalloys operating under non-steady conditions in aggressive environments. The new approach proposed here offers several innovations in concept: separation of creep strength and fracture criteria, short time high precision evaluation of the consequences of thermomechanical exposures, setting limiting critical property values to establish unambiguously appropriate criteria for end of part life.

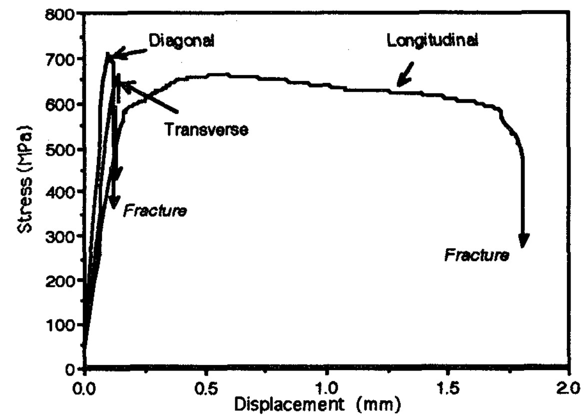

Figure 10 Effect of exposure in air at 1000C for 24h. on CDR results for the three orientations at 900C

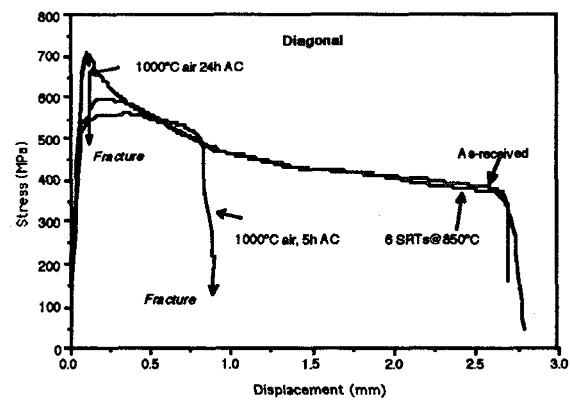

Figure 11 Effect of exposures at 1000C on CDR results for diagonal specimen

The apparent advantage in creep strength in the longitudinal direction for low strain rates (see figures 8) is, in part, a consequence of the lower modulus, e.g. for a fixed strain on loading the starting stress is less and there is less inelastic strain accumulated during relaxation for the longitudinal orientation. This advantage was not seen in unpublished work for tests started at a fixed stress. Thus, when comparing the creep strength for different orientations in anisotropic material the effect of loading procedure must be recognized. No direct comparison has so far been made with conventionally cast GTD111, although it is expected to be closely similar to the transverse and diagonal orientations.

The stress vs. strain-rate curves readily provide a basis for alloy development and optimization of creep strength. They may also be used directly to set design stresses. If a more traditional representation is desired, one approach is to cross plot the data in terms of pseudo stress vs. inelastic strain curves at fixed inelastic strain rates. Sets of such curves are shown in figures 3 and 6. Normally, the designer would see similar curves crossplotted from creep curves at constant time intercepts to give isochronous stress vs. strain curves. From curves, such as those shown in figures 3 and 6, creep curves can be constructed, if desired, by taking horizontal sections at fixed stresses. At the intersection points, for the indicated strain, the time is calculated by dividing that strain by the inelastic strain rate. A more convenient approach may be to take vertical cuts so that a plot of stress vs. time for a fixed creep strain may be plotted and extrapolated as desired. For example, figure 4 shows such a plot for the transverse orientation which is of the same form as that often used to establish design stresses based on extrapolation of long time creep tests. It should be noted that these are ways to manipulate the relaxation data for presentation: there is no intrinsic advantage in using any of these representations.

For cast superalloys little effect of prior exposure, including 1000C treatments, has been observed for creep strength(2). Even a factor of five on creep rate may not have sufficient effect on stress to cause concern because of the strong stress dependence of creep rate. However, a strong effect on fracture resistance based on the CDR test, especially from GPE, should create major concern. A suggested approach to quantifying this concern is to define a minimum acceptable CDR displacement at failure. For example, for the miniature specimens tested at 800C and 1%/hour this might be set at 0.5mm. Such a criterion would be valid for material in new components and also for material taken from components at any stage of their operating life. Additional refinements of such a failure criterion for service exposures might allow certain regions of the blade material to drop below this level, provided the bulk of the blade retained a good fracture resistance. For example, trailing edge sections of a small IN738 blade were found to be the only region embrittled after 65,000 hours service(7).

Conclusions

1. A new "Design for Performance" methodology may be cheaper, faster and fundamentally superior to traditional development and design procedures for high temperature applications which are currently based on long time testing.

2. A high precision short time stress relaxation test (SRT) is used to evaluate the creep strength in terms of stress vs. creep rate covering up to five orders of magnitude in creep rate.

3. In tests at at 900C, the longitudinal orientation has higher creep strength at low stresses and lower creep strength at high stresses.

4. A constant displacement rate test (CDR) is used to evaluate fracture resistance at the intermediate temperature of 800C.

6. Based on this new approach, there appears to be no clear advantage in directional solidification for this alloy in terms of creep strength.

7. By contrast, resistance to fracture, especially after high temperature exposure in air, is improved substantially for longitudinally oriented specimens of GTD111 compared with diagonal and transverse oriented specimens.

8. Proposed design criteria for both creep strength and fracture resistance based on the new methodology may be used directly for life management of operating components.

Acknowledgements

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