NEW INTERPRETATION OF RUPTURE STRENGTH

USING THE POTENTIAL DROP TECHNIQUE

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Summary

The effects of zirconium and carbon on the rupture behavior of an experimental blade alloy were examined and analysed by using the notched rupture test and the dc potential drop technique. Differences in the rupture behavior, not detectable by simply comparing rupture times, revealed by using the experimental technique described in this paper, provided more in depth understanding of the material's behavior and useful guidance to the alloy developer. The results of this work clearly demonstrate that minor chemistry modifications in nickel base alloys do not necessarily affect the resistance to crack initiation and crack propagation in a similar manner.

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Introduction

The performance and reliability of industrial gas turbines can be reduced by the premature degradation of critical hot gas components. The principal degradation mechanisms are creep, hot corrosion and thermal fatigue (1,2). The first two presently seem to be limiting in some of the designs, and as a result the alloy developer aims to improve creep and hot corrosion resistance.

Recent advances in understanding high temperature behavior of nickel base superalloys, indicated that improved creep performance implies resistance to high temperature deformation, crack initiation, crack propagation, and equally important resistance to environmental degradation during exposure to high temperatures (3-5). All these aspects of materials behavior should be taken into account when designing a new alloy for high temperature applications.

For this purpose, new technologies combined with conventional practices, have been developed to provide more in-depth understanding of materials behavior. One such procedure based on the dc potential drop technique and the notch stress rupture test is described in this paper. The dc potential drop technique, commonly used to measure crack length (6,7), has also been used to monitor deformation, detect crack initiation and measure crack propagation characteristics in axisymmetric notched bars (8-10).

The necessity to look at initiation and propagation separately, results from the fact that the relative importance of degradation mechanisms is not necessarily the same during the initiation and propagation stages. Chemistry modifications designed to improve rupture strength can adversely affect the material's resistance to crack initiation and propagation. The work in this paper demonstrates these concepts and offers a new way of evaluating rupture strength.

Materials

The material used in this work was an experimental high strength cast bucket type nickel base superalloy. Two modified chemistries, the first with lower zirconium than normal and the second with higher carbon concentration, were compared with the baseline chemistry. The exact chemical composition of these experimental alloys, are absolutely unimportant to the arguments presented here.

Specimen Geometry and Testing Procedures

Notched stress rupture tests were performed on a dead-load lever arm testing machine on axisymmetrically notched bars. Two types of notched geometries were used, the "U" notch geometry, shown in Figure 1, and the "V" notch, shown in Figure 2. In the "U" notch a significant volume of material is subjected to almost the same stress and state of stress (11-13) and fracture usually initiates internally, thus minimizing environmental interactions (14,15). These features in addition to the fact that deformation and fracture occur in a confined volume of material which can be easily monitored, make the "U" notch specimen the ideal tool for studying rupture behavior. On the other hand the "V" notch geometry is designed, mainly to measure the material's resistance to crack initiation. Two identical notches 1/2" apart were ground accurately into the gage length of the notched specimens in order to facilitate metallographic examination of creep damage distribution at fracture.

The tests were monitored in real time using the dc potential drop technique. A constant current of 4A was passed through the specimen and the change in potential across the two notches was measured during testing. For this purpose, two pairs of platinum wires were attached by spot welding at points where the notch intersects the straight section of the specimen. A third pair of probes, serving as the "reference probe", attached on the straight section of the specimen, 1/2" away from the notch. The reference probe is used to compensate for current and temperature fluctuations (9). Extensometry was also used for measuring the total axial displacement. A diagram with the location of the potential probes and the extensometer is shown in Figure 3.

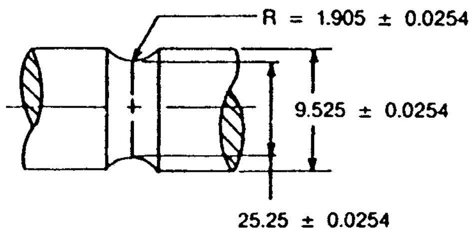

Figure 1 U notch geometry.

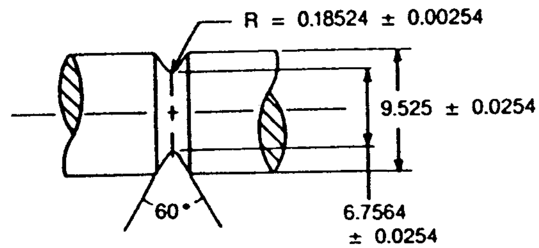

Figure 2 V notch geometry.

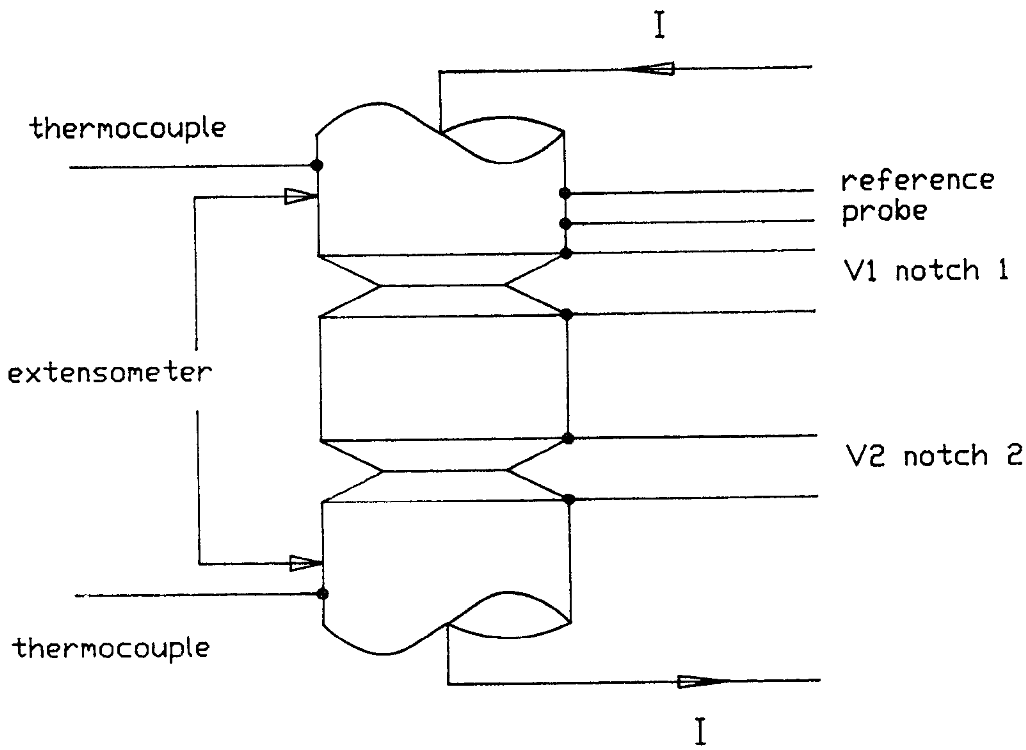

Figure 3 Schematic of notched specimen indicating the location of potential probes and extensometer.

Basics - Fundamentals

The potential change across the notch, measured during a notch rupture test is due to creep deformation and damage accumulation (i.e., cavities and cracks). Prior to the nucleation of damage the increase in potential is caused only by creep deformation. By establishing a calibration relationship between strain and potential for the specific specimen type, creep strain can be measured by using the specimen as a strain gage (5,9). With the nucleation and growth of cracks, the potential increase measured across the notch, becomes greater than the value expected from creep deformation.

Experimental support of the above arguments is given in Figure 4, where the potential across the failed notch of duplicate tests is plotted versus time. Despite comparable initial deformation rates among the two specimens, early initiation, marked with the departure of the potential curve from linearity, resulted in shorter rupture life. For the same reason, in Figure 5 the potential curve across the failed notch, in a double notched specimen, deviated first from linearity. The potential increase across the unfailed notch was from the beginning smaller, because of slower deformation and damage accumulation rates. Based on the principles described here, isopotential lines represent isodamage lines, therefore the ratio t/t^* in Figure 5 indicates the time when the damage across the failed notch was comparable to the damage across the unfailed notch at fracture. Since the material in both notches is the same, and thus behaves the same, the same ratio represents the fraction of the life of the unfailed notch that has been exhausted. Therefore, the projected rupture life of the unfailed notch, if testing were to be continued tested, would equal $(t/t^*) \times t_r$. Indeed, the potential data in Figure 5, replotted versus time normalized with the rupture life for each notch, shown in Figure 6, suggest that the behavior of the material in the two locations is the same. The difference observed in Figure 5 is just scatter which translated to some time drift. Consequently, one can quantify the extent of damage in the failed notch at a known fraction of its rupture life, by examining the damage in the unfailed notch at fracture.

Finally, with the potential drop technique it was easy to verify that crack initiation in the U notched specimen occurred late in life, as indicated in Figure 7. The tertiary stage of the displacement curve, shown in the same figure, was triggered by the fast crack growth in the failed notch. On the other hand, initiation takes place earlier in the V notched specimen, in which measurements of displacement gave no indication of cracking (see Figure 8).

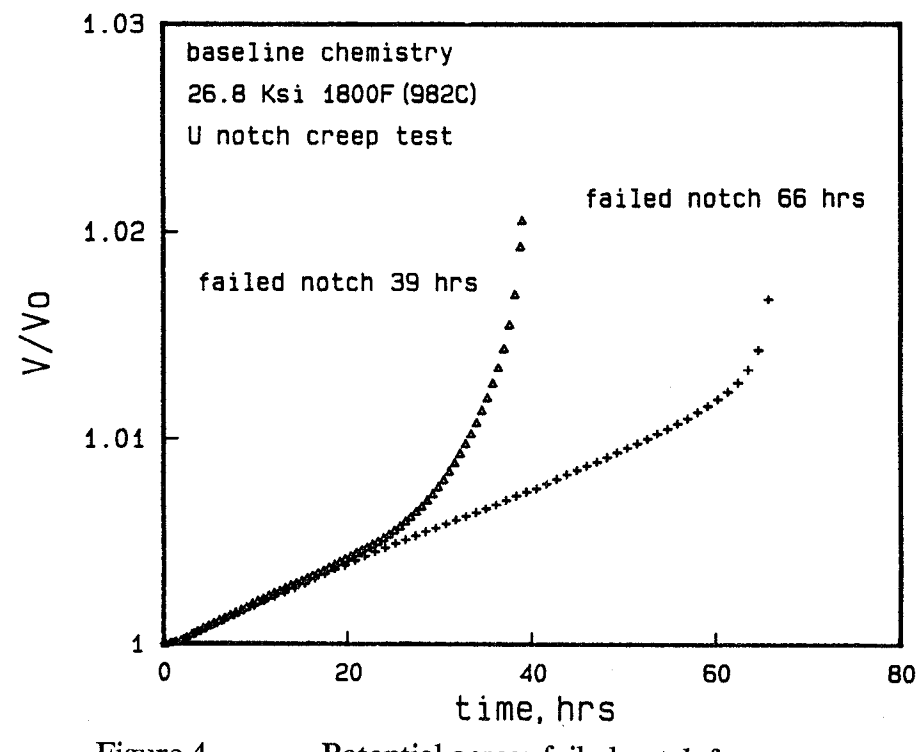

Figure 4 Potential across failed notch for repeat tests.

Results and Discussion

The approach described in the previous section was used to analyze the effects of zirconium and carbon on the rupture behavior of a cast bucket alloy. The evaluation of the three alloys was limited to a specific test condition. The rupture times for both type of notched tests, shown in Figures 9 and 10, were comparable, within scatter, for all three alloys.

The potential drop measurements across the failed notch of the U notched specimens also indicated similarity in behavior (see Figure 11). The initial deformation rate and the onset of crack propagation, detected between 75% - 80% of the rupture life for all the three alloys, were very close. Significant differences were observed in the potential drop across the failed notch of the V notched specimens (see Figure 12). Crack initiation occurred around 20%,

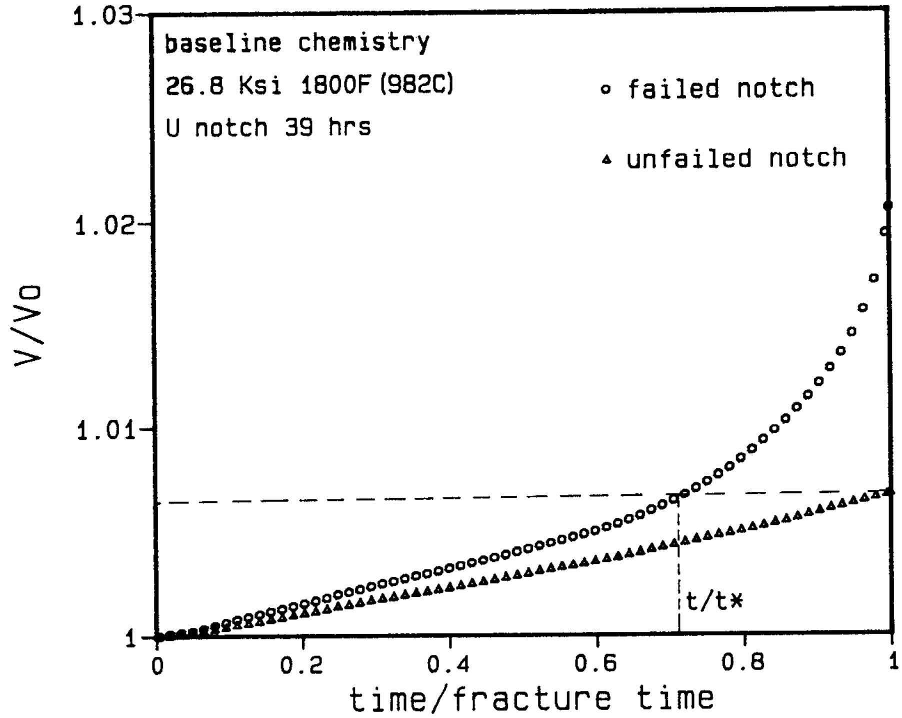

Figure 5 Potential curves for failed and unfailed notch.

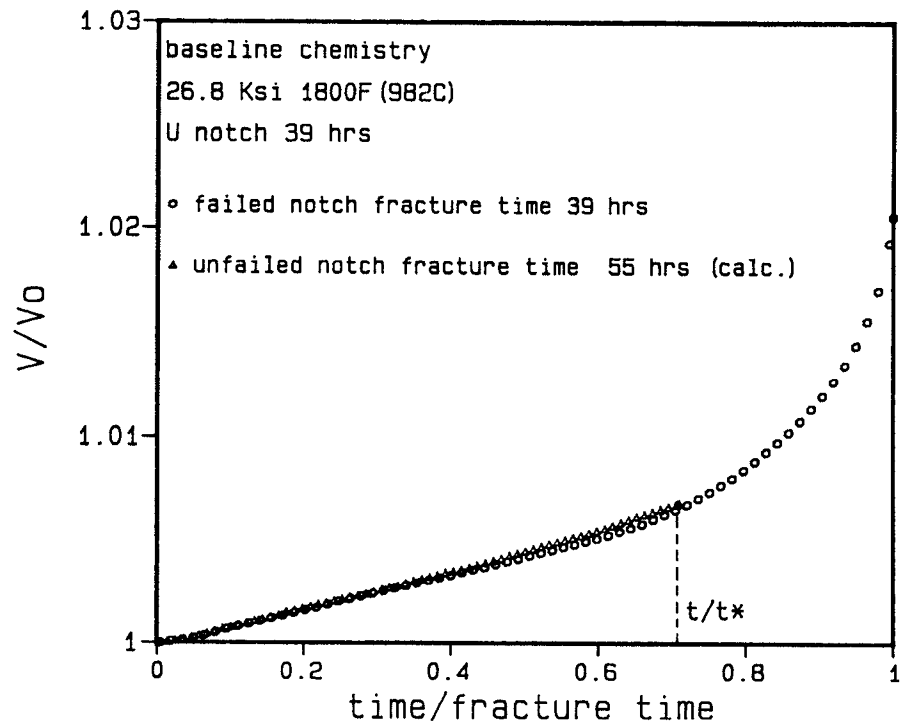

Figure 6 Potential changes versus time normalized with the fracture time for the failed notch and a calculated fracture time for the unfailed notch.

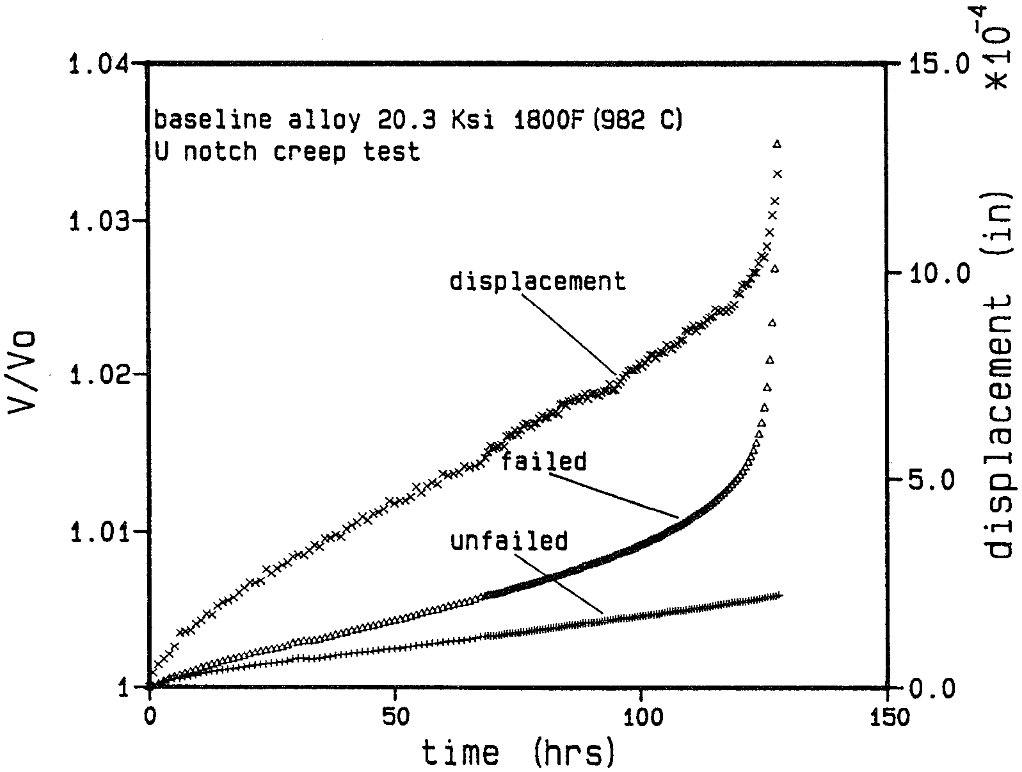

Figure 7 Displacement and potential measurements in a U notch creep test.

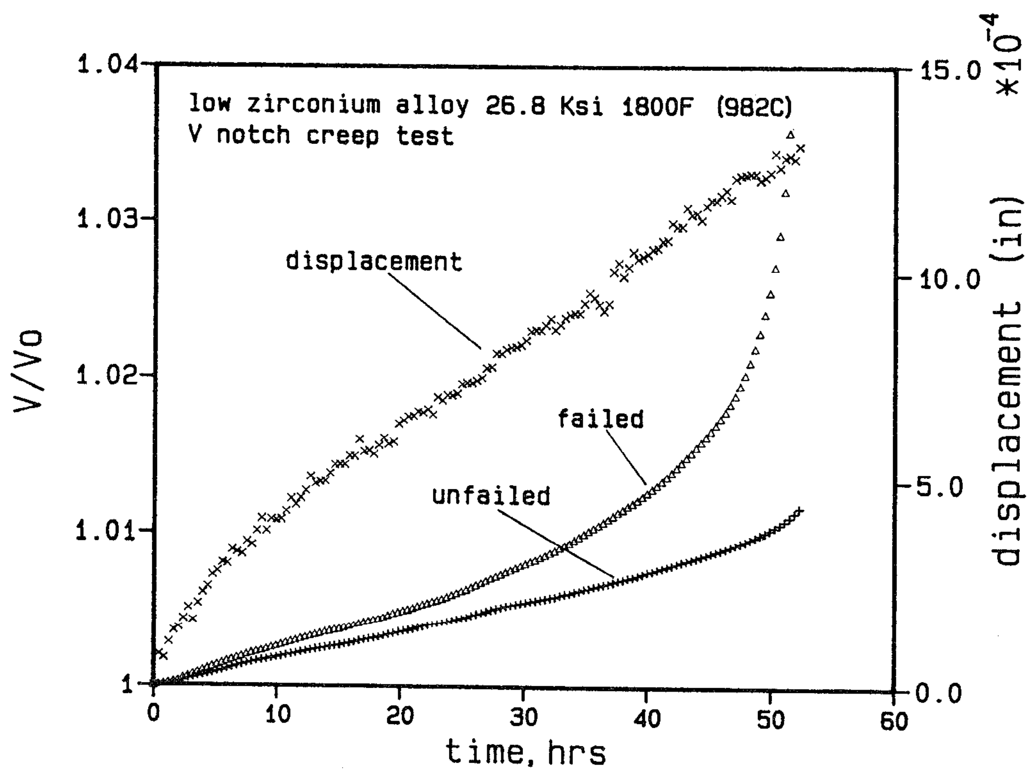

Figure 8 Displacement and potential measurements in a V notch creep test.

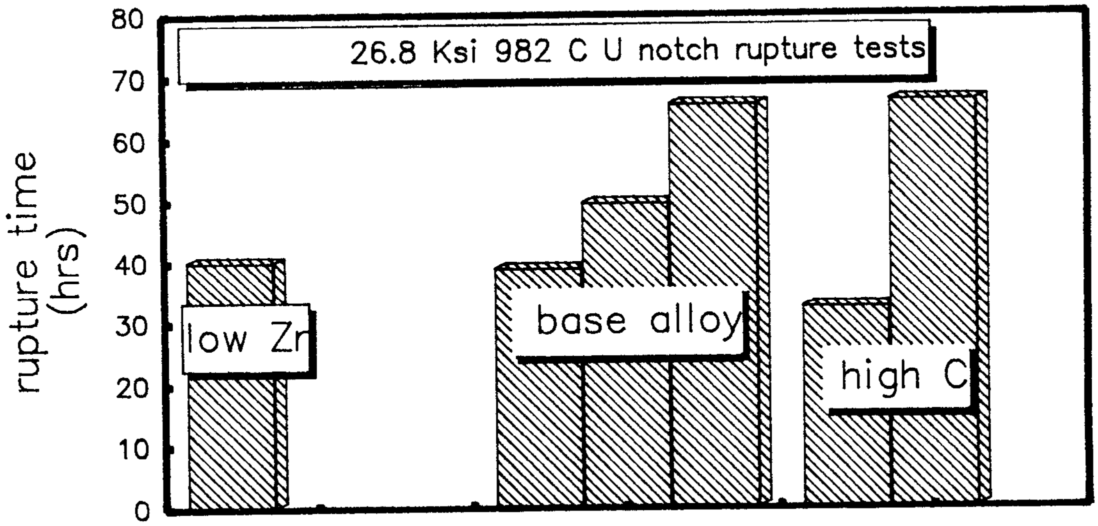

Figure 9 U notch rupture data.

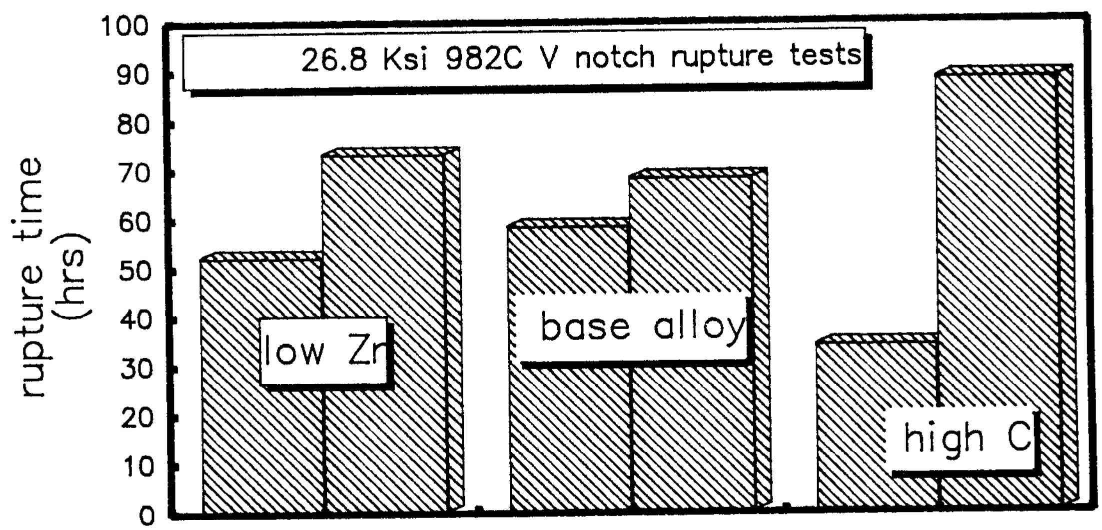

Figure 10 V notch rupture data.

40% and 80% of the rupture life for the low zirconium, the baseline and the higher carbon alloys respectively. The reduction in the zirconium level made the alloy less resistant to crack initiation but better in sustaining cracking. The opposite effects were observed with the addition of carbon in the alloy. Thus, the specific modifications changed both the crack initiation and propagation characteristics of the alloy. The effects on crack propagation are expected to be more pronounced, since the U notched creep data, which measure the resistance to creep deformation and crack initiation, were not significantly different. Indeed, crack growth rates for the high carbon alloy increased by an order of magnitude with respect to the baseline alloy (see Figure 13). Unfortunately crack propagation data for the low zirconium alloy were not available. It is important to point out that these results are pertinent to the specific test condition and no generalizations should be made without additional testing.

The enhancement of creep properties of nickel base superalloys with zirconium and carbon has been often reported in the literature (16,17). In contrast to their unambiguous effects, the mechanisms have resisted clarification. Both change the chemistry and microstructure of the grain boundaries and consequently affect time dependent properties. The addition of carbon to the alloy under consideration caused the precipitation of fine grain boundary carbides between the larger carbides observed in the baseline alloy. Fine carbides at the grain boundaries can further inhibit grain boundary sliding and make crack initiation more difficult. At the same time they reduce the alloy's tolerance to sustain damage by

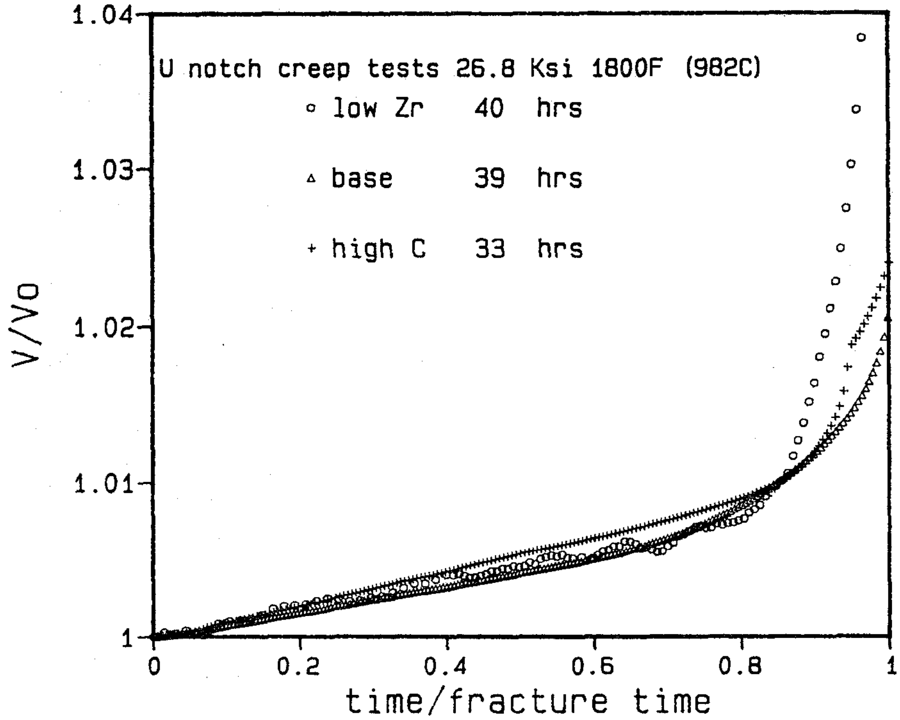

Figure 11 Potential change across the failed notch in U notch creep tests.

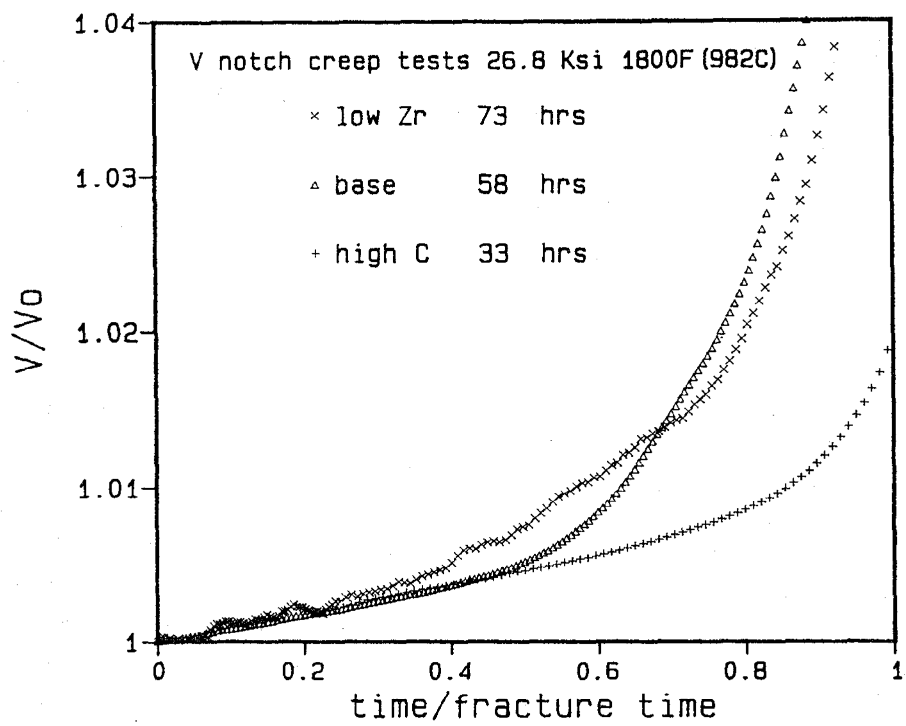

Figure 12 Potential change across the failed notch in V notch creep tests.

weakening its resistance to crack growth. Carbides have been reported to be detrimental to the resistance of the material to environmentally assisted cracking (18,19). The potential drop technique and the analysis described in this work can certainly provide additional information necessary for understanding adverse effects and develop a knowledge base for improving the performance of superalloys.

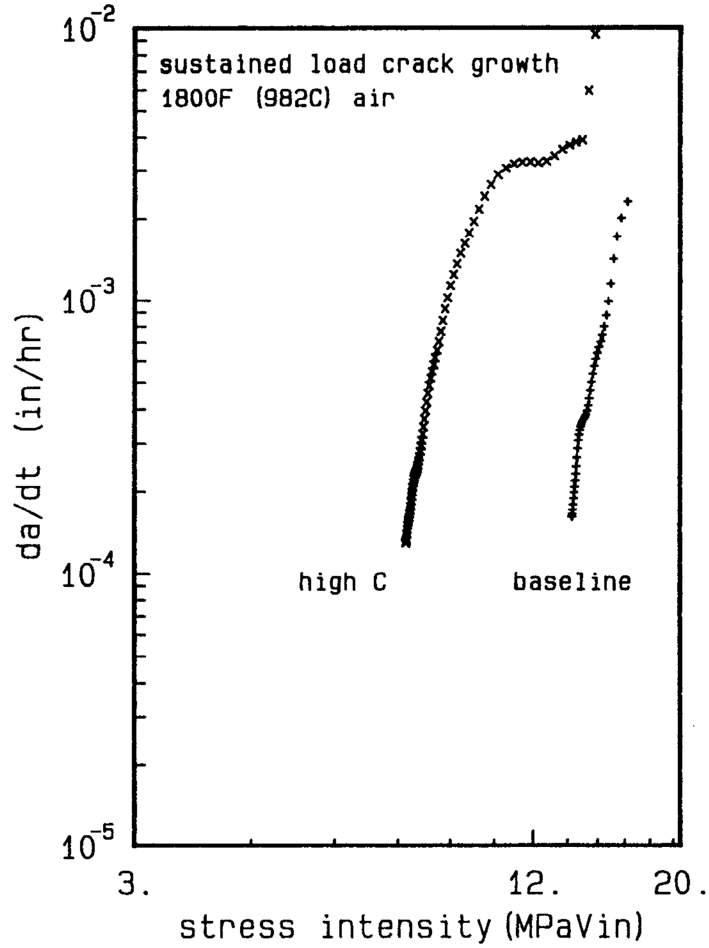

Figure 13 Sustained load crack propagation data.

Concluding Remarks

The resistance of a material to high temperature deformation, crack initiation and crack propagation constitutes its rupture strength. The work presented in this paper demonstrates that chemistry modifications can adversely affect resistance to crack initiation and propagation and as a result these processes ought to be looked at separately. The dc potential drop technique and notched rupture test, combined with the experimental methodology described here, helped interpret and understand rupture strength by analyzing life to crack initiation and crack propagation.

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