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Turbine Blade Refurbishment

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13. ABSTRACT *(Maximum 200 words)*

An investigation of metallurgical improvements and repair procedures to extend the service life to F404 high pressure turbine blades has been conducted. The first phase of the investigtion was directed towards the evaluation of directionally solidified Rene'80H superalloy specimens and blades and has been previously published. In the study reported herein, the elevated temperature creep-rupture properties of single crystal Rene'N4 specimens were determined and compared to the creep properties of the directionally solidified Rene'80H specimens. For the range of stresses and temperatures investigated, the creep-rupture life of single crystal specimens was at least twice that of the directionally solidified specimens. In addition, it was proposed to extend the life of turbine blades by refurbishment of damaged blade tips with MERL 72 weld overlays. The creep-rupture behavior and interfacial integrity of composite Rene'N4/ MERL 72 specimens was found to be satisfactory and comparable to composite Rene'80H/MERL 72 specimens. Comparisons of creep performance of single weld specimens (to simulate a tip repair) and re-weld specimens (to simulate a second tip repair) showed that the creep life of re-welded specimens was reduced compared to the single weld condition. The creep results and metallographic observations of the creep failure processes are presented and discussed.

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TURBINE BLADE REFURBISHMENT

INTRODUCTION

The previous study concerning high pressure turbine blade life extension explored metallurgical means to increase the service lifetime of directionally solidified Rene'80H (DS-R80H) superalloy turbine blades. Included in that investigation were elevated temperature creep-rupture studies of directionally solidified specimens and an investigation of the effect of hot isotatic press (HIP) processing on creep-rupture life. Blade tip refurbishment by MERL 72 weld repair was simulated by composite DS-R80H/MERL 72 specimens and evaluated on the basis of creep-rupture life. In addition, a metallographic study was performed on specimens in the creep study and on new and repaired turbine blades subjected to an ASMET (Accerated Service Maintainance Engine Test) run. The results of the first phase of the program were documented in the NRL Memorandum Report 6861[1].

In the present investigation, the creep-rupture behavior of the single crystal Rene' N-4 (R'N4) alloy was evaluated at 871 and 982°C. Also, the present effort examined the performance of DS-R80H creep specimens containing a MERL 72 weld metal center section which was notched and re-welded to simulate the repair of a previously repaired blade. The work included an investigation of the effect of HIP processing on creep rupture life of welded specimens. Additionally, single crystal R'N4/MERL 72 composite specimens were fabricated and tested at 871°C to determine the interfacial integrity and creep-rupture behavior of a simulated single crystal blade tip repair.

EXPERIMENTAL PROCEDURES

To facilitate property comparisons, experimental test conditions for the R'N4 evaluations were selected on the basis of the test parameters determined for the previous DS-R80H evaluations in the first phase of the program. The single crystal bar stock was purchased from the Whitehall Casting Division of Howmet Corporation. Creep-rupture tests were conducted in air at 871 and 982°C (1600 and 1800°F) at selected stresses in the range of 207 to 352 MPa (30 to 51 ksi) using the test specimen design previously employed[1]. The R'N4 specimens were tested in the as-cast condition and the chemical analysis (supplied by Howmet Corp.) of the single crystal alloy is reported in Table 1. The crystals were

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oriented so that the specimen stress axis was parallel to the [111] direction and specimen elongation during creep loading was measured with a linear variable displacement transducer attached to the specimen grips. Reported values of percent elongation were calculated with the assumption that all of the measured elongation was confined to the specimen gage section of 1.125 inches.

MERL 72 welds were inserted in DS-R80H and R'N4 specimens either as a single weld(to simulate a blade tip repair) or as a re-weld(to simulate a second tip repair). The nominal composition of the MERL 72 weld alloy is given in Table 1. These hybrid creep specimens were fabricated by vee-notching a test specimen, and while it was fixtured to retain axiallity, building up the notched area with weld metal. After fabrication, selected specimens were HIP processed by Chromalloy Division Oklahoma to the parameters shown in Table 1. The composite DS-R80H/MERL 72 weld specimens received the heat treatment listed in Table 1 and the R'N4/MERL 72 weld specimens were tested in the as-welded condition. Because of the large disparity in creep strength between Rene'80 and MERL 72, most of the creep deformation occurred in the weld zone. Since the gage length of this zone was difficult to determine, only values of percent reduction in area (% R.A.) were reported for the weld specimens.

Diamond pyramide hardness (DPH) profiles of the weld specimen gage section were determined using a microhardness tester employing a 100 gf load and a 13 sec cycle time. These DPH measurements were taken along the longitudinal direction of a chord section formed by polishing 0.15 mm (0.006 in.) below the cylindrical surface of the creep specimen gage section. The microstructures of the R'N4 and MERL 72 were investigated using conventional metallographic procedures. Samples were hand ground on silicon-carbide-coated papers to a final 10 micrometer grade, wheel polished using diamond paste to a final 1/4 micrometer grade and etched in a solution of 5 g of $CuCl_2$, 100 ml of HCl and 100 ml ethanol prior to optical microscopic examination.

RESULTS AND DISCUSSION

<u>CREEP-RUPTURE PROPERTIES OF SINGLE CRYSTAL R'N4:</u> The creep behavior of single crystal R'N4 specimens was evaluated at 871 and 982°C. These results are shown in Figures 1 and 2. In addition, previously reported creep data for DS-R80H specimens are included for comparison. The creep-rupture performance of the R'N4 specimens was found to be superior to the DS-R80H specimens at both test temperatures. For the conditions of this study, single crystal specimens exhibited at least a factor of two increase in creep life over the directionally solidified polycrystalline specimens. The creep-rupture properties of R'N4 and DS-R80H specimens are summarized in Table 2. The superior creep resistance of the single crystal specimens over that of the polycrystalline specimens would be expected because at these temperatures and stresses creep deformation modes directly or indirectly related to grain boundaries can dominate material response in this alloy. When compared with equiaxed polycrystals, it is known that improved

creep response can be achieved in alloys with highly elongated boundaries oriented parallel to the stress axis (DS-R80H) or to a higher degree in single crystal alloys which are entirely free of grain boundaries (R'N4).

Metallographic examination of tested R'N4 creep specimens revealed that failure was primarily a consequence of environmentally assisted creep crack growth. Figure 3 is a longitudinal section of a specimen showing surface oxide and and oxide filled cracks which have initiated on the surface and grown into the interior of the specimen. Adjacent to the oxide is a denuded zone which is free of precipitates. Observations in the electron microscope show that the oxide layers are rich in chromium, titanium and aluminum. This explains the depletion of these strengthening alloying elements in the matrix and the disolution of gamma prime precipitates which are rich in titanium and aluminum. It is known that creep strength is a direct function of solutioned and reprecipitated gamma prime. The affinity of aluminum and titanium to the oxide can give rise to the deletion of precipitates along the crack path and the subsequent reduction in creep crack growth resistance. Oxidation reactions are also suspected of injecting diffusion vacancies into the matrix and thereby possibly contributing to the reduction in creep strength of the alloy.

Other forms of creep damage were evident in the microstructure as shown in Figure 4. A phenomenon preceding the formation of creep cracks may result from precipitate shearing or the decohesion of carbide particles in the matrix. As shown in Figure 4a, the boundaries of the carbide that are in shear have separated from the matrix and the unsupported matrix then cracked normal to the stress axis in a tensile mode. This prevalent phenomenon, Figure 4b, is observed internally in the R'N4 alloy and appears to occur in the absence of any oxidation reaction. This type of inhomogeneous deformation may form in the early stages of creep and, when it occurs near the specimen surface, it may be a mechanism by which cracks can initiate and subsequently lead to creep failure through environmentally driven creep crack growth.

<u>CREEP-RUPTURE PROPERTIES OF MERL 72 WELD ALLOY:</u> In the inital study, blade tip refurbishment by MERL 72 weld repair was simulated by composite DS-R80H/MERL 72 specimens. Also in this study, the creep performance of re-welded specimens, which served to simulate the second repair of a blade tip, was evaluated. The study was additionally designed to investigate the effect of HIP processing on creep-rupture life of re-welded DS-R80H/MERL 72 specimens. The creep-rupture results at 871°C for the HIP processed and not-HIP processed re-welded specimens are compared with previously reported creep-rupture results for not-HIP processed single weld specimens in Table 3. From Table 3 it can be seen that the re-weld procedure produced a significant reduction in creep life of not-HIP processed weld specimens. HIP processing of the re-welded specimens reduced porosity in the weld and improved creep-rupture life, however, creep performance was still reduced compared to single weld performance. The ductility of the re-welded specimens was superior

to that of single weld specimens and the ductility was improved slightly by HIP processing. Within each specimen condition grouping, ductility decreased with decrease in stress.

Metallographic studies were performed to investigate the relationship between creep life and microstructure for specimens with MERL 72 gage sections. Weld center sections of single and re-weld creep specimens were polished and etched to reveal details of the weld microstructure. Examination of single and re-weld specimens showed that weld inserts were similar in size. It was also observed that both single and re-weld microstructures can exhibit severe precipitate segregation however this condition was more prevalent in the re-welded specimens. An example of the normal MERL 72 microstructure is shown in Figure 5a and an area from the same specimen exhibiting precipitate segregation is shown in Figure 5b. These areas possessed lowered deformation resistance and are thought to be a result of variations in weld chemistry associated with the multiple weld pass procedure. In the MERL 72 weld alloy, cracks propagated along the arms of the dendrites which formed during the weld solidification process. As shown in Figure 6, the topography of the fracture surface profile was greatly influenced by variations in the orientation of the dendritic structure.

To further examine these microstructures, Vickers hardness measurements were made longitudinally along the specimen gage length from a polished section 0.15 mm below the specimen surface. Hardness measurements started and ended in the DS-R80H portions of the specimen and covered the entire MERL 72 weld center section. The results of the hardness measurements are shown in Figure 7 for single and re-welded specimens. The data show that hardness does not abruptly change at the mixing zone between the DS-R80H and MERL 72 alloy, although microstructurally the transition between the two alloys appears very sharp. The MERL 72 alloy would be expected to have a significantly lower hardness than the Rene' 80H alloy and this was reflected by the dip in hardness at the center of the specimen, Figure 7. The rapid softening at the center of the weld zone, however, was found to be more severe for the re-welded specimens.

The hybrid creep specimens were fabricated by vee-notching a DS-R80H specimen and, while axially fixtured, the notched area was repaired with weld metal. With the re-weld specimen the weld zone was vee-notched and the welding procedures were repeated. The surface hardness data suggest that, when the Rene'80H mixes with the MERL 72 weld alloy during welding, the hardness of the weld increases because of hardening constituents in the base metal. Because of the vee-notch geometry, the base metal makes an increasingly smaller contribution to MERL 72 weld alloy hardness from the edge of the weld to the center. For the re-welded specimens, this effect is even more exaggerated because the base metal is now primarily the MERL 72 weld alloy. Because the re-welded specimen contained areas of precipitate segregation in the weld, some of the reduction in hardness must also be attributed to that effect. It appears, however, that the primary contributing factor in the reduction of creep-rupture lives of the re-welded specimens is related to weld dilution effects. The creep lives for the re-welded specimens probably more accurately reflect the true creep-rupture behavior of MERL 72 weld metal.

Single crystal blade tip refurbishment was also simulated with composite specimens and evaluated on the basis of creep-rupture life. The procedures used to fabricate the R'N4 composite specimens were identical to those of the DS-R80H composite specimens. The results of the R'N4/MERL 72 creep-rupture tests are summarized in Table 3. In general the creep response of single crystal R'N4/MERL 72 specimens was similar to that observed for the DS-R80H/MERL 72 specimens in that the re-welded specimens exhibited inferior creep properties when compared with the single weld condition. As with the DS-R80H/MERL 72 specimens, it was the combination of increased weld dilution effects and greater precipitation segregation in the re-welded specimens which is believed to be responsible for the increased creep rates and reduced lives for this condition. As shown in Table 3, the creep life of the R'N4 composite weld specimens was greater than that of the DS-R80H composite specimens. The two groups of weld specimens possessed different heat treatment histories which may account for these differences. Overall, all composite weld specimens exhibited minimal porosity and good interfacial integrity between the weld and base metal.

SUMMARY

The creep-rupture test results have demonstrated that the creep life of the single crystal Rene' N-4 alloy to be more that twice that of the directionally cast Rene' 80H alloy for the conditions of temperature and stress of this study. Composite R'N4/MERL 72 specimens, designed to simulate a blade tip repair, exhibited good matrix/weld interfacial integrity and possessed creep-rupture lives comparable to DS-R80H/MERL 72 specimens. Re-weld specimens, designed to simulate a second blade tip repair, showed reduced creep lives compared to the single weld condition. HIP processing improved creep lives of re-welded specimens but not to the level of the single weld specimen. To determine whether these positive creep results will translate into extended service for high pressure turbine blades, an exposure of new and repaired R'N4 single crytal blades in an ASMET (Accerated Servive Maintenance Engine Test) run will be required.

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REFERENCES

1. Smith, H.H. and Michel, D.J., "High Pressure Turbine Blade Life Extension," NRL Memorandum Report 6861, Aug. 28, 1991.

Table 1

Chemical Analyses, HIP Processing Parameters and Heat Treatment Schedules

Chemical Analysis of R'N4 (Wt.%)

C	Mn	Si	P	S	Cr	Ni	W	Fe	Co	N
.06	<.01	<.04	<.005	.0005	9.64	Bal	5.83	.03	7.50	2.3
Mo	Al	Ti	Cb+Ta	Zr	B	Cu	V	Hf	Mg	
1.50	4.29	3.46	.48 4.80	.01	.003	<.10	<.10	.14	<.0035	

Nominal Composition of MERL 72 Weld Alloy (Wt.%)

Co	Cr	Ni	W	Ta	C	Al	Ti	Hf	Y
Bal	25.0	15.0	9.0	3.0	.35	4.0	.25	1.2	.04

HIP cycle

1200C (2192F), 172.4 MPa (25ksi)
Hold for two (2) hours
Cool to 1037C (1900F) (cooling rate of 50C/minute)
Cool to room Temperature (cooling rate of 30C/minute)

Post-weld Heat Treatment

Heat to 1190C (2175F), hold for two (2) hours, cool to R.T.
Heat to 1052C (1925F), hold for four (4) hours, cool to R.T.
Heat to 871C (1600F), hold for sixteen (16) hours,
Cool to R.T.

Table 2

Tabulation of Creep-Rupture Properties

Spec. No.	Test Cond. MPa/°C	Life hrs.	Elong. %	R A. %	Remarks
E1397-1	207/982	162.9	18.0	45.0	R'N4
E1397-2	207/982	176.9	20.4	49.1	R'N4
D1397-1	352/871	719.4	12.3	39.3	R'N4
D1397-2	352/871	714.2	14.8	39.0	R'N4
L491	207/982	56.9	26.5	63.7	DS-R80H
C491	352/871	304.5	18.2	42.1	DS-R80H

Table 3

Creep-Rupture Properties of MERL 72 Weld at 871°C

Spec. No.	Stress (MPa)	Rupture Life (hours)	R.A. (%)
DS-R80H/MERL 72 Weld			
<u>Single Weld</u>			
S491-1	352	1.3	46.1
S491-2	276	14.5	40.2
W491	228	43.0	36.3
<u>Re-weld</u>			
U787-B	276	2.3	58.5
O787-B	228	14.8	45.9
C787-A	228	11.5	57.4
<u>Re-weld, HIP</u>			
U787-A	276	6.7	59.6
O787-A	228	23.6	49.5
R'N4/MERL 72 Weld			
<u>Single Weld</u>			
K1397-1	228	82.4	5.1
<u>Re-weld</u>			
L1397-1	228	18.4	19.5

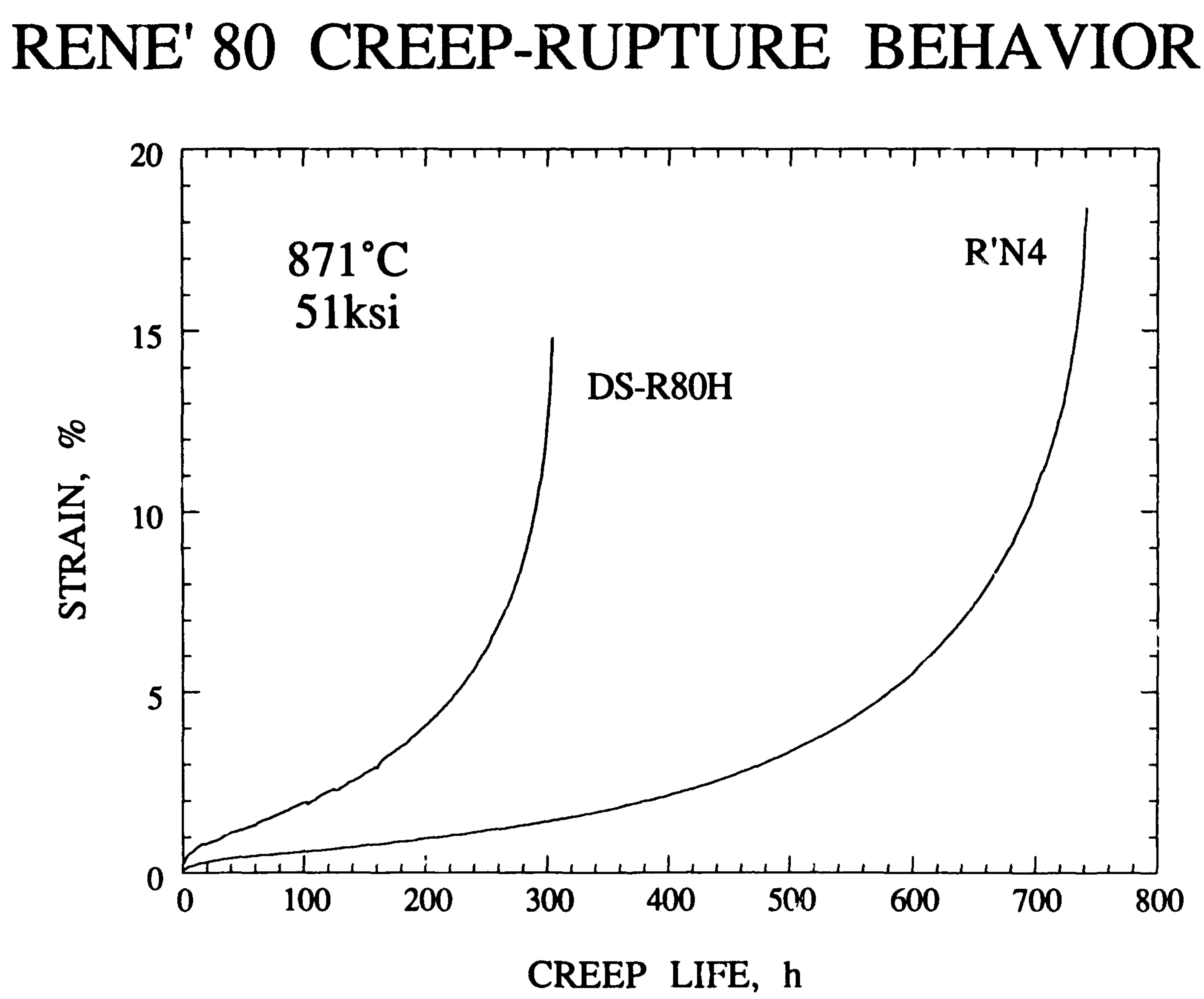

Figure 1. Creep response of R'N4 and DS-R80H specimens tested at 352 MPa and 871°C.

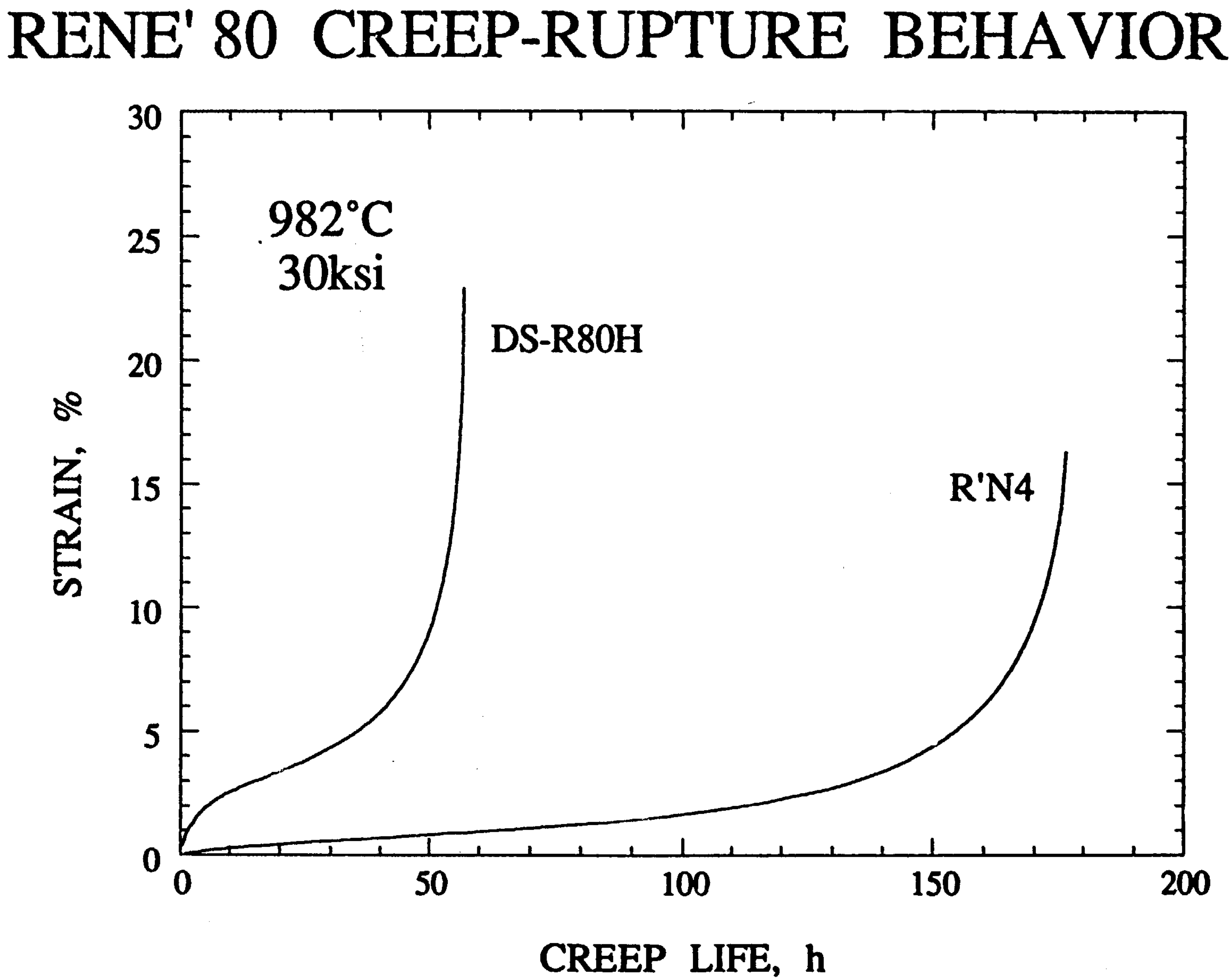

Figure 2. Creep response of R'N4 and DS-R80H specimens tested at 207 MPa and 982°C.

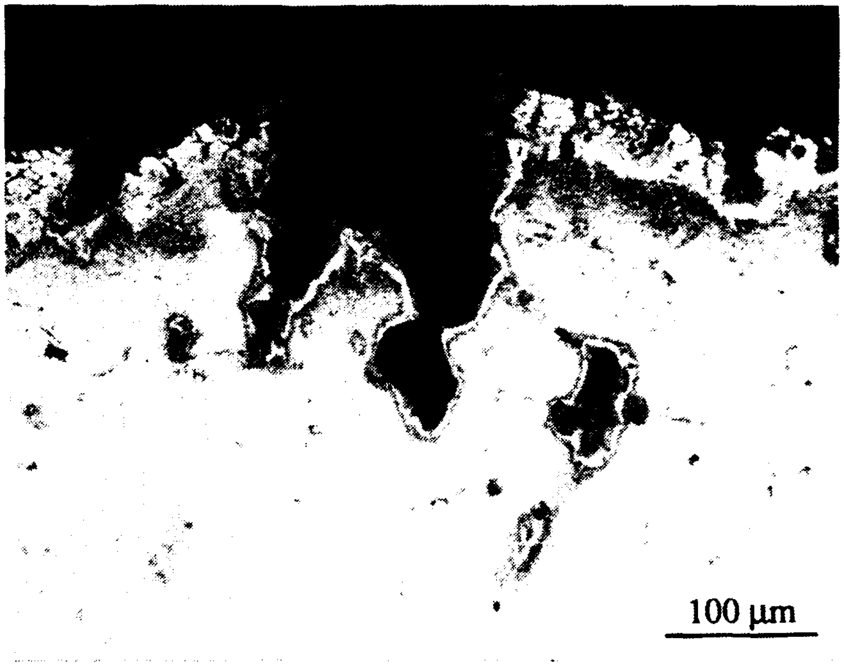

Figure 3. Optical photomicrograph of a polished and etched section of E1397-1 (R'N4) tested at 982°C showing the details of a typical surface crack.

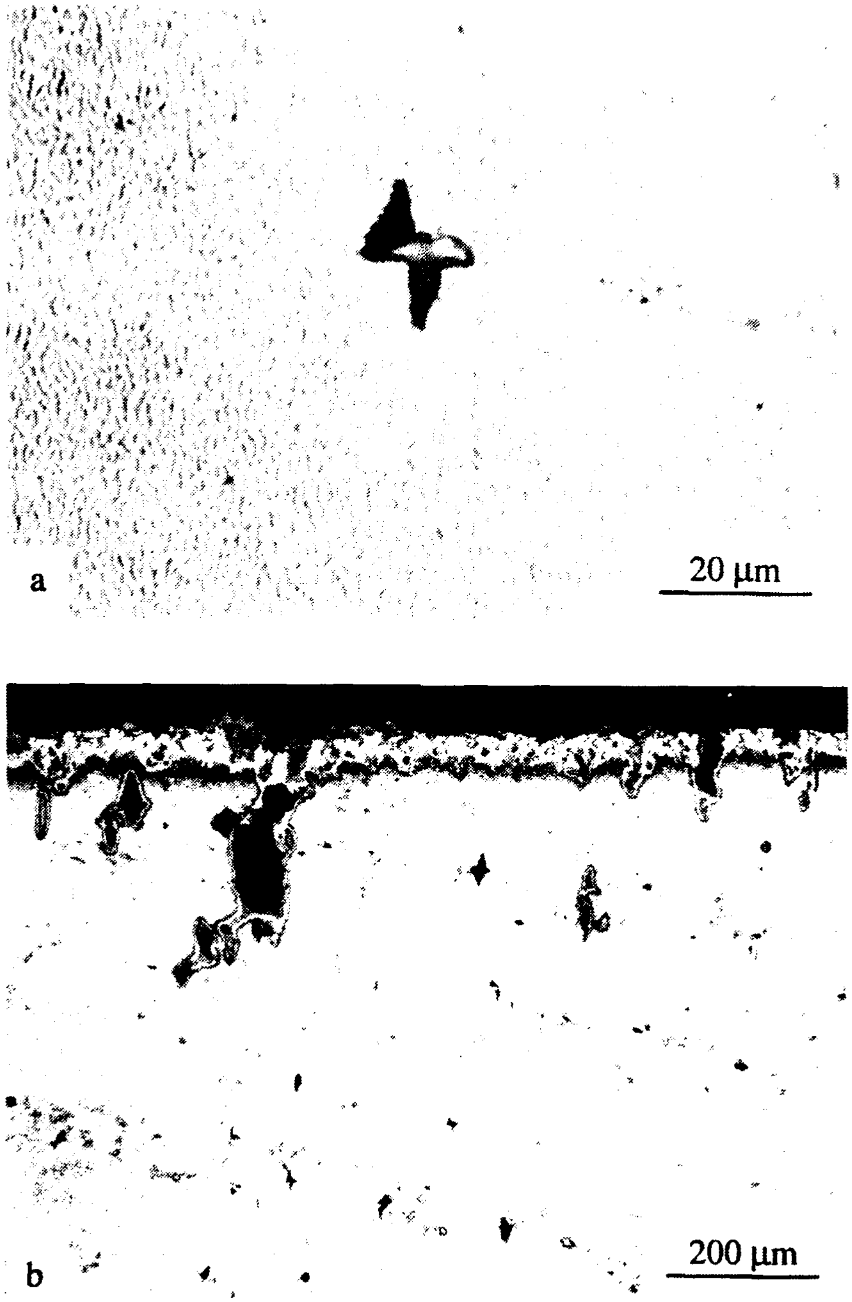

Figure 4. Optical photomicrograph of a polished and etched section of E1397-1 (R'N4) tested at 982°C showing: (a) Cracking associated with a precipitate which has separated from the matrix (The matrix is composed of gamma prime rafts which have coalesced during creep testing perpendicular to the tensile axis); (b) and the prevalence of this type of cracking throughout the specimen section.

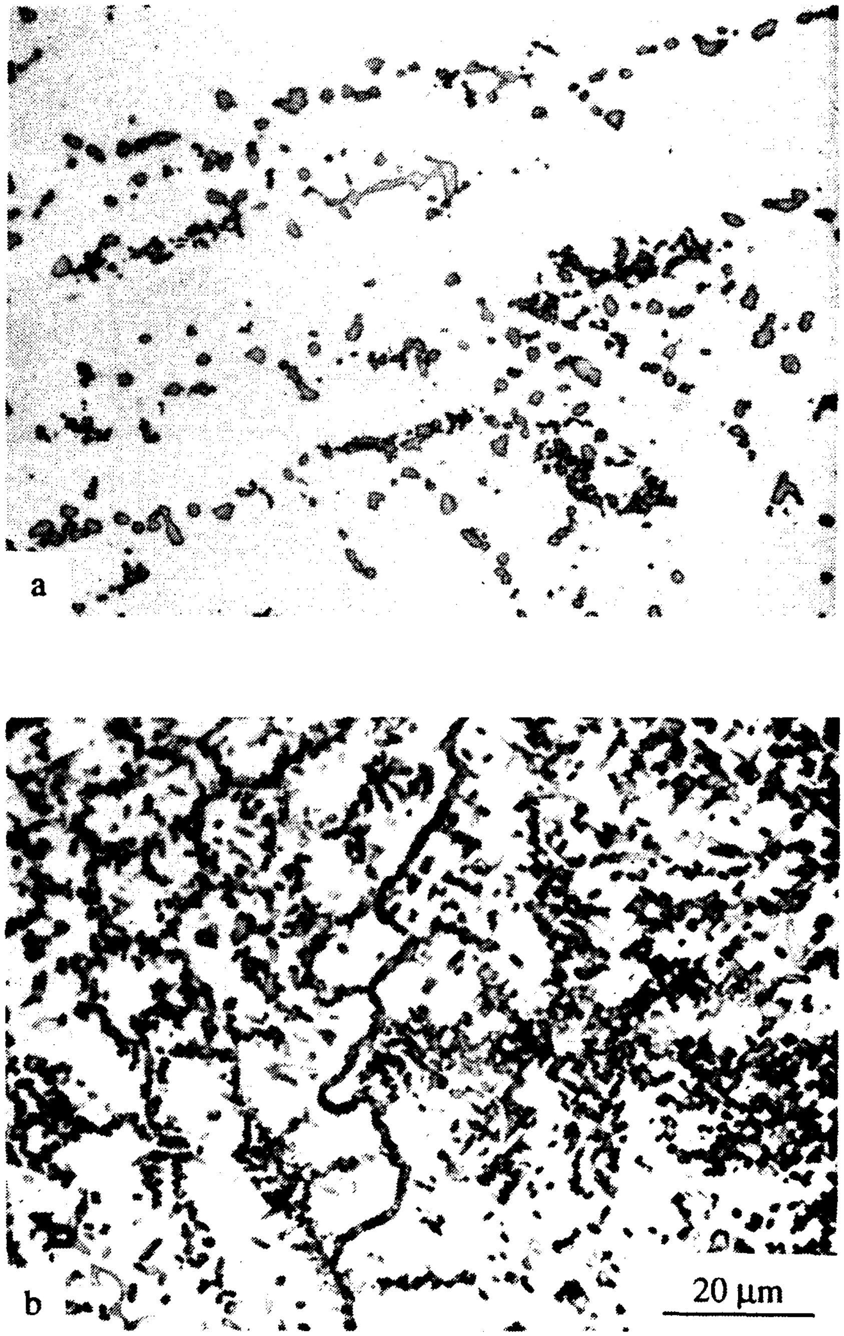

Figure 5. Optical photomicrographs of a MERL 72 re-weld specimen microstructure: (a) Typical weld microstructure and (b) an area displaying severe precipitate segregation in the weld.

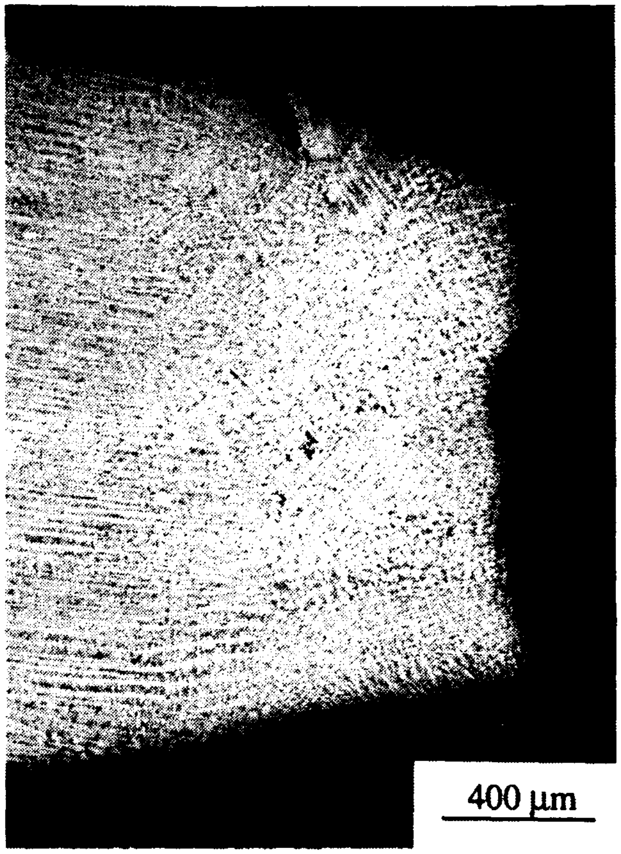

Figure 6. Optical photomicrograph of a polished and etched section of L1397-1 (MERL 72, re-weld) tested at 871°C showing the fracture surface profile and microstructure of the weld in the necked portion of the failed specimen.

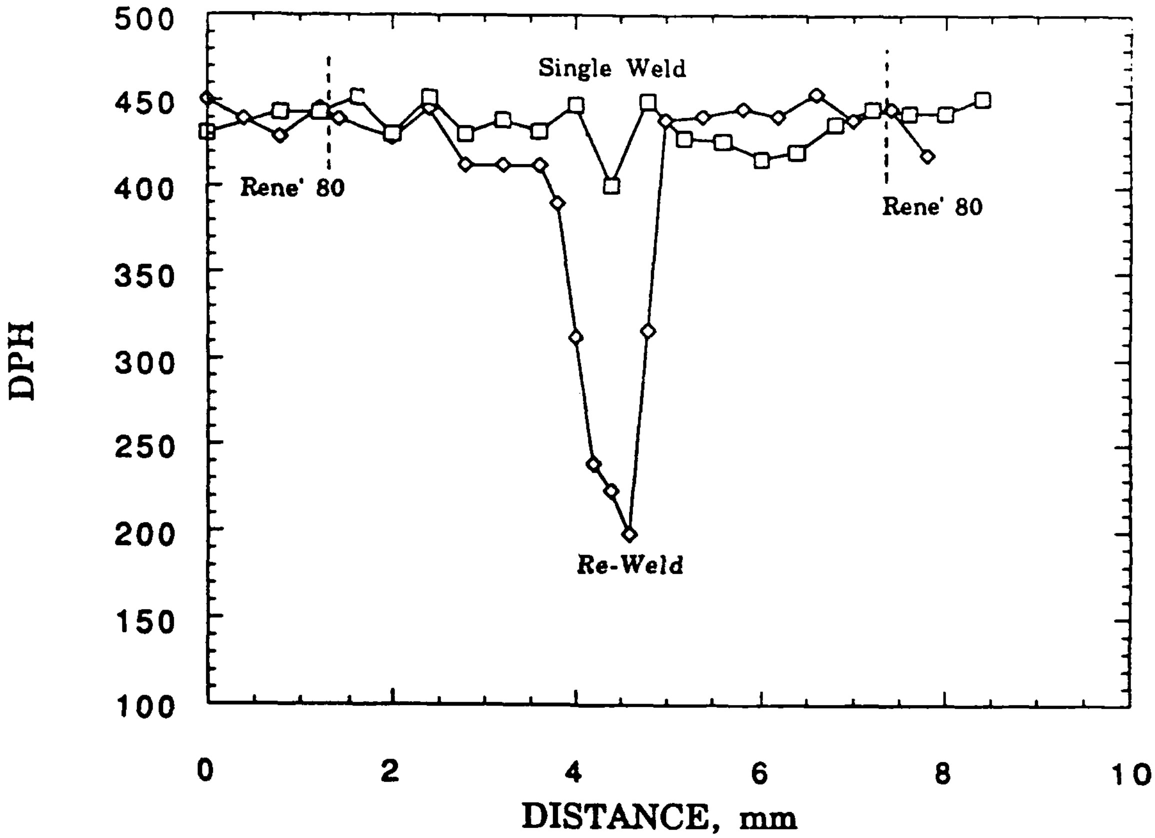

Figure 7. Diamond Pyramid Hardness (DPH) measurements of the MERL 72 single and re-weld microstructures taken on a polished surface formed by grinding 0.15 mm below the cylindical specimen surface.