EFFECT OF THERMOMECHANICAL PROCESSING

ON THE PROPERTIES OF RENE'220W

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Abstract

A thermomechanical processing approach using sheet rolling practice was developed for Rene'220W alloy which exhibits an attractive balance of tensile, creep, rupture, and crack growth properties. Rene'220W is a Ni-Cr-Co superalloy which is structurally similar to Inconel 718. The primary difference in chemistry between Rene'220W and Inconel 718 is the substitution of cobalt for iron. In Rene'220W, alloy strengthening occurs through precipitation of gamma double prime and gamma prime. Precipitation of delta phase will also occur when processing the material below the delta solvus temperature of approximately 1080°C. Results of this study indicate that the crack growth and creep/rupture behaviors are sensitive to the specific thermomechanical processing path. The range in hold time crack growth rates obtained at 650°C was greater than 10X. The preferred processing approach produced a warm-worked, directional microstructure with few, if any, recrystallized grains, and with creep and rupture properties about 27°C better and hold time crack growth behavior far superior to fine grain Inconel 718. The goal was to obtain equivalent tensile properties and 27°C higher creep/rupture properties than fine grain Inconel 718 without a degradation in hold time crack growth resistance. This processing approach, while feasible in sheet form, may be difficult to transition to a production process for thick sections.

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Introduction

Rene'220W is a wrought version of Rene'220C, a cast alloy developed by GE's Corporate Research Center [1] that offers about a 50°C improvement in properties over cast Inconel 718. The alloy is similar to Inconel 718 with the primary difference being the substitution of cobalt for the iron in Inconel 718. Like Inconel 718, Rene'220 is strengthened by gamma double prime and gamma prime. The precipitation of delta phase will occur with processing below the delta solvus temperature of approximately 1080°C versus 1000°C for Inconel 718.

Wrought Rene'220 has the required strength properties for advanced gas turbine disk applications and would be an economically attractive alloy for replacing Inconel 718 where creep has become a limiting property. Prior to this study, the alloy had not demonstrated acceptable high temperature crack growth properties necessary to satisfy recently implemented damage tolerant design practices. Accordingly, this thermomechanical processing study was conducted to investigate several combinations of warm worked and recrystallized structures with the intent of improving the 650°C crack growth behavior without impairing the alloy's tensile and creep/rupture properties.

Materials and Processing

Sheet was produced for this study using a laboratory rolling mill to save time and conserve material versus a forging approach. In the preliminary metallographic investigation, slices were cut from a Rene'220 billet (200 mm diameter) made from a Teledyne Allvac triple melt (VIM+ESR+VAR) heat. The ingot chemical analyses are given in Table I.

Table I Chemical Analysis of Rene'220 - Heat 6401

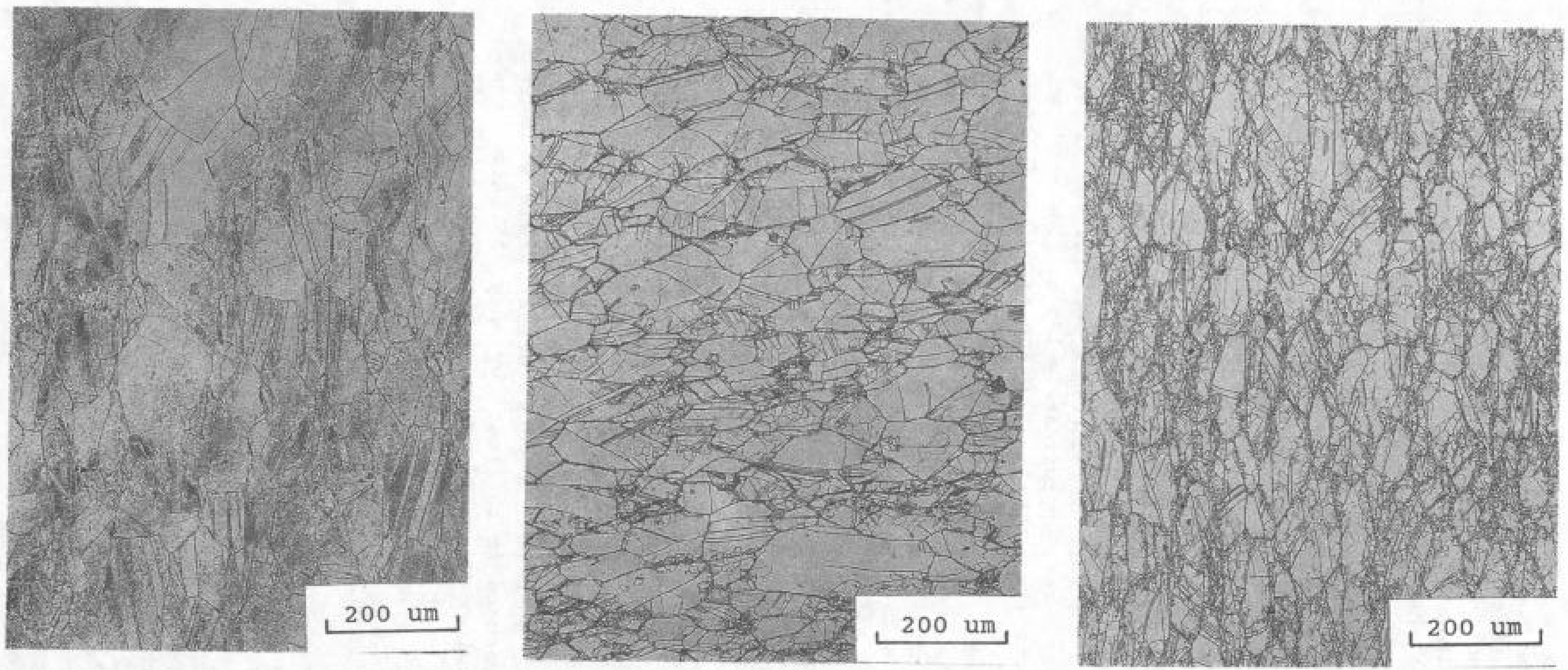
Elements	VAR Ingot Top	VAR Ingot Bottom
Carbon	0.017	0.018
Sulfur	0.0003	0.0003
Molybdenum	3.05	3.01
Chromium	18.13	17.93
Nickel	balance	balance
Cobalt	11.96	11.89
Iron	0.24	0.20
Phosphorus	0.001	0.001
Niobium	5.03	5.03
Tantalum	2.96	2.97
Zirconium	0.01	0.01
Titanium	0.98	1.00
Aluminum	0.50	0.53
Silicon	0.05	0.01
Boron	0.0086	0.0105
Oxygen	<.0010	<.0010
Nitrogen	0.0039	0.0034

Billet slices were cut into 25 mm x 25 mm x 75 mm long coupons and were hot rolled 50% at 1080°C (approximately the delta solvus). These pieces were then cut into smaller pieces and re-rolled at 14°C temperature intervals between 968°C and 1080°C with metallographic samples removed at reduction intervals of approximately 15, 30, 45, 60 and 75 percent. All rolling reductions were 10-15% per pass with reheats between rolling passes. The samples were then metallographically examined to establish parameters producing the desired levels of recrystallization. Microstructures for several finish rolling temperatures at total reduction of 40% can be seen in Figure 1. All reductions at 968°C resulted in 0% recrystallization. At 996°C, 100% recrystallization occurred at a total reduction of 40%. These results were used to select processing parameters for the subsequent rolling of material for mechanical property evaluation.

For this work, additional 25 mm thick transverse billet slices were cut and pre-rolled 80% (to 5 mm thick) at 1080°C. These sheets were then cut in half and finish rolled at a temperature below the delta solvus. Rolling temperatures in the range of 955°C-988°C were investigated with a total reduction of either 25% or 50%. All rolling reductions were 10% to 15% per pass with reheat between passes. Sheets approximately 125 mm wide x 500 mm long were produced. The sheets then received an age of 760°C/8 hrs + 730°C/24 hrs + 690°C/24 hrs. Test specimens were machined from each sheet following this heat treatment. Microstructural features spanning the range of processing conditions can be seen in Figure 2. As in the cast version of Rene'220, optimum strengthening is associated with the formation of the gamma prime/gamma double prime "sandwich" structure.(2) In Rene'220W, precipitation of "delta" plates will occur with exposures of several hours at temperatures of approximately 830°C and higher. In Rene'220W, the "delta" plates have been characterized as a mixture of the orthorhombic phase, and of closely related DO_{19} and DO_{24} hexagonal phases(3); these phases have also been identified in the "delta" plates in the cast version of the alloy.(2) In Figure 2, the "delta" plates can be seen in the SEM micrographs. The magnification is inadequate to resolve the gamma prime/gamma double prime structures. Sheet with 50% reduction yields a "pancake" grain morphology. A large amount of inter- and intragranular delta precipitation results when the sheet is rolled at 955°C with 50% reduction. Less delta precipitation is observed when the sheet is rolled at 988°C with 50% reduction. Rolling at 968°C with 25% reduction produces levels of delta precipitation similar to that observed in the sheet rolled at 988°C with 50% reduction. Note that a much coarser grain size is obtained when the sheet is reduced in thickness by only 25%. Also, the amount of the "pancake" morphology is greatly reduced for sheet with 25% total reduction.

Specimen Geometry and Test Technique

Elevated temperature tensile and creep/rupture tests were performed on sheet specimens. All specimens were machined from the sheets in the L-T orientation. The tensile tests were performed per ASTM specification E21-79, while the creep/rupture tests were performed per ASTM specification E139-83. The specimen geometry can be seen in Figure 3. Crack growth testing was performed using the pin loaded single edge notch (SEN) specimen geometry, which can be seen in Figure 4. The nominal gage section was 6.35 mm wide x 2.0 mm thickness. All crack growth specimens were machined with the specimen axis parallel to the rolling direction (L-T orientation). All of the data were acquired using the direct current electrical potential drop technique. This technique is a modification of the method described by Gangloff.(4) The direct current potential drop

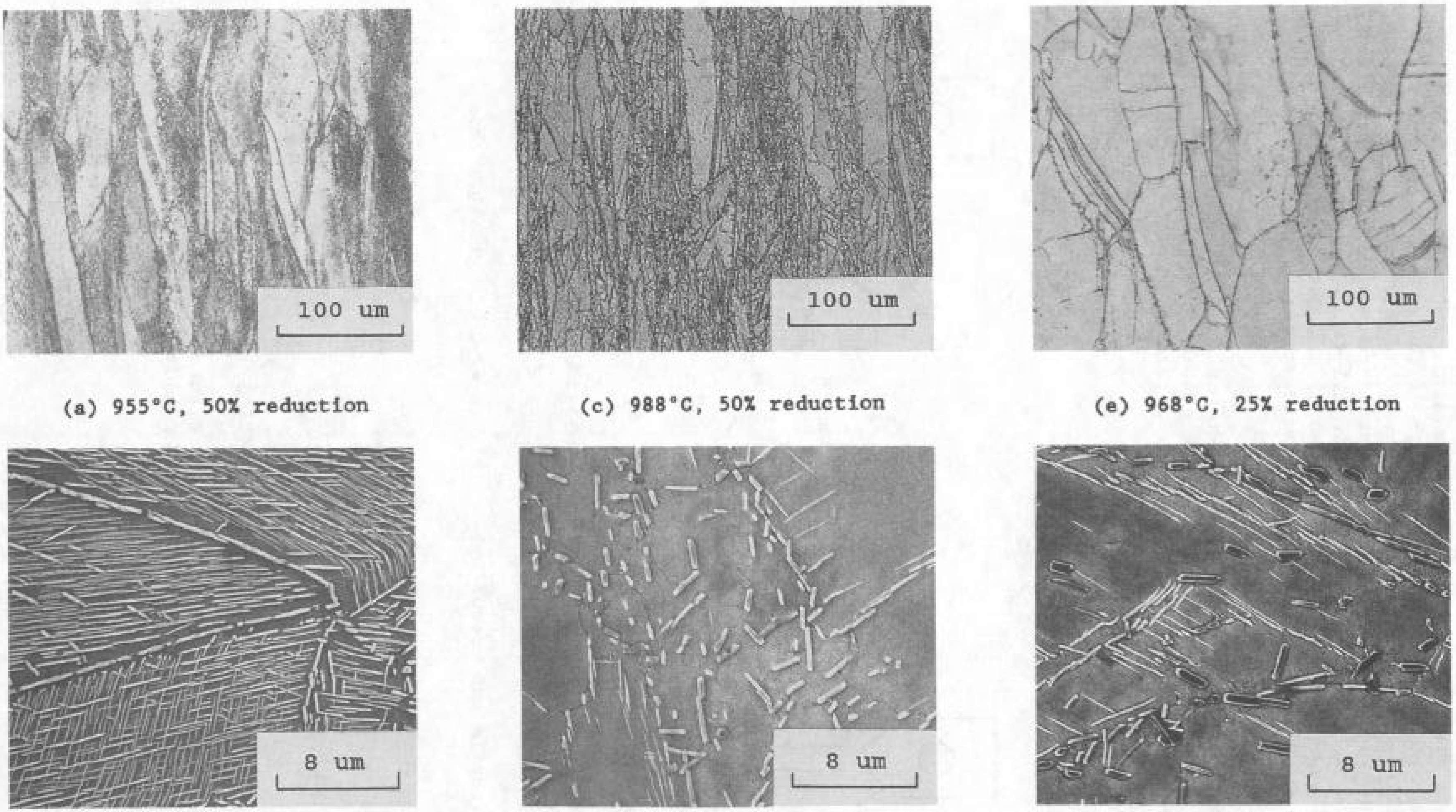


968°C - 0% Rx

980°C - approx 20% Rx

996°C - 100% Rx

Figure 1. Rene'220W thermomechanical processing pre-study - sheet hot-rolled from transverse billet slices - 40% reduction.



(a) 955°C, 50% reduction

(c) 988°C, 50% reduction

(e) 968°C, 25% reduction

(b) 955°C, 50% reduction

(d) 988°C, 50% reduction

(f) 968°C, 25% reduction

Figure 2. Microstructural features spanning the range of processing conditions in Rene'220W sheet.

technique has been adapted to the SEN geometry by Wilcox and Henry.[5] A fatigue precrack was initiated at room temperature and 10 Hz from a 0.3 mm deep EDM notch which was placed in one edge of the specimen. The fatigue precrack was allowed to grow to a nominal depth of 0.35 mm. The precrack was then marked via heat tinting. The elevated temperature test was then started after the heat tint was completed. All tests were performed in constant load amplitude mode at R ratio=0.05 and nominal maximum gage section stress of 520 MPa, and were terminated at a target Kmax value of 55 MPa$\sqrt{m}$.

The potential solution developed by Johnson[6] was used to convert potential data to crack length data. Crack growth rates were calculated using the seven point polynomial method. Stress intensity values were calculated using the Tada[7] solution.

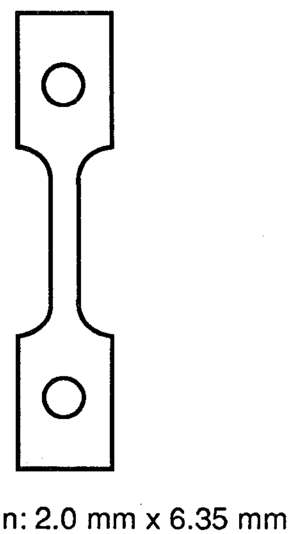


Figure 3. Tensile and creep/ rupture specimen.

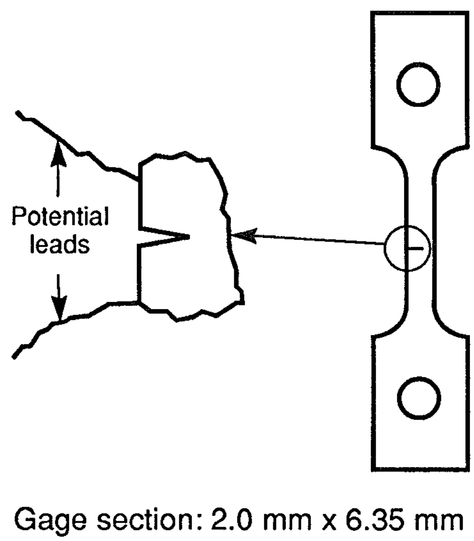


Figure 4. Crack growth specimen.

Mechanical Properties

The tensile and creep/rupture properties are summarized and compared with fine grain Inconel 718 forging properties in Table II.

Table II

Property	-----Rolling temperature------				Fine Grain Inconel 718
	---50% reduction---			25% reduction	
	955°C	968°C	988°C	968°C	
400°C 0.2%YS (MPa)	1257	1331	1395	1362	1251
400°C UTS (MPa)	1613	1551	1530	1451	1377
Tensile elongation (%)	8.4	11.0	14.0	10.0	12.1
Creep at 620°C, 827 MPa (hrs to 0.2% creep)	0.6	0.6	2.6	194	237 (593°C)
Rupture 677°C/725 MPa (hrs)	16	22	39	202	146 (650°C)

The 400°C tensile strength of the R'220W sheet is equal to or better than fine grain IN718 forging. The creep and rupture capability of the sheet with 50% reduction did not meet the program goal. The hold time crack growth data for sheet with 50% reduction is plotted in Figure 5. A small acceleration in crack growth rate can be seen with increasing rolling temperature from 955°C to 988°C. As part of the effort to improve the creep resistance, some rolled and direct aged material was subsequently solutioned (1038°C/1 hour) and aged. Crack growth data from this material, also plotted in Figure 5, shows that the hold time crack growth resistance of the re-solutioned and aged material is greatly inferior to the others. However, lowering the total reduction to 25% during rolling produced a dramatic improvement in creep/rupture behavior. Table II shows that R'220W sheet with 25% reduction exhibits about a 27°C creep and rupture advantage over fine grain IN718 forging at equivalent stress levels. The hold time crack growth data for sheet rolled at 968°C with 25% total reduction is also plotted in Figure 5. For a rolling temperature of 968°C, the sheet with 25% reduction exhibits only a modest acceleration in crack growth rate, but has much superior creep and rupture resistance compared to the 50% reduction sheet.

The 650°C crack growth data for sheet rolled at 968°C with 25% total reduction is plotted in Figure 6 along with similar data for fine grain Inconel 718 forging. The hold time data for the Rene'220W sheet were also plotted in Figure 5. Compared to the continuous cycling baseline, Rene'220W exhibits only a small acceleration in hold time crack growth rate at 650°C, in contrast to a 10X increase for Inconel 718. The Rene'220W behavior is very favorable for a wrought nickel-base superalloy at 650°C.

These results illustrate that the mechanical properties of the Rene'220W alloy can be varied greatly with changes in the specific processing/heat treatment approach.

Microscopy

Delamination was documented to occur ahead of the propagating fatigue crack during the interrupted crack growth experiments. The delamination was perpendicular to the crack plane, and was observed in all of the warm-worked microstructures investigated. Mode I crack propagation was macroscopically observed for all processes. The amplitude of the

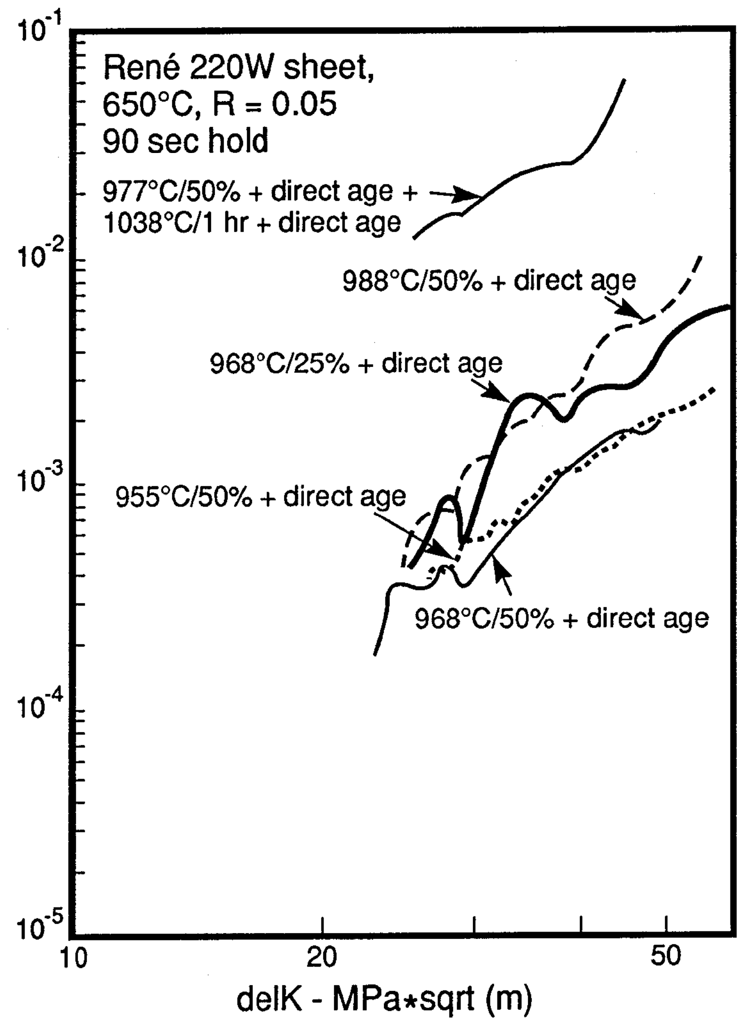


Figure 5. Hold time (1.5 sec-90 sec-1.5 sec) crack growth behavior of Rene'220W sheet at 650°C.

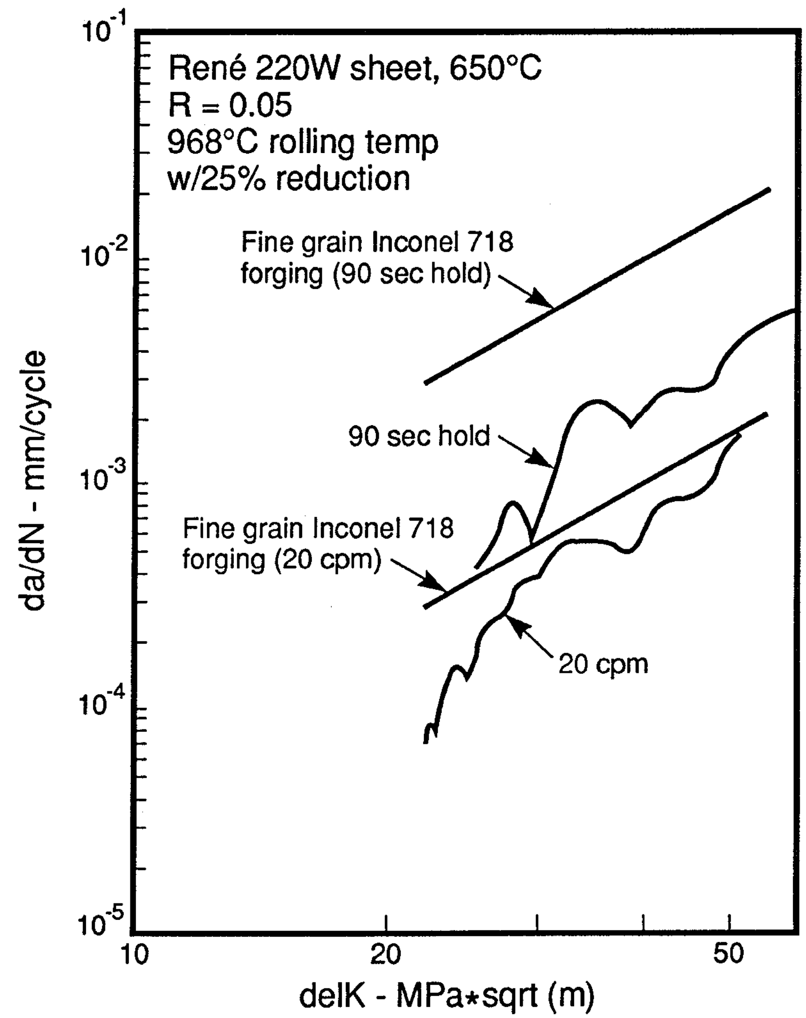
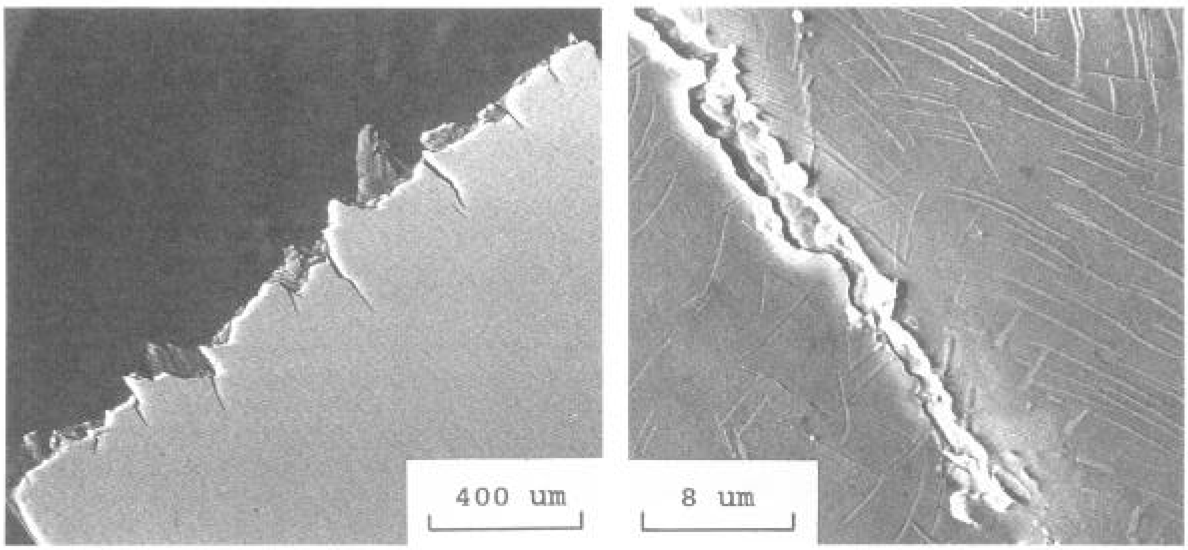


Figure 6. Continuous cycling and hold time crack growth behavior of Rene'220W sheet (968°C rolling temperature and 25% reduction) vs. fine grain Inconel 718 forging at 650°C.

delamination was symmetrical with respect to specimen thickness, as seen in Figure 7(a). The micrographs in Figure 7 were obtained using high resolution scanning electron microscopy (SEM). Figure 7(a) is a cross section transverse to the fracture surface in the direction of the propagating crack. This specimen is from a sheet rolled at 968°C with 50% reduction. The amplitude of delamination was a maximum near the mid-thickness, and a minimum near the specimen surface, suggesting that the local stress state at the crack tip influences the delamination behavior. The state of stress is closest to plane strain at the mid-thickness; at this point, crack tip constraint is maximized. Further examination was concentrated on the volume of material within the crack tip plastic zone (near the fracture surface). Matrix microcracking was observed; these microcracks were typically arrested or deflected at the delta precipitates. In addition, large deformation of delta precipitates was observed without precipitate fracture (see Figure 7(b)). The fractographic evidence suggests that the warm-worked microstructure can accommodate a large magnitude of crack tip deformation, which is consistent with the favorable crack propagation behavior.



a) b)

Figure 7. Rene'220W crack growth specimen. a) Cross section of specimen. View is in the direction of crack propagation. b) Microstructure near the tip of a delamination crack.

Discussion

It was demonstrated that both the crack growth and the creep/rupture behaviors of Rene'220W are sensitive to the specific thermomechanical processing history. For a total reduction in thickness of 50%, the amount of delta plate precipitation was maximized at the lowest rolling temperature of 955°C. In this condition, the alloy exhibited the best crack growth behavior and the worst creep/rupture behavior. Increasing the rolling temperature to 988°C resulted in a slight decrease in hold time crack growth resistance with only a marginal improvement in creep/rupture behavior. A smaller volume fraction of delta plates was observed when the rolling temperature was increased from 955°C to 988°C. Rolling at the higher temperature of 988°C would increase the amount of niobium available for the precipitation of gamma double prime, thus increasing the creep/rupture resistance. However, for a total reduction of 50%, the creep/rupture resistance of the sheet did not meet the program goal.

Decreasing the final rolling reduction from 50% to 25% produced a large increase in creep/rupture resistance with only a small decrease in hold time crack growth resistance. Both the crack growth and creep/rupture behaviors met the program goals and were superior to fine grain Inconel 718 forging. The micrographs in Figure 2 indicate that the volume fraction of delta plates was similar for the sheet rolled at 988°C with 50% reduction and the sheet rolled at 968°C with 25% reduction. However, the creep/rupture resistance of the sheet with 25% reduction was superior to any of the sheet with 50% reduction. The grain size was much coarser in the sheet with 25% reduction. The large increase in creep resistance with increasing grain size agrees with observations in a thermomechnaical processing study of Inconel 718.[8]

The thermomechanical processing approach developed for Rene'220W in this study yields an attractive balance of tensile, creep, rupture, and crack growth properties. This balance of properties was shown to be superior to fine grain Inconel 718 forging.

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