FATIGUE LIFE EXTENSION

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Abstract

Potential fatigue rejuvenation processes have been carried out on fatigue-damaged material both with and without observable surface-connected fatigue cracks. The fatigue life of fatigue-damaged MAR-M246(Hf)(DS), a directionally solidified nickel-base superalloy used in turbine airfoils, was extended by reheat treatment. The fatigue life of fatigue-cracked Inconel 718, a wrought nickel-base superalloy used in a wide variety of advanced rocket engine components, was extended by electron-beam welding to close off the surface-connected crack, followed by hot isostatic pressing and reheat treatment.

Introduction

This paper describes a continuing study of possible techniques for rejuvenating the fatigue life of materials through various combinations of surface treatment, hot isostatic pressing, and reheat treatment. Potential rejuvenation techniques were investigated for MAR-M246 (Hf)(DS), a directionally solidified nickel-base superalloy and for Inconel 718, a wrought nickel-base superalloy.

The rejuvenation techniques are directed at the removal of fatigue damage and restoration of the initial alloy microstructure. Rejuvenation techniques have received considerable attention with respect to aircraft gas turbine engine applications (Ref. 1, 2, and 3). In the refurbishment of engine components, hot isostatic pressing (HIP) and/or reheat treatment are commonly carried out for rejuvenation of creep and stress rupture properties (Ref. 4). Rejuvenation of fatigue damage has received less attention, with limited success (Ref. 5).

Because the multiple aspects of fatigue damage and fracture necessitate several approaches to rejuvenation, it was anticipated that damage prior to crack initiation might be repaired through reheat treatment, while damage that includes significant surface cracking would require a combination of surface treatment and hot isostatic pressing.

Materials and Procedures

The alloys studied under this program include MAR-M246(Hf)(DS), a directionally solidified nickel-base superalloy, and Inconel 718, a wrought nickel-base superalloy. Alloy compositions are listed in Table 1 and heat treatments are listed in Table 2.

Table 1. Alloy Compositions

ALLOY	NOMINAL COMPOSITION, WEIGHT PERCENT												FORM
	Ni	Cr	Co	W	Mo	Ti	Al	Ta	B	Zr	Hf	C	
MAR-M246(Hf)(DS)	bal	9	10	10	2.5	1.5	5.5	1.5	0.015	0.05	1.7	0.15	DIRECTIONALLY SOLIDIFIED
	Ni	Cr	Mo	Cb	Al	Ti	Fe	Mn	Si	C			
INCONEL 718	bal	18.6	3.1	5.0	4.0	0.9	18.5	0.20	0.30	0.40			WROUGHT

Table 2. Heat Treatment and Rejuvenation Process Parameters

	HEAT TREATMENT	HIP PARAMETERS
MAR-M246(Hf)(DS)	2230 F FOR 2 HOURS IN ARGON, COOL TO ROOM TEMPERATURE; 1600 F FOR 24 HOURS IN ARGON; COOL TO ROOM TEMPERATURE	2050 F 30 KSI 3 HOURS
INCONEL 718	1900 F FOR 30 MINUTES IN ARGON, COOL TO ROOM TEMPERATURE; 1400 F FOR 10 HOURS IN ARGON, FURNACE COOL TO 1200 F; TOTAL AGE TIME 20 HOURS	1800 F 30 KSI 3 HOURS

The experimental approach was to first obtain baseline fatigue data for each specific alloy heat and testing condition. Cylindrical fatigue test specimens (Fig. 1) were tested in air at a stress ratio (R = minimum stress/maximum stress) of -1 at the temperatures and maximum stress levels listed in Table 3.

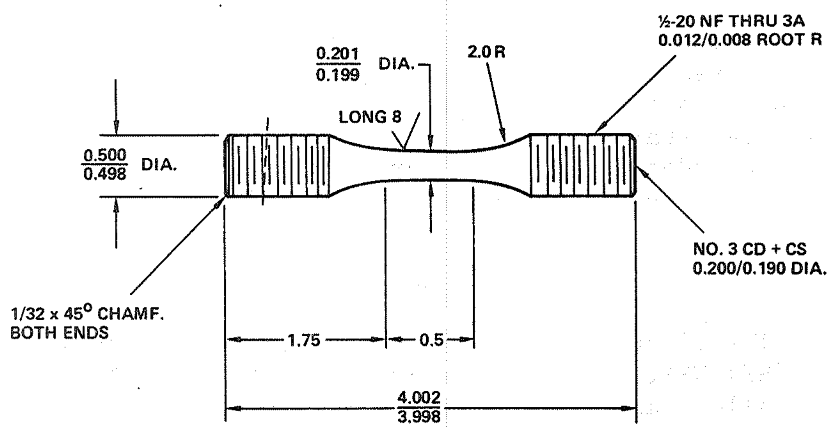


Fig. 1. Cylindrical Fatigue Test Specimen

Table 3. Baseline Fatigue Test Conditions

ALLOY	TEST TEMPERATURE		MAXIMUM STRESS	
	C	F	MPa	KSI
MAR-M246(Df)(DS)	843	1550	552 441 359	80 64 52
INCONEL 718	593	1100	662 524 441	96 76 64

These baseline tests of fatigue life to failure defined the fatigue-damage conditions for the fatigue rejuvenation testing. To test fatigue rejuvenation effects, specimens were initially damaged by cycling to 70 percent of the log mean value of the baseline fatigue life. Next, the planned rejuvenation processes were carried out, and finally, the fatigue-damaged rejuvenated specimens were tested to failure.

As a second method of preparing fatigue-damaged specimens for rejuvenation process testing, precracked specimens were prepared by creating a fatigue crack in an oversized, prenotched cylindrical specimen. The original prenotch was thereafter removed by machining the specimen to final size (Fig. 2). These specimens were used to test techniques for repair of existing fatigue cracks.

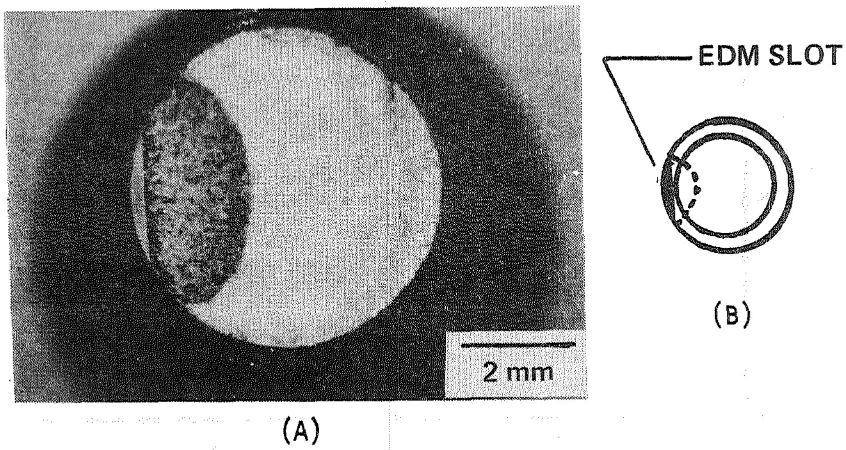


Fig. 2. (A) Heat-Tinted Area Indicates the Extent of the Fatigue Precrack Grown from the Notch. (B) As the Specimen is Machined to Final Dimensions, the Notch is Machined Away Leaving the Fatigue Precrack

At each specific stress level, statistical comparisons were made between the baseline data and the damaged, rejuvenation-processed material data using the statistical t-test (with all data transformed into log units) to assess the significance of differences between the two sets of data.

Results and Discussion

Figures 3 and 4 present the baseline fatigue lives for MAR-M246(Hf)(DS) and for Inconel 718.

MAR-M246(Hf)(DS) baseline fatigue fracture surfaces displayed several systematic features. At the higher stress levels, crack initiation was predominately at subsurface interdendritic porosity. Crack initiation and propagation were entirely Stage II, perpendicular to the principle stress. Figure 5 shows this initiation of interdendritic porosity and Stage II crack propagation.

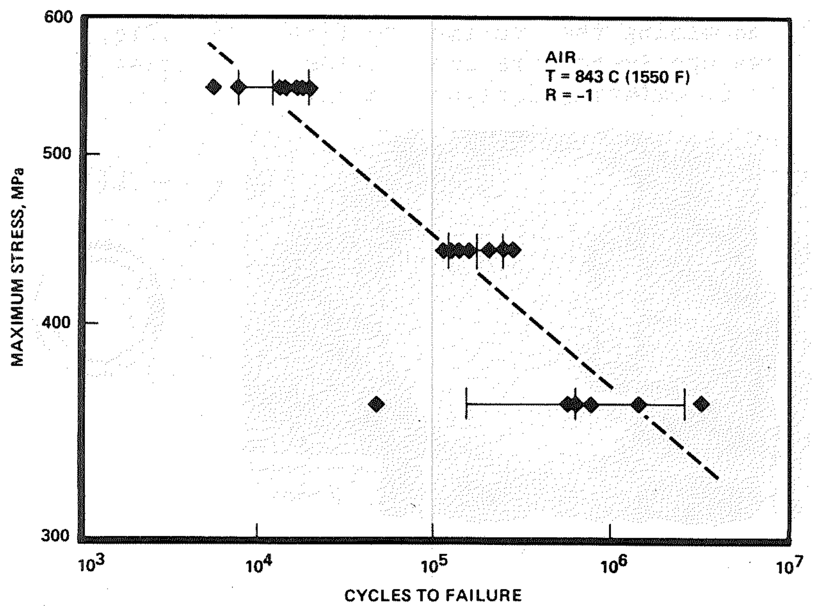


Fig. 3. MAR-M246(Hf)(DS) Baseline Fatigue Life

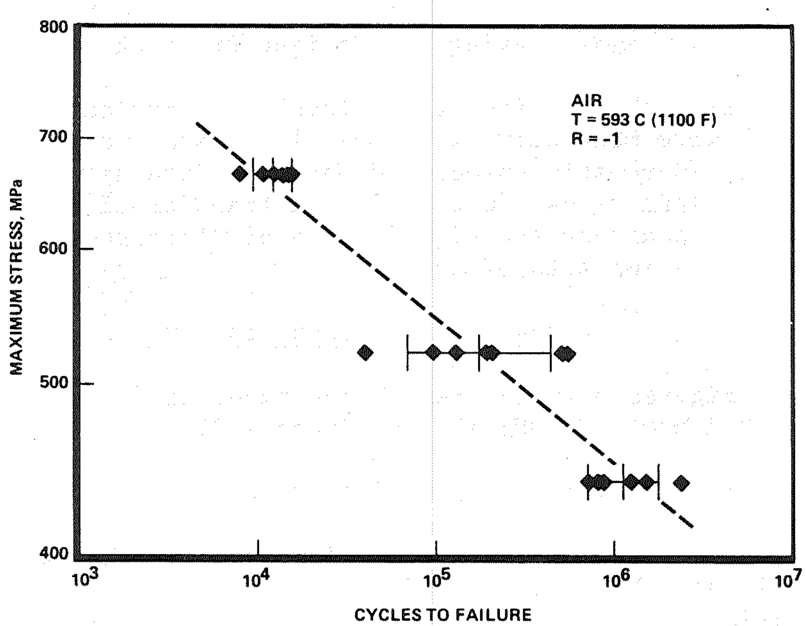
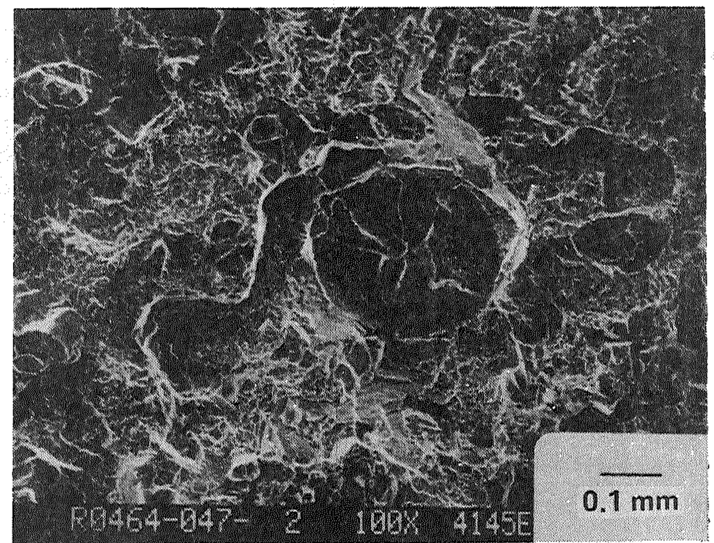
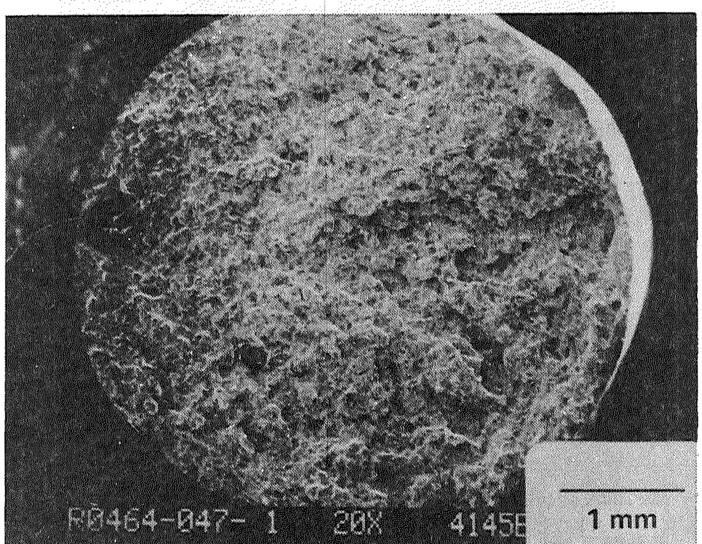


Fig. 4. Inconel 718 Baseline Fatigue Life



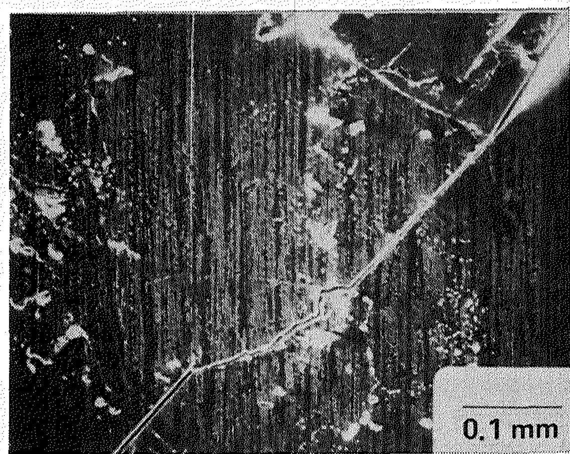
(A) CRACK INITIATION AT INTERDENDRITIC POROSITY



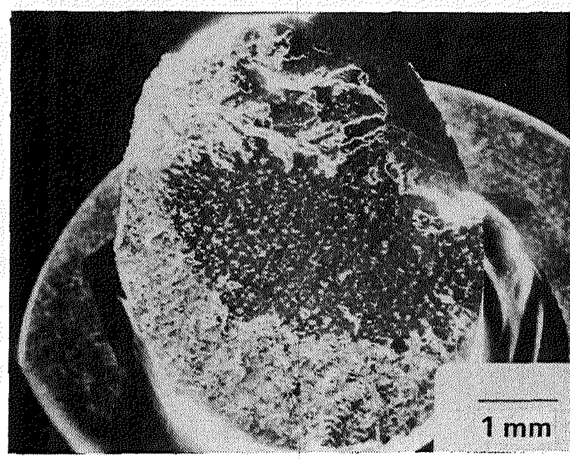
(B) STAGE II CRACK PROPAGATION

Fig. 5. Fatigue Fracture of MAR-M246(Hf)(DS) at a Maximum Stress of 552 MPa (80 ksi) at 843 C (1550 F) in Air at R = -1 (15,800 Cycles to Failure)

At the lower stress levels, initiation was predominately at the specimen surface. In several cases, carbides could be identified as probable initiation sites, and crack initiation and propagation were predominately Stage I, crystallographic. Figure 6 shows this crystallographic cracking at a surface carbide and the extensive crystallographic crack propagation.



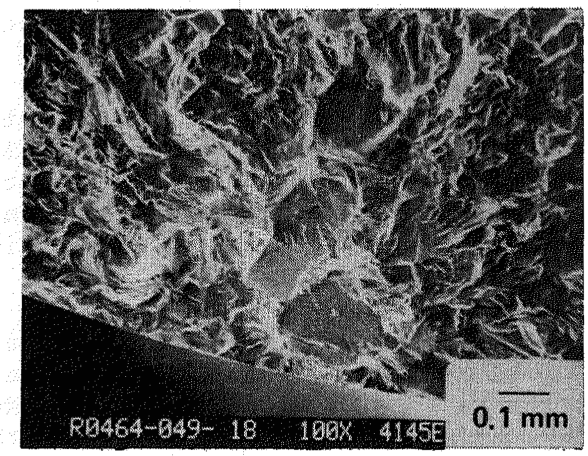
(A) SURFACE CARBIDE AT THE CRYSTALLOGRAPHIC CRACK



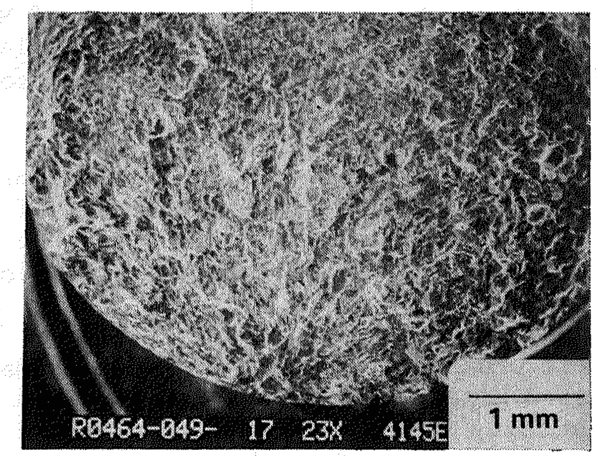
(B) STAGE I, CRYSTALLOGRAPHIC CRACK PROPAGATION

Fig. 6. Fatigue Fracture of MAR-M246(Hf)(DS) at a Maximum Stress of 359 MPa (52 ksi) (611,400 Cycles to Failure)

Inconel 718 baseline fatigue fracture surfaces, as shown in Fig. 7, generally displayed near-surface or surface crack initiation. The transgranular propagation mode was a mixture of Stage I and Stage II. No systematic variations as a function of stress level were noted in fatigue crack initiation or propagation mode.



(A) NEAR-SURFACE CRACK INITIATION



(B) MIXED STAGE I AND STAGE II TRANSGRANULAR CRACK PROPAGATION

Fig. 7. Fatigue Fracture Surface for Inconel 718 at a Maximum Stress of 524 MPa (76 ksi) (515,000 Cycles to Failure)

Rejuvenation of Fatigue-Damaged Material

The approach for evaluating the fatigue rejuvenation processes was to prepare fatigue-damaged specimens, apply to rejuvenation process, and test the remaining fatigue life. Specimens were fatigue to 70 percent of the mean log fatigue life at the same test conditions as in the baseline tests. Next, specimens were fluorescent penetrant inspected, and any with detectable surface-connected fatigue cracks were removed from the group of specimens. Typically, approximately 5 percent of the specimens either failed during this initial fatigue exposure or failed to pass the fluorescent penetrant inspection. Remaining specimens were processed through the candidate rejuvenation technique, then tested to failure, again at the same fatigue conditions as the baseline test.

Table 2 presents the rejuvenation process details for MAR-M246(Hf)(DS) and for Inconel 718. The reheat treatment schedules are identical to the standard initial heat treatments for the two alloys. In the case of MAR-M246(Hf)(DS), the HIP schedule was chosen based on microstructural studies that indicated significant carbide morphological changes during exposure of MAR-M246 (Hf)(DS) to temperatures in the vicinity of 1149 C (2100 F) for 4 hours. The decision was made to HIP below that temperature.

In the case of Inconel 718, the HIP temperature was chosen based on studies of grain growth of wrought Inconel 718. This HIP temperature is near the maximum that may be utilized without producing significant grain growth.

Figure 8 presents results for fatigue-damaged reheat-treated MAR-M246(Hf)(DS) and for virgin heat treated MAR-M246(Hf)(DS). All comparisons are between the numbers of cycles to failure following rejuvenation (over and above any preceding damage cycles) and the baseline number of cycles to failure; therefore, if fatigue lives were completely rejuvenated, the two sets of data would be not significantly different.

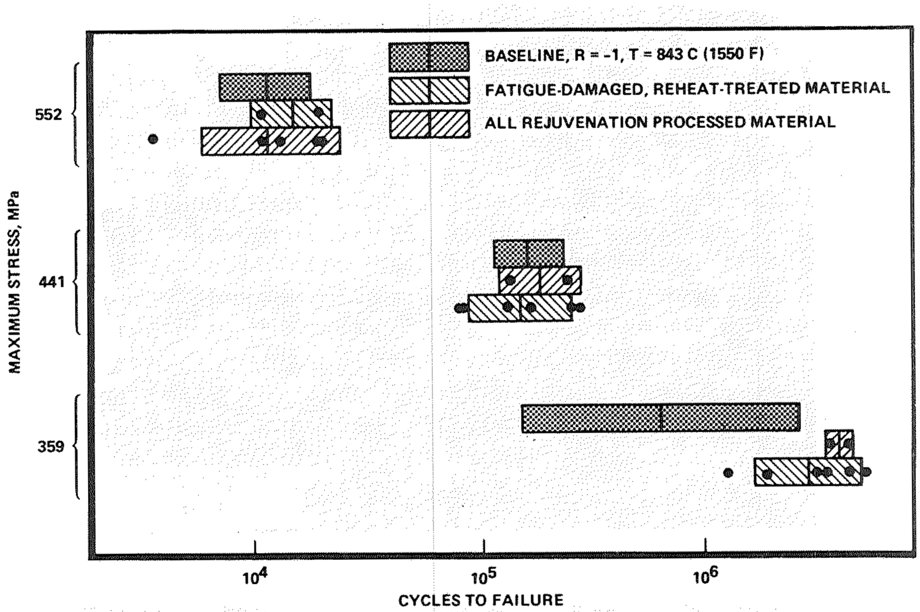
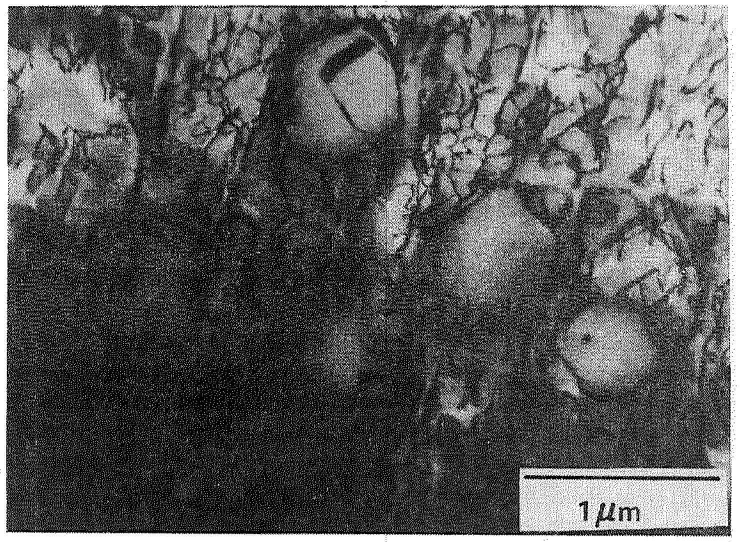


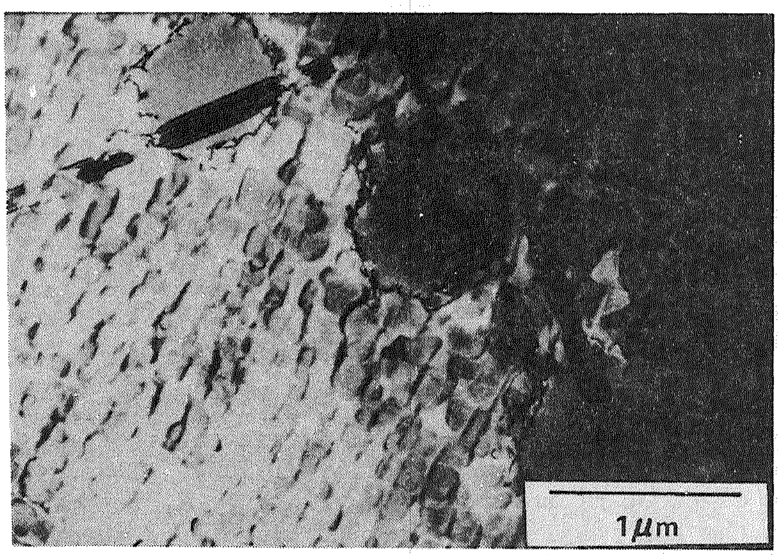
Fig. 8. Rejuvenation of Fatigue-Damaged MAR-M246(Hf)(DS)

At stress levels of 552 MPa (80 ksi) and 441 MPa (64 ksi), the lives of damaged rejuvenation-processed specimens are equivalent to the baseline lives, indicating complete rejuvenation. In the case of the 359 MPa (52 ksi) results, the lives following fatigue damage and rejuvenation are actually significantly higher than the baseline fatigue lives.

Reheat treatment, in this case, was shown to be very effective as a means of rejuvenating the fatigue life of fatigue-damaged MAR-M246(Hf)(DS). Transmission electron microscopy, shown in Fig. 9. revealed that the high dislocation density developed during fatigue exposure is annealed out during reheat treatment. The fatigue damage developed in the vicinity of carbides during fatigue exposure was also evident in the TEM observations (Fig. 10), and further TEM study indicated that some of this localized damage remained following reheat treatment.



(A)



(B)

Fig. 9. MAR-M246(Hf)(DS) TEM Micrographs Showing (A) High Dislocation Density Developed During Fatigue Damage and (B) Decreased Dislocation Density and Increase in Stacking Faults and Dislocations at Precipitate Interfaces After Reheat Treatment

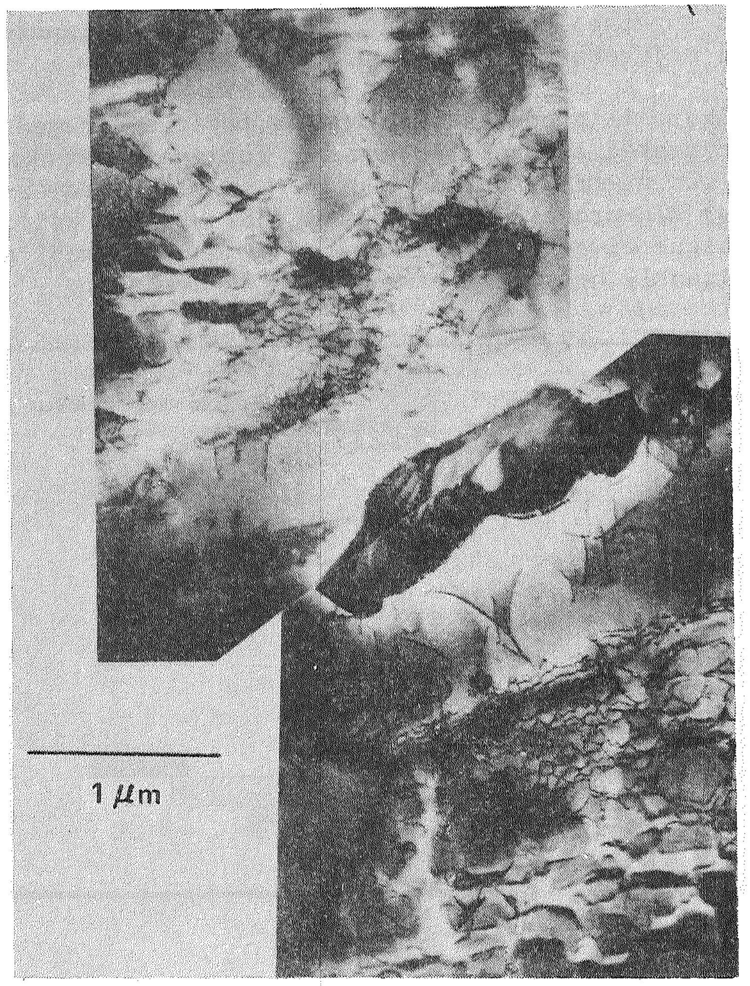


Fig. 10. TEM Micrograph of Fatigue Damage in MAR-M246(Hf)(DS) in the Vicinity of a Tungsten Carbide. Fatigue Exposure: 359 MPa (52 ksi), R = -1, 843 C (1550 F), 442,000 Cycles (70 Percent of Mean Life)

HIPing of fatigue-damaged MAR-M246(Hf)(DS) at 1112 C (2050 F)/3 hours/207 MPa (30 ksi) followed by reheat treating had no additional beneficial effect over reheat treatment alone. Both reheat treatment results and HIP plus reheat treatment results are grouped together and plotted on Fig. 8 and designated as "all rejuvenation processed material."

Figure 11 presents results for fatigue-damaged, reheat-treated Inconel 718 and for fatigue-damaged HIPed, reheat-treated Inconel 718. In all cases except for HIP-processed material at 662 MPa (96 ksi), the fatigue lives following rejuvenation treatment are significantly below the baseline fatigue lives.

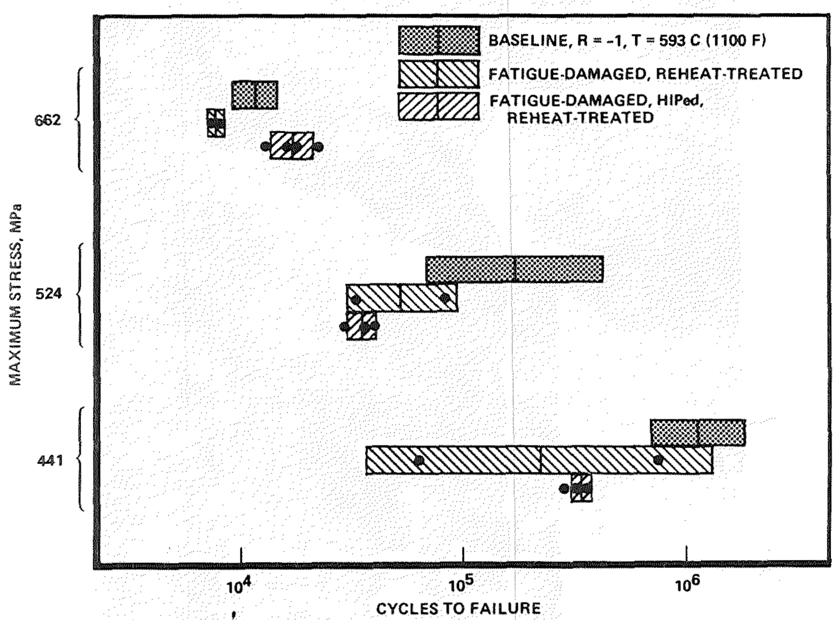


Fig. 11. Rejuvenation of Fatigue-Damaged Inconel 718

Rejuvenation of Precracked Material

A number of precracked specimens were prepared by propagating fatigue cracks in notched, oversized specimens, then machining to the final specimen diameters, leaving sharp surface cracks at the midpoint of the gage length in the cylindrical specimens.

Specimens were rejuvenated by electron-beam welding to seal the crack opening, HIPing at those conditions listed in Table 2 to heal the crack, and reheat treating to restore the precipitate microstructure (Fig. 12).

Fig. 12. Inconel 718 that has been Precracked, EB Welded, HIPed, and Reheat Treated. The EB Weld is at the Top of the Photograph. A Trace of the Healed Crack is Evident in the Center.

For Inconel 718, the precracked, rejuvenated processed material lives, as shown in Fig. 13, approach, but do not equal, the baseline Inconel 718 fatigue lives, indicating partial recovery of fatigue damage.

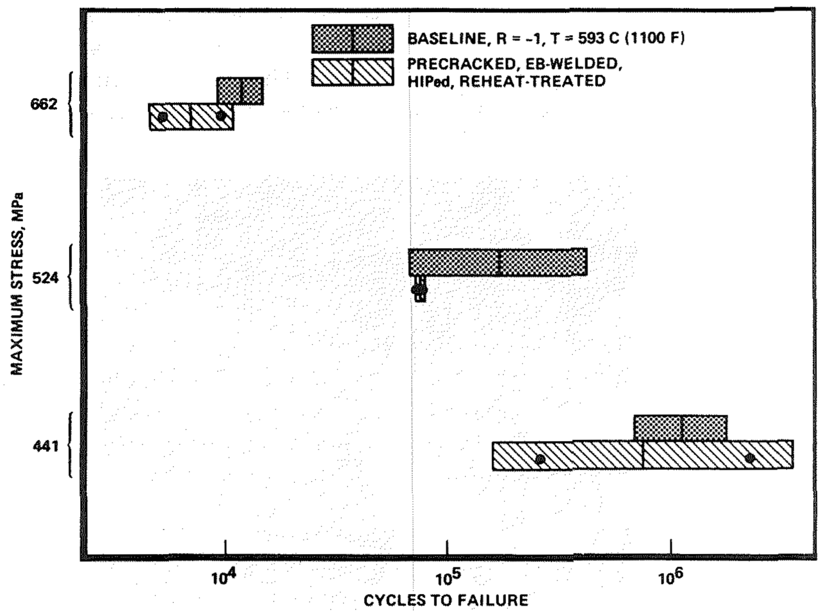


Fig. 13. Rejuvenation of Fatigue Precracked Inconel 718

Conclusions

1. Reheat treatment of fatigue-damaged MAR-M246(Hf)(DS) can remove previous fatigue damage and rejuvenate fatigue life.
2. HIPing of MAR-M246(Hf)(DS) at 1121 C (2050 F)/3 hours/207 MPa (30 ksi) prior to reheat treatment provides no additional beneficial effect.
3. Inconel 718 containing a single, large fatigue precrack may be partially rejuvenated by electron beam welding and HIPing to close off and heal the crack, followed by reheat treatment.
4. Attempts to rejuvenate fatigue-damaged Inconel 718 by reheat treatment or by HIPing and reheat treatment were unsuccessful.

These conclusions are based on progress to date under an on-going program. Continuing work is directed at obtaining further experimental data to increase the level of confidence in the conclusions, and at obtaining more detailed understanding of the processes through further microstructural and fractographic examination.

Acknowedgements

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