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Effects of Thermal and Thermo-Mechanical Treatments on the Mechanical Properties of Centrifugally Cast Alloy 718

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The ability of thermal and thermo-mechanical treatments to impart improved microstructural and mechanical properties to nickel-base engine components has been investigated for centrifugally cast alloy 718. The effects of hot isostatic pressing (HIP) or thermal homogenizing treatments on the tensile, creep and fatigue properties of cast alloy 718 were evaluated at 427, 538 and 649°C. The results indicated that either HIP or thermal homogenizing processing of the as-cast alloy, followed by an aging treatment, produced improved fatigue crack propagation resistance when compared on the basis of stress intensity factor range. Creep life and ductility were reduced by both processing treatments but to a lesser degree by the homogenizing treatment. The mechanical behavior of the HIP processed and homogenized material is discussed on the basis of microstructural changes produced in the as-cast alloy by the processing treatments. (Keywords.)

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EFFECTS OF THERMAL AND THERMO-MECHANICAL TREATMENTS ON THE MECHANICAL PROPERTIES OF CENTRIFUGALLY CAST ALLOY 718

INTRODUCTION

Modern casting methods have been successfully used to improve the mechanical properties of nickel-base superalloys cast-to-shape. The success of these techniques has suggested that the improved casting methods have the potential to produce large cast section sizes whose mechanical properties are comparable to forged and machined components, but with substantial savings in material and manufacturing costs.

Recent research at NRL has been directed toward the determination of the mechanical properties and microstructure of centrifugally cast alloy 718. In Phases I & II of the program (1), it was shown that the centrifugal casting process produced a porosity-free microstructure with relatively uniform chemistry and tensile properties. Fatigue properties were the primary concern for this compressor application and the results indicated that the fatigue crack propagation performance of the cast alloy 718 was similar to that for wrought alloy 718 at test temperatures of 427, 538 and 649°C (800, 1000 and 1200°F). Although the centrifugal casting process resulted in acceptable creep and fatigue properties, the microstructure exhibited deleterious segregation of the solute elements to Laves, interdendritic and carbide phases. Preliminary experiments with hot isostatic pressing (HIP) of the cast alloy indicated that the interdendritic segregation and Laves structure could be effectively solutioned and suggested that thermo-mechanical treatments could lead to improved mechanical properties.

This report presents work conducted in Phases III & IV of the program and describes the influence of thermo-mechanical treatments on the fatigue and creep properties of centrifugally cast alloy 718. The results indicate that at 427, 538 and 649°C substantial improvements in fatigue crack propagation resistance can be realized by HIP processing or thermal homogenization of the as-cast alloy before aging. Compared to as-cast creep properties, creep-rupture life was reduced in the HIP processed alloy at 649°C, and to a lesser extent also reduced in the homogenized material at 538°C.

EXPERIMENTAL PROCEDURE

The chemical composition and heat treatment schedule of the as-received cast alloy 718 discs are given in Table 1. Additional details regarding the manufacture and the results of chemical and microstructural analyses of the discs has been reported previously (1). The as-cast alloys were given either a thermal or thermo-mechanical treatment designed to improve the

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TABLE 1

Chemical Composition and Heat Treatment of Cast Alloy 718

Composition (wt. %)

C 0.056	Cr 19.60	Co 0.10
Mn 0.010	Ni 53.40	Fe Bal.
P 0.004	Ti 1.05	Cu 0.010
S 0.004	Al 0.48	B 0.003
Si 0.010	Mo 3.09	Nb/Ta 5.22

Aging Treatment

Heat to 718°C (1325°F), hold 8hr, furnace cool at 56°C (100°F)/hr to 621°C (1150°F), hold 8 hr, air cool.

mechanical properties of the casting by the re-solutioning of the interdendritic and Laves phases. One group of specimens was HIP processed at 1200°C (2192°F) for four hours at 10.6 MPa (15 ksi) while the other was thermally homogenized at 1143°C (2089°F) for two hours. Both groups of specimens were then cooled rapidly from the solutioning temperature to prevent the reprecipitation of the Laves phase. All specimens were aged using the same two-step treatment shown in Table 1 before testing.

The mechanical equipment, test procedures and specimens employed in the present work are similar to those of earlier phases of this program and have been described in detail (1). For the present phase of the program, tests were conducted in air at 427, 538 and 649°C on material cast at 50 and 200 rpm. Tensile tests were conducted with a crosshead speed of 1.27 X 10^{-2} cm/min (5 X 10^{-3} in/min) and compact tension fatigue tests were conducted at a stress ratio of 0.05 at 0.17 hz. The load axes of the tensile, creep and fatigue specimens were oriented either perpendicular or parallel to the radial direction of the cast disc. Shear punch tests were employed to survey changes in strength and ductility produced by different thermal/thermo-mechanical treatments applied to the as-received alloy. The shear punch technique (2) measures the yield and ultimate load developed during the punching of a 3 mm (0.118 in.) disc from a thin foil. These shear values are correlatable to tensile yield and ultimate strengths and provide a simple means of determining changes in mechanical properties produced during thermal processing.

Microstructural features of the casting and details of the fracture processes were investigated using conventional optical and electron microscopic techniques. Sectioned and polished metallographic samples were etched in an $HF:HNO_3:H_2O$ solution of the volume ratio 1:2:8.

RESULTS

The effect of HIP processing and thermal homogenization was examined by comparing the microstructures and the tensile, creep and fatigue properties of the cast alloy before and after these treatments.

Hot Isostatic Pressing

The purpose of the HIP processing was to remove any porosity and to provide for re-solutioning of the interdendritic solute segregation and Laves phases present in the as-cast alloy. Although no measurable densification was found, the comparison of the as-cast and HIP processed microstructures in Fig. 1 indicated that HIP processing reduced interdendritic segregation and Laves phases. The interdendritic segregation (hazy network) and Laves phase (large gray blocky precipitates) in Fig. 1a have been shown (1) to be associated with the crack path in post-test creep and fatigue specimen examinations. Figure 1b shows that HIP processing has effectively reduced the interdendritic and Laves structure with the retention of most of the carbide (white precipitate) population.

The tensile and creep-rupture properties of the HIP processed alloy were characterized at 649°C for cast mold speeds of 50 and 200 rpm. These results are summarized in Tables 2 and 3 along with previous results (1) for the as-cast material. The tensile results in Table 2 show that HIP

TABLE 2

Cast Alloy 718 Tensile Properties at 649°C

Mold Speed/ Specimen Orientation	0.2% Yield Strength (MPa)		Ultimate Strength (MPa)		Total Elongation (%)	
	As-Cast	HIP	As-Cast	HIP	As-Cast	HIP
50RPM/Transverse	618	614	694	627	5.1	2.1
50RPM/Radial	601	645	696	661	6.6	4.5
200RPM/Transverse	612	646	705	674	6.4	3.6
200RPM/Radial	601	632	688	661	4.2	4.1

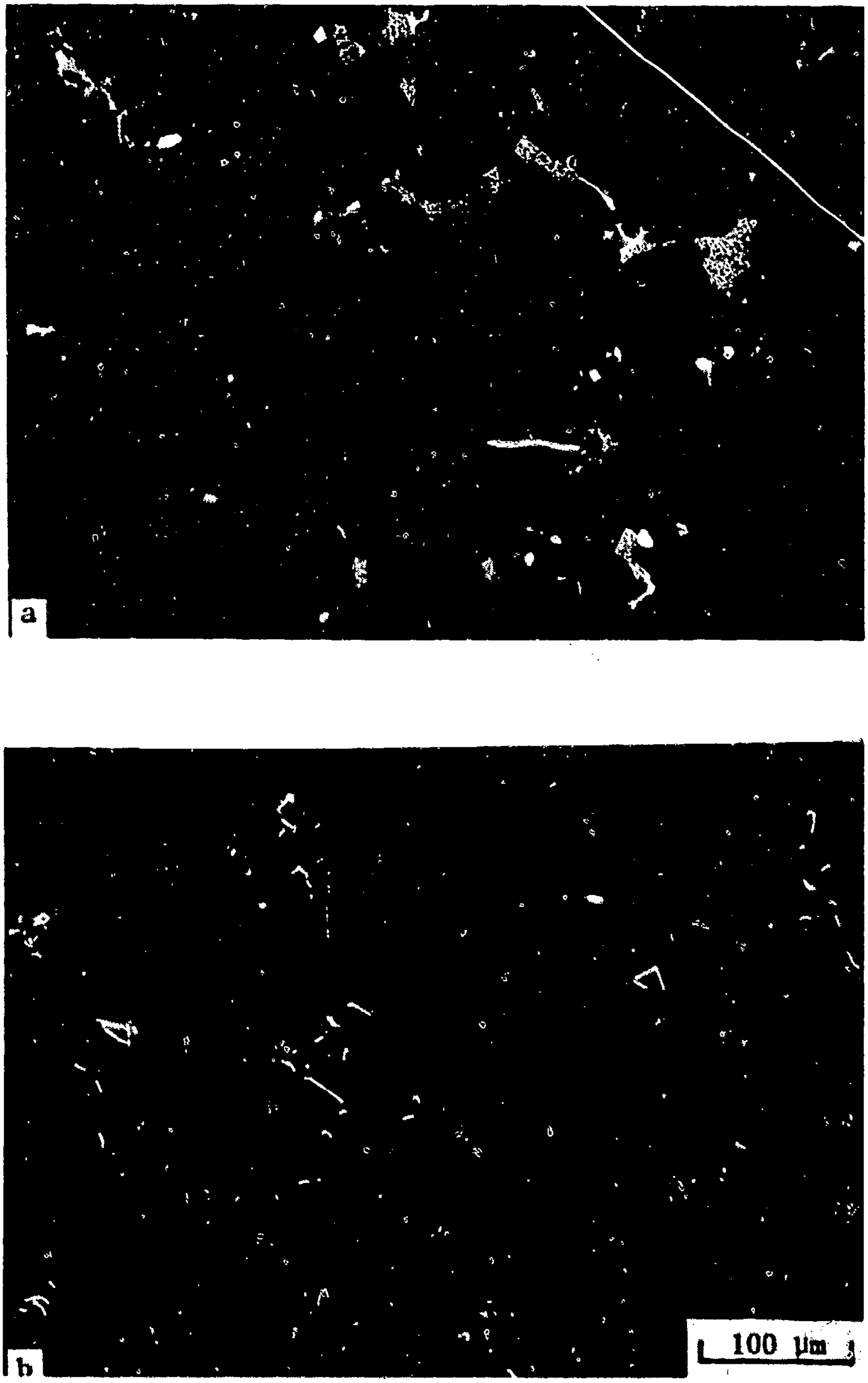

Fig. 1 — Backscatter electron micrographs of duplex aged cast alloy 718 microstructure: (a) as-c condition; (b) HIP processed condition.

processing generally increased the tensile yield strength at 649°C when compared with the as-cast material. However, the ultimate tensile strength and ductility at 649°C were reduced by HIP processing. In Table 3, the creep-rupture results show that the creep life of the HIP processed alloy and the rupture strain were considerably reduced at 649°C when compared to the as-cast material. Creep stresses were selected on the basis of a design criteron of 85% of yield stress. The combination of increased yield strength but decreased ultimate strength in the HIP processed alloy resulted in poor creep-rupture properties as compared to the as-cast material.

TABLE 3

Cast Alloy 718 Creep Properties at 649°C

Mold Speed/ Specimen Orientation	Creep Stress* (MPa)		Rupture Life (Hours)		Rupture Strain (%)	
	As-Cast	HIP	As-Cast	HIP	As-Cast	HIP
50RPM/Transverse	525	521	147	32.0	6.9	0.3
50RPM/Radial	512	548	145	2.1	4.3	0.1
200RPM/Transverse	521	549	250	1.0	8.3	0.2
200RPM/Radial	511	545	235	0.5	4.1	0.2

*85% of tensile yield stress

The fatigue crack propagation behavior of the HIP processed cast alloy was determined at 427 and 649°C. These results are compared with the as-cast fatigue crack propagation results for 50 and 200 rpm mold speeds in Figs. 2 and 3. The results show a marked improvement in fatigue crack propagation resistance after HIP processing when compared on the basis of stress intensity factor range. HIP processing produced the largest improvement in the fatigue properties of the 50 rpm alloy, which, in the as-cast condition, exhibited reduced crack propagation resistance compared with the 200 rpm alloy. In addition, the comparison of these results with those of conventional wrought 718 alloys (3,4) reveals that the crack propagation resistance of HIP processed cast alloy 718 was superior at the temperatures of this study.

Examinations of the fracture surfaces of fatigue and creep specimens clearly showed the effect of HIP processing on subsequent failure processes. In Fig. 4, fatigue fracture surfaces of as-cast and HIP processed alloy 718 are compared at 427 and 649°C. It is evident that for these temperatures and material conditions, fatigue crack growth was strongly crystallographic and strongly affected by microstructure. The fatigue fracture surfaces were formed predominantly by cyclic plastic shear deformation. However, for the as-cast condition, brittle fractures occured across the Laves phases as

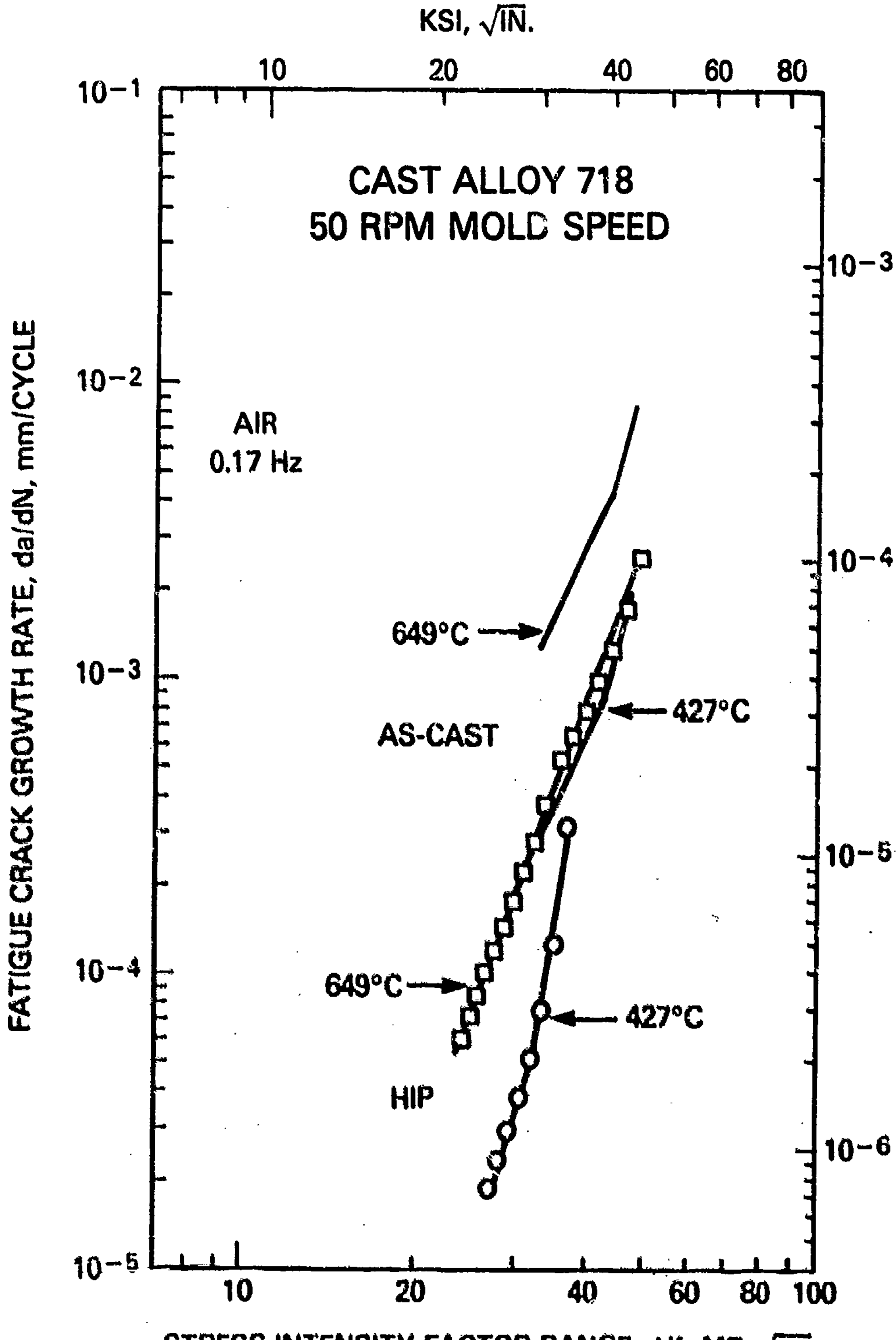

Fig. 2 — Fatigue crack propagation performance of HIP processed and as-cast alloy 718 (50 rpm mold speed) in air at 0.17 Hz at 427 and 649°C. The specimens were oriented such that crack growth was in a plane perpendicular to the radial direction of the casting.

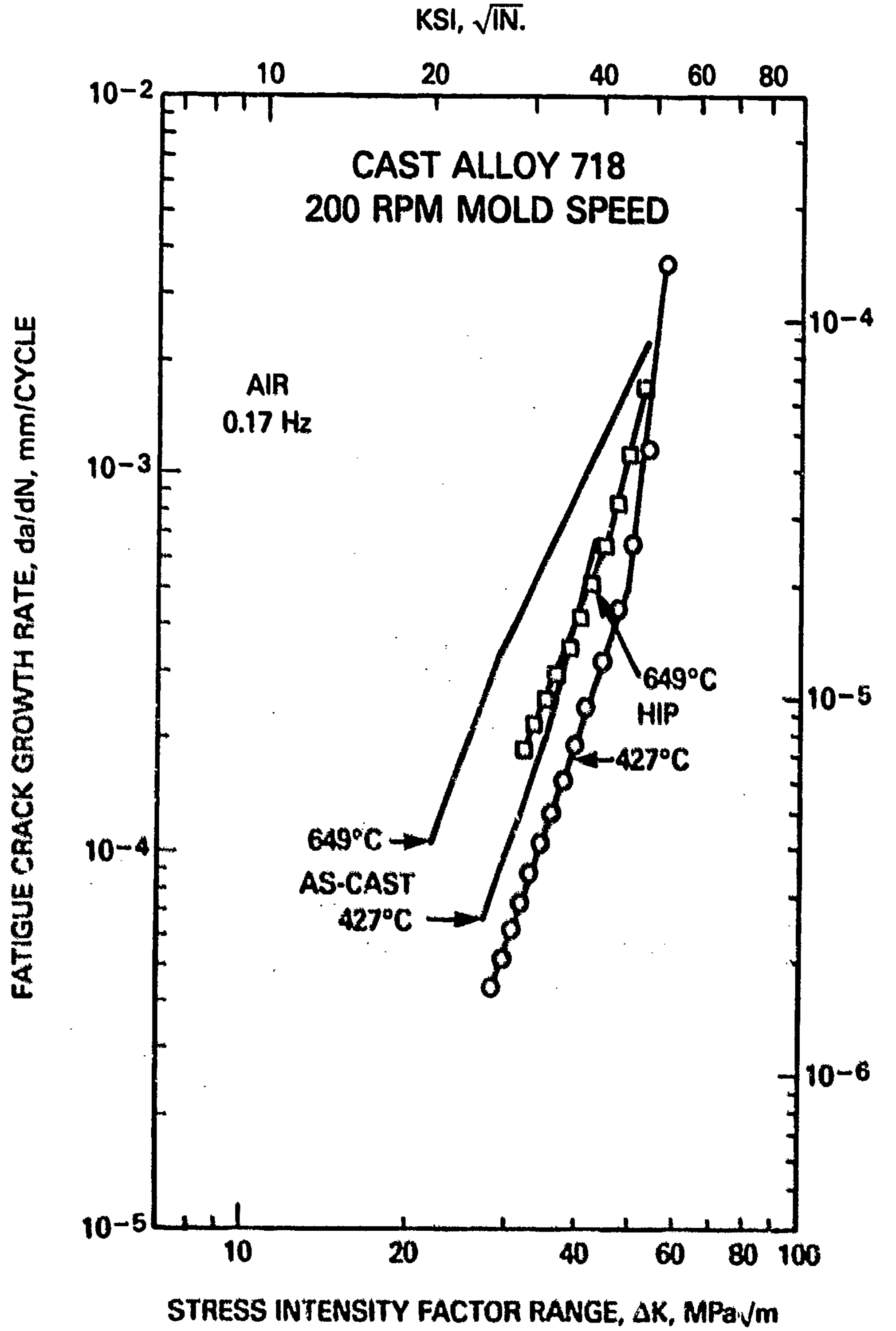

Fig. 3 — Fatigue crack propagation performance of HIP processed and as-cast alloy 718 (200 rpm mold speed) in air at 0.17 Hz at 427 and 649°C. The specimens were oriented such that crack growth was in a plane perpendicular to the radial direction of the casting.

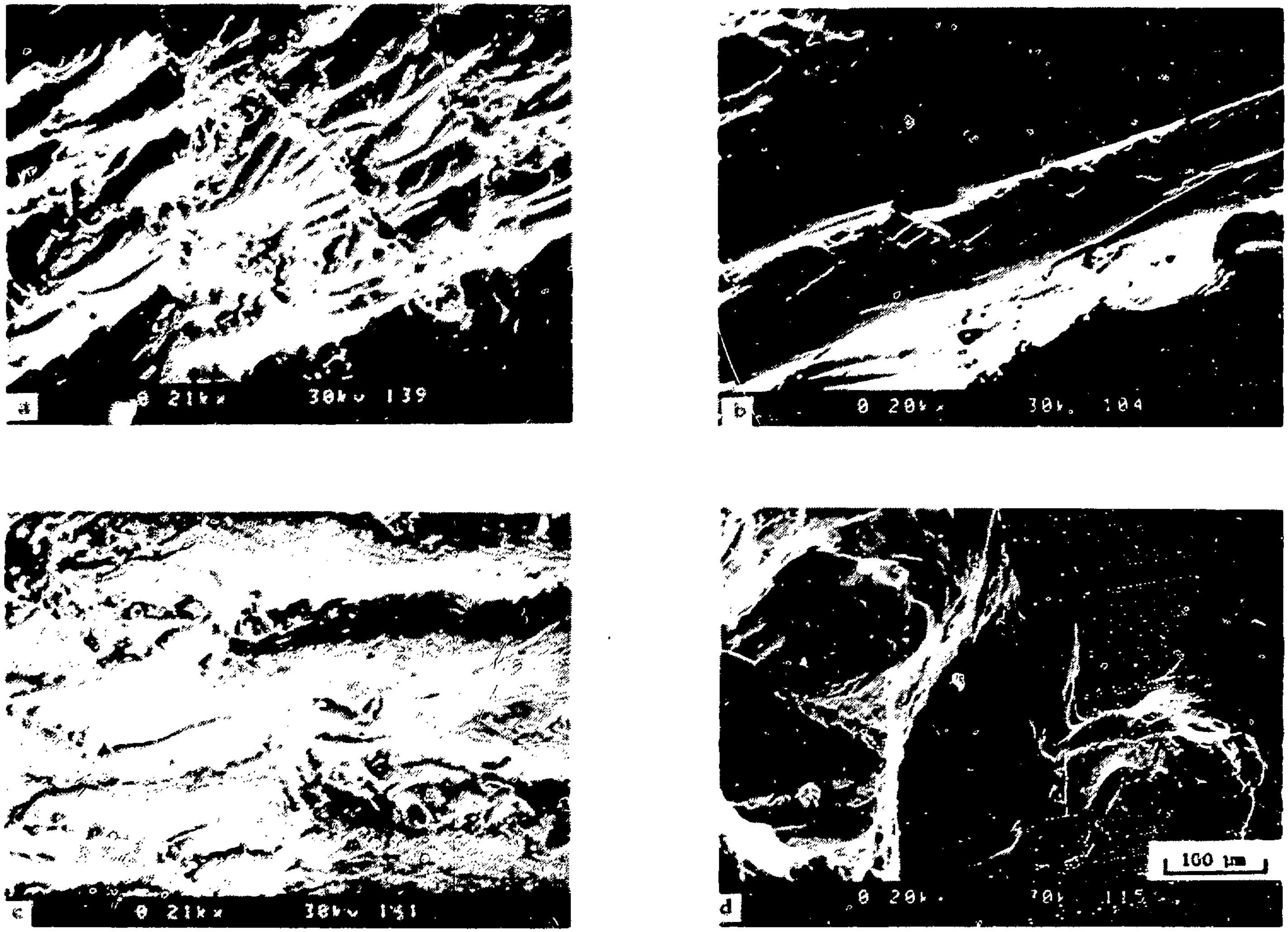

Fig. 4 — SEM fracture surface micrographs of alloy 718 cast at 200 rpm and fatigue tested at 427 and 649°C in the as-cast and HIP processed condition: (a) as-cast, 427°C; (b) HIP processed, 427°C; (c) as-cast, 649°C; (d) HIP processed, 649°C.

shown in Fig. 4a and 4c. In the as-cast alloy, cracks grew along crystallographic shear planes until they intersected the Laves structure and were reinitiated, whereas, in the HIP processed condition, Fig. 4b and 4d, cracks grew unrestricted along favorably aligned dendrite arms. A similar coarsened fracture surface morphology was observed for creep specimens tested in the HIP processed condition. The fracture surface contained areas of dimpled rupture suggesting that creep cracks grew along dendrite arms until the specimen failed through tensile overload.

Thermal Homogenization

Because the as-cast alloy 718 was found to be fully dense, a thermal treatment schedule was developed which would, as with the HIP process, improve the microstructural properties of the casting by dissolution of the interdendritic and Laves phases. The homogenized and aged microstructure is shown in Fig. 5 and is similar to the microstructure produced by HIP processing, Fig. 1b. A limited number of tensile, creep and fatigue specimens were homogenized and tested to verify that the improvement in fatigue crack growth resistance was primarily due to the thermal component of the HIP process.

Comparison of the as-cast and homogenized alloy fatigue results indicated that the homogenizing heat treatment is also effective in reducing fatigue crack growth rates, as shown in Fig. 6 for a test temperature of 538°C. The magnitude of the improvement in crack propagation resistance was similar to that achieved at 427 and 649°C by HIP processing. The fatigue fracture surface and section view of the fatigue crack are shown in Fig. 7 for the homogenized alloy tested at 538°C. In Fig. 7a, the fatigue fracture surface morphology for the homogenized condition is shown to be similar to that of the HIP processed condition, Fig. 4b and 4d, at 427 and 649°C. As with the HIP processed alloy, the specimen failed by a plastic shear process with the main crack growing unimpeded along dentrite arms as shown in Fig. 7b.

The creep properties of cast 718 at 538°C are reported in Table 4 for the alloy in the as-cast and homogenized conditions. Creep evalutions conducted on the homogenized material for creep stresses equal to those of previous as-cast tests for comparable mold speed/orientations resulted in similar creep behavior for the 50 rpm casting but with reduced properties for the 200 rpm casting. Although no direct comparison between the creep properties of the HIP processed and homogenized alloy conditions can be made, the creep life and ductility for the homogenized alloy at 538°C was superior to that for HIP processed alloy at 649°C for creep stresses determined on the basis of fraction of yield strength. Also, when compared on the basis of fraction of yield strength, the homogenizing treatment reduces, although not to the extent of HIP processing, the creep properties of the as-cast alloy.

The relationships between yield point load and maximum load in the shear punch test with that in a tensile test were determined experimentally at room temperature for the as-cast and HIP processed conditions. Typical load-displacement curves for the shear punch test are shown in Fig. 8 for the 200 rpm material. The curves have been normalized on the basis of thickness in order to compare the flow properties of the cast alloy as a

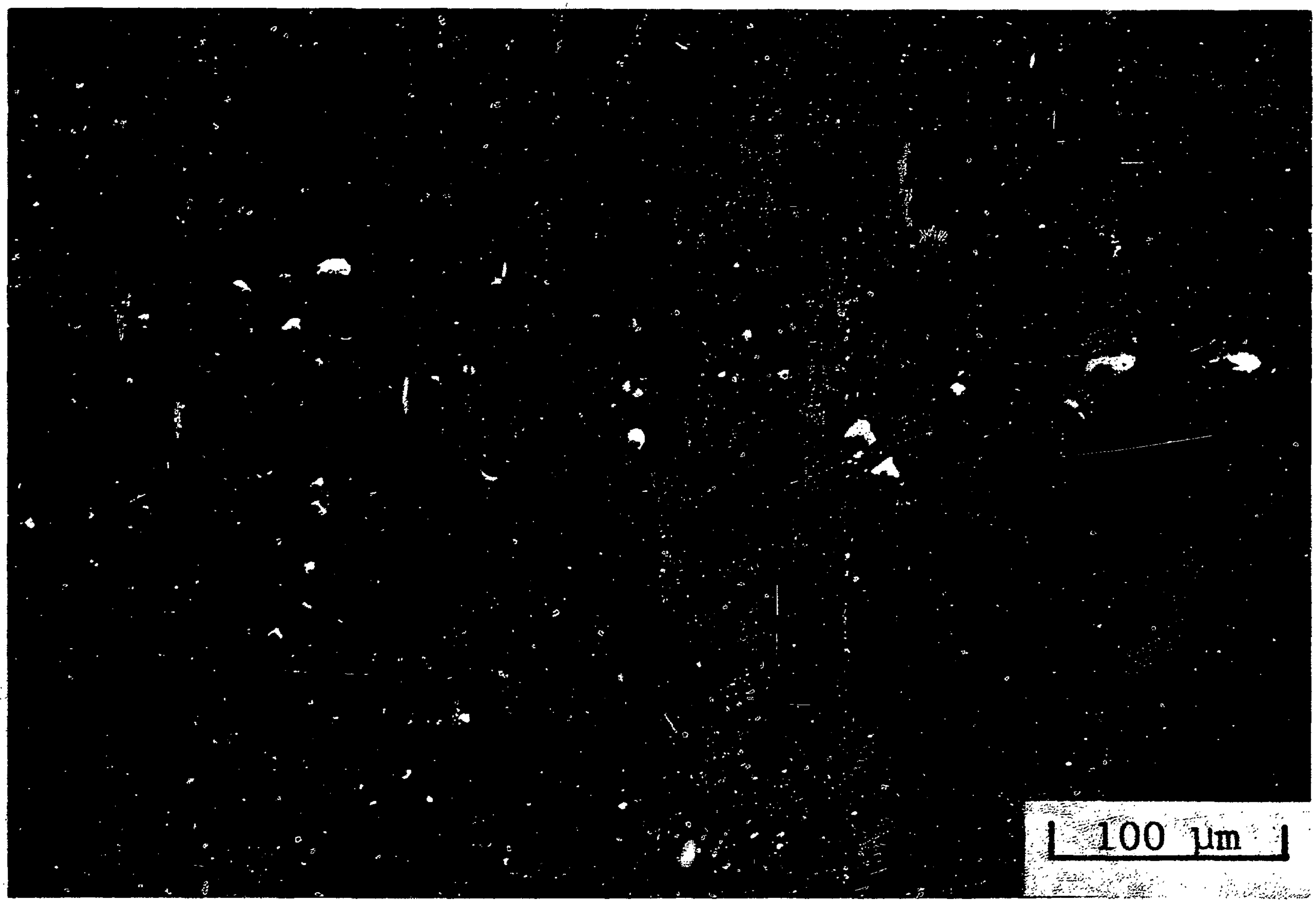

Fig. 5 — Backscatter electron micrograph of cast alloy 718 microstructure following thermal homogenization and duplex aging.

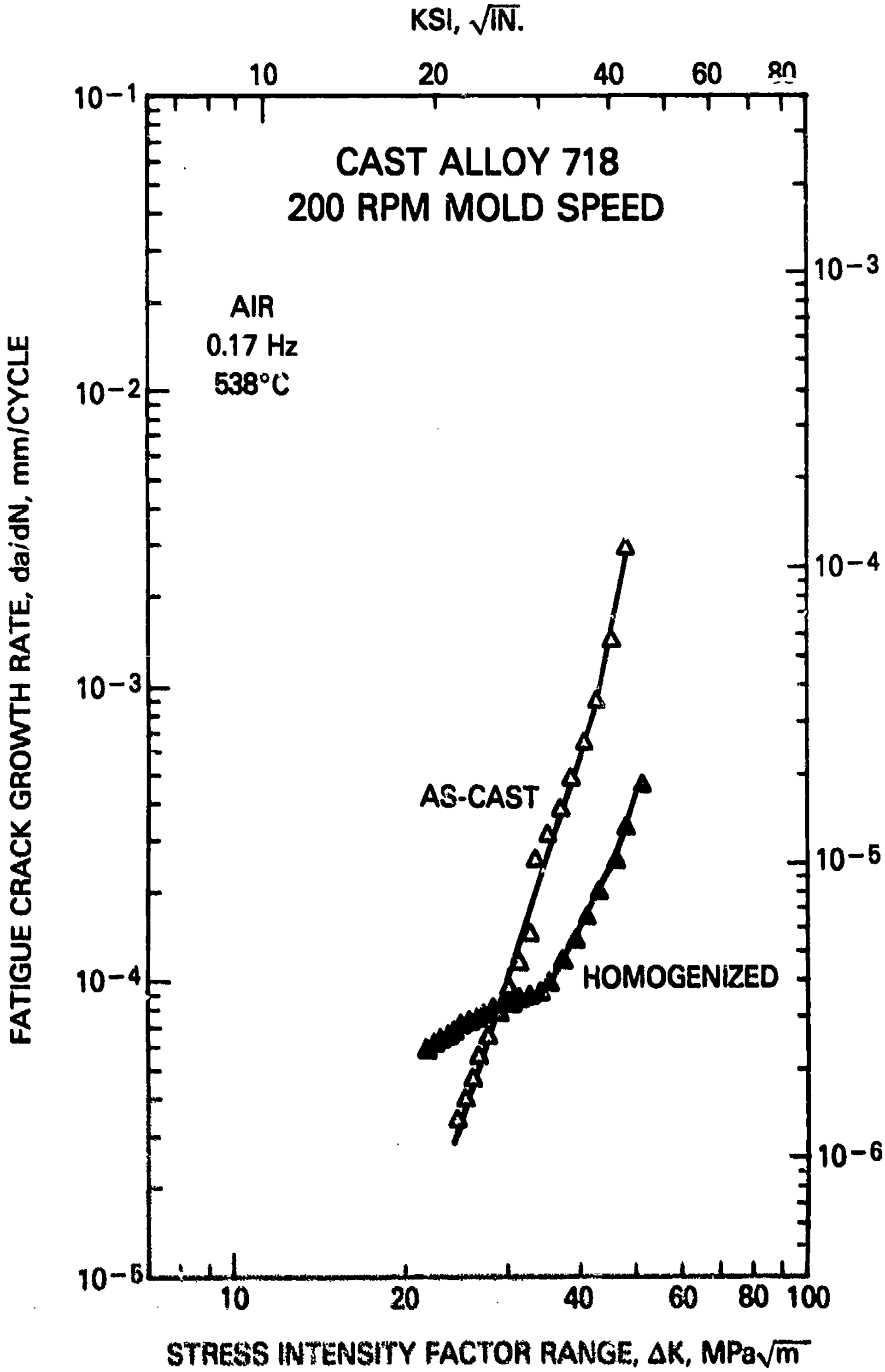

Fig. 6 — Fatigue crack propagation performance of thermally homogenized and as-cast alloy 718 (200 rpm mold speed) in air at 0.17 Hz at 538°C. The specimens were oriented such that crack growth was in a plane perpendicular to the radial direction of the casting.

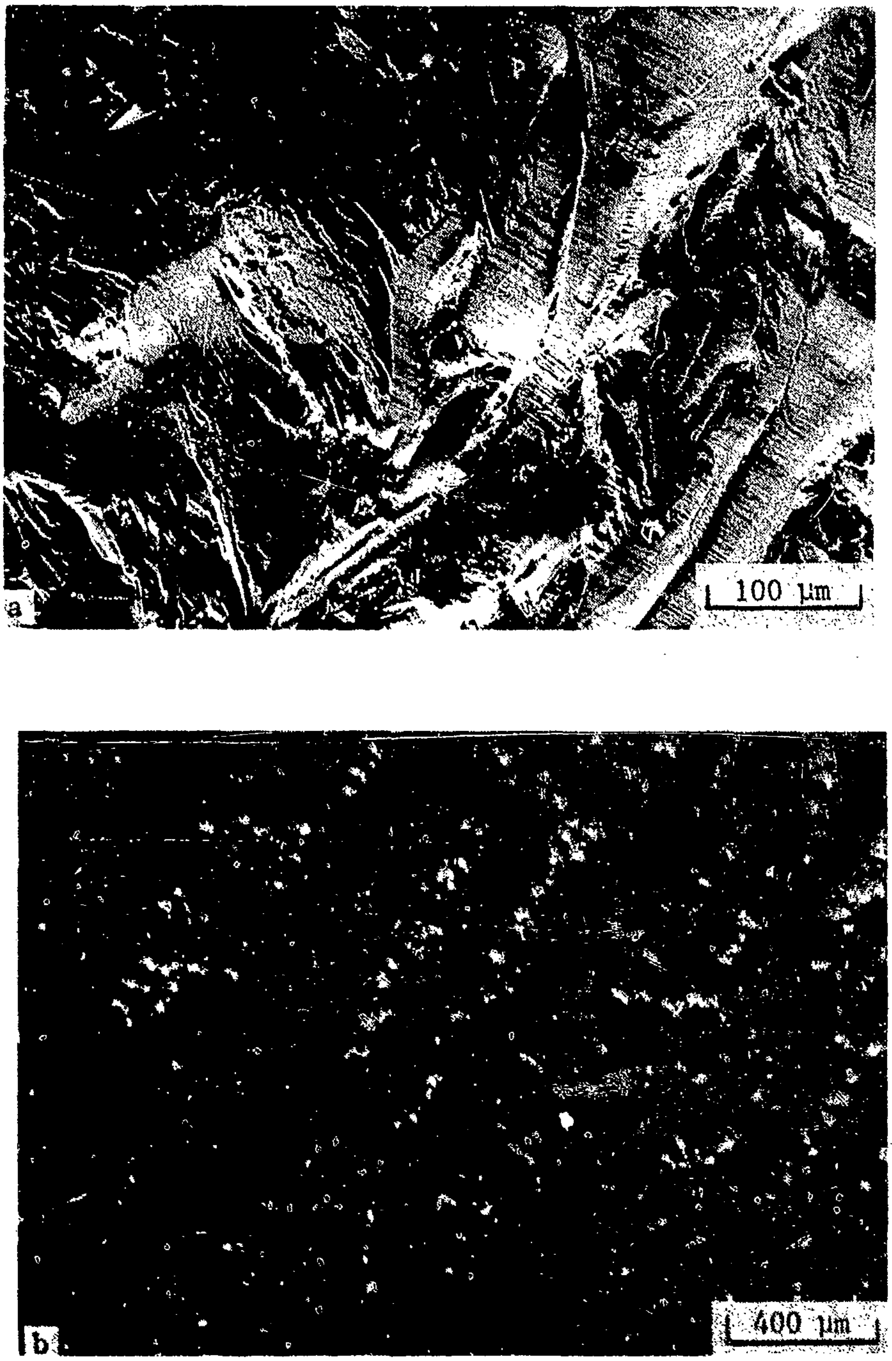

Fig. 7 — Fracture surface and section view micrographs of alloy 718 cast at 200 rpm and fatigue tested at 538°C: (a) fracture surface; (b) backscatter electron micrograph of crack section.

TABLE 4

Cast Alloy 718 Creep Properties at 538°C

Mold Speed for Radial Specimen Orientation	Creep Stress (MPa)		Rupture Life (Hours)		Rupture Strain (%)	
	As-Cast	Homo	As-Cast	Homo	As-Cast	Homo
50 RPM	611	611	1000	1000	0.3*	0.3*
50 RPM		692		35		2.8
200 RPM	624	624	1000	638	0.3*	2.2

*Creep strain after 1000 hours without specimen failure

function of alloy condition. Examination of Fig. 8 reveals that HIP and homogenization processing of as-cast alloy 718 increased the yield point load and the maximum load. Aging the as-cast alloy for 1000 hours at 649°C produced minimal change in the yield point load, but decreased the maximum load. The shear flow properties for the 50 rpm material showed similar trends. The results from the shear punch evaluations are summarized in Table 5.

The data obtained from the shear punch tests were correlated with corresponding tensile properties determined at room temperature for the as-cast and HIP processed conditions. The correlation constant C, in the expression,

$$\tau = C\sigma_t \qquad (1)$$

where τ and σ_t are the shear and tensile stress at the yield point, was determined for the 50 and 200 rpm material in the as-cast and HIP processed conditions. The room temperature tensile results and empirical correlation constants are given in Table 6. As indicated by the lower correlation constant, the shear stress at the yield point was found to be less for the 50 rpm casting than the 200 rpm casting. The variation in shear strength with mold speed was not reflected in the tensile properties which showed similar yield strength values for both speeds. The results indicate that the flow properties of cast 718 are different depending on whether the prevailing loading mode was a shear or tensile process. Thus, the large variation of the tensile correlation constant with mold speed and processing condition suggests that the properties cast 718 can be highly sensitive to microstructure and stress state.

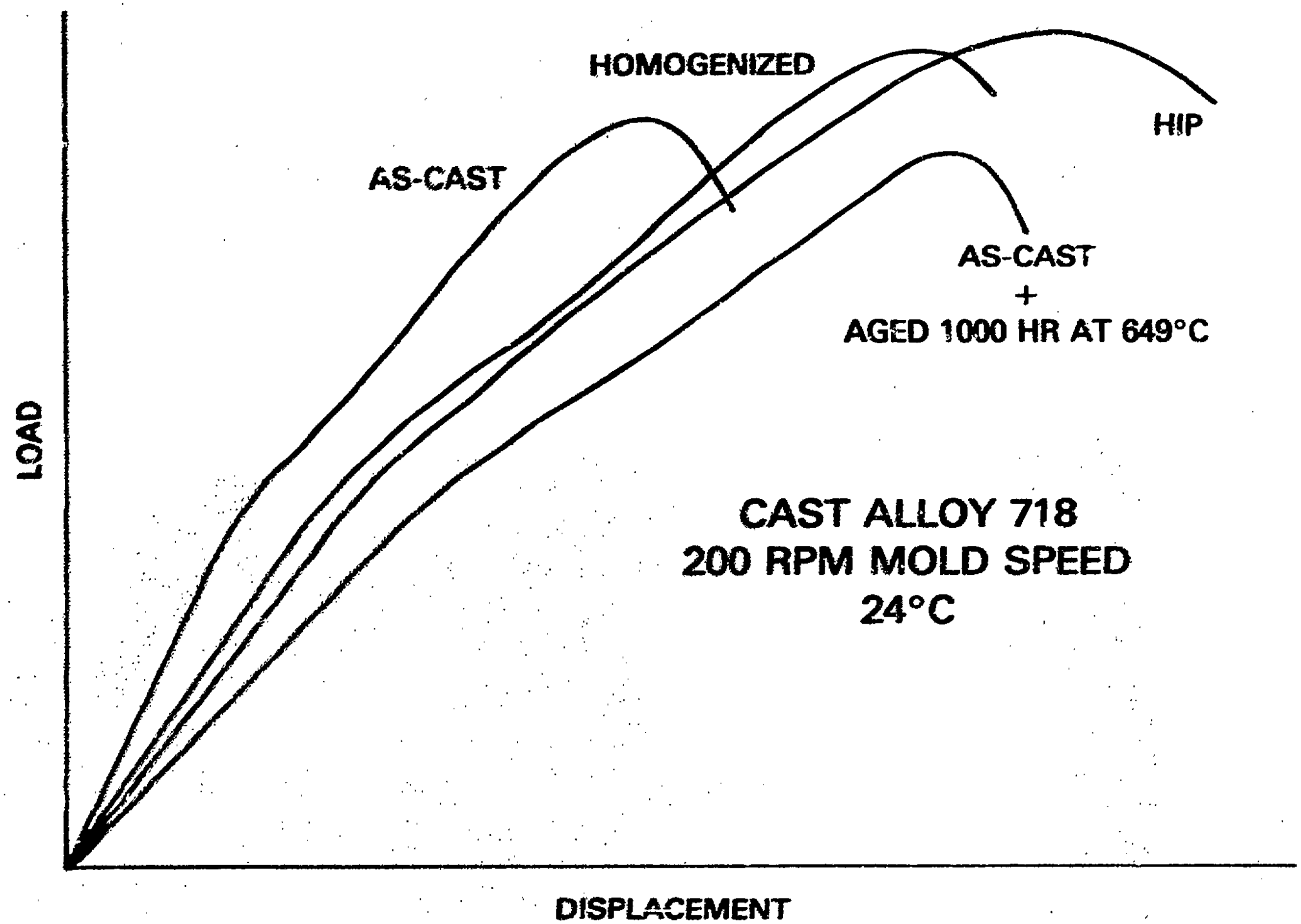

Fig. 8 — Typical load versus displacement curves generated during shear punch testing of cast alloy (200 rpm) in as-cast, aged, homogenized and HIP processed conditions.

TABLE 5

Shear Properties of Cast 718 at 24°C

Mold Speed/ Specimen Orientation	Condition	Shear Stress, MPa	
		@Yield Point	@Max. Load
50RPM/Radial	As-Cast	316	500
200RPM/Radial		356	549
50RPM/Radial	HIP	418	952
200RPM/Radial		369	950
50RPM/Radial	Homogenized	378	860
200RPM/Radial		362	952

TABLE 6

Tensile Properties of Cast 718 at 24°C

Mold Speed/ Specimen Orientation	Condition	0.2% Yield Strength (MPa)	Ultimate Strength (MPa)	Correlation Constants	
				Y.S.	UTS
50RPM/Radial	As-Cast	711	815	0.4	0.6
200RPM/Radial		703	871	0.5	0.6
50RPM/Radial	HIP	826	854	0.4	1.1
200RPM/Radial		829	885	0.5	1.1

DISCUSSION

The results of this study show that either HIP processing or a thermal homogenizing treatment can impart improved crack propagation resistance to centrifugally cast alloy 718. The experimental data indicated that the observed improvement in fatigue properties was related to microstructural changes produced by the processing treatments. The processing dissolved the interdendritic solute segregation and the Laves phases formed during solidification and provided enhanced precipitation reactions with an increase in effective grain size.

A number of mechanisms may be responsible for the improvement in crack growth resistance of processed cast alloy 718. Because processing re-solutions the interdendritic segregation, additional constituents are available for the subsequent precipitation strengthening reactions during aging. This benefit is reflected in the increased tensile and shear properties of the processed casting. Other factors which may contribute to the improvement of the processed alloy fatigue properties are crack deflection and crack closure effects. Comparison of the fracture surfaces of HIP processed or homogenized specimens with as-cast specimens indicated that fracture surface topography was significantly coarsened for the processed conditions. It has been shown (5) that crack path tortuosity in fatigue can reduce the effective stress intensity factor and result in reduced linear growth rates compared to those of an undeflected crack. Roughness induced crack closure may also be effective for microstructures which produce tortuous crack paths such as observed for processed cast alloy 718. As with crack deflection, crack closure reduces the effective stress intensity factor and consequently crack growth rates (5).

The results of this study also show, that while tensile tests may reflect inherent variations in plastic properties, it is important to measure flow behavior in a process that occurs by shear by performing deformation tests in shear. Because fatigue crack growth in cast alloy 718 was a cleavage process, which proceeded by localized shear mechanisms, the shear punch technique proved more useful than the tensile test for assessing the effects of processing on the properties of the alloys. While tensile results reflected the increase in tensile strength produced by processing, differences in strength between the 50 and 200 rpm mold speed alloys were not reflected in the tensile values, although the fatigue properties were found to be sensitive to mold speed. Shear punch measurements of shear stress at yield point showed an effect of mold speed that was consistent with fatigue crack propagation behavior at 649°C.

SUMMARY

The results of this study indicate that the increased resistance to fatigue crack growth of cast alloy 718 after HIP processing or homogenization results primarily from enhanced strength, crack deflection effects and roughness induced crack closure. Although crack deflection is not generally considered as an important mechanism in wrought 718, the unique microstructure of processed cast 718 permits deflecting segments which are a substantial fraction of the crack length and which possess large angles of deviation. This beneficial fatigue behavior is considered to arise in cast

718 due to an active shear mechanism of crack growth and the large effective grain size of the processed casting. The crack deflection mechanism produces a reduction in the effective stress intensity factor and results in reduced crack growth rates. The use of materials, such as cast alloy 718, whose microstructure develops a tortuous crack path, shows promise as an important design methodology for applications for which high strength levels and improved resistance to fatigue crack initiation and growth are required.

RECOMMENDATIONS

The experimental research in Phases I thru IV was conducted on centrifugally cast discs of uniform cross sectional area. However, actual compressor impellers will have wide variations in section thickness. For example, the hub of the casting will be massive compared to the fins. Solidification rates in the fins will be more rapid because of the smaller section size and location on the perimeter of the mold. Since the composition of the microstructure may be affected by the rate of cooling of the casting, the chemistry and fatigue properties of the impeller may differ from the flat discs.

In the present study, comparison of the shear punch and tensile results with fatigue behavior indicated that differences in the fatigue properties of cast 718, as a function of mold speed or condition, could be more accurately determined from shear property measurements. The good correlation of fatigue properties with the shear measurements was related to the fact that the fatigue failure mechanism was primarily a shear process. Because alloy 718 deforms by planar slip up to 0.3-0.5 T_m, the deformation processes are of a similar character during the elevated temperature fatigue tests and the room temperature shear punch tests. Therefore, representative shear punch elvaluations should be possible at room temperature.

It is recommended that the chemical and mechanical properties of the prototypic compressor impeller be investigated in Phase V to ascertain any possible variations in properties due to section size effects. Further, it is recommended that the shear properties be determined as a function of section size before and after thermal homogenization. These results will provide further understanding of the relationship between the microstructure and mechanical properties of centrifugally cast 718 for Naval applications.

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