THE EFFECT OF LAVES PHASE ON THE MECHANICAL PROPERTIES OF WROUGHT AND CAST+HIP INCONEL 718

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Abstract

The effect of varying amounts of Laves phase on the mechanical properties of wrought and cast+HIP Inconel 718 is discussed. When present as a continuous or semicontinuous grain boundary network in wrought Inconel 718, Laves phase dramatically reduces room temperature tensile ductility and ultimate tensile strength, with room temperature impact and fracture toughness properties and elevated temperature ductility also reduced. Laves may also act as a preferred crack initiation and propagation site, resulting in reduced low cycle fatigue (LCF) capability and accelerated fatigue crack growth rates. Laves present as large globular aggregates in cast+HIP Inconel 718 significantly reduces room temperature tensile and elevated temperature stress rupture properties. In addition, the phase acts as a preferred crack initiation and propagation site, resulting in significant reductions in smooth and notch LCF capability and an accelerated fatigue crack growth rate. Methods for controlling Laves phase in wrought and cast+HIP Inconel 718 are discussed.

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Introduction

Of the diverse phases potentially present in Inconel 718, Laves phase has been generally accepted as being deleterious to the mechanical properties of the alloy. During the early development and characterization work (Refs. 1 through 3), Laves was associated with reduced tensile strength and ductility. A more recent evaluation (Ref. 4) attributed the scatter in tensile and low cycle fatigue (LCF) properties to the presence of Laves and identified the specimens at the low end of the scatter bands as containing significantly more Laves than those at the upper end. A larger amount of work has been published (Refs. 5 and 6) showing Laves to reduce the ductility and toughness of Inconel 718 weldments. Laves can reduce the mechanical properties of Inconel 718 through several mechanisms with the most dominant probably being brittle fracture of the phase. In addition, Laves consumes large amounts of Nb depleting the matrix of the principal hardening element. A third way Laves can reduce mechanical properties is due to melting of the phase and subsequent microfissuring during welding, resulting in preexisting linear discontinuities.

Laves is a brittle, intermetallic phase that forms in Inconel 718 usually as a result of segregation, although it is possible to form it in the solid state. The phase is hexagonally close packed and has a $MgZn_2$ lattice type. Relative to the matrix, the phase is enriched in Si, Mo and Nb and is generally accepted to be of the form $(Ni,Fe,Cr)_2$ (Nb,Mo,Ti). Typical microprobe results for Laves in cast Inconel 718 support this:

Composition (weight percent)

	Ni	Fe	Cr	Ti	Al	Mo	Nb	Si
Laves	34.5	11.5	12.2	0.85	-	8.1	26	0.85
Matrix	52.9	19.3	18.6	1.0	0.6	3.0	5.2	0.14

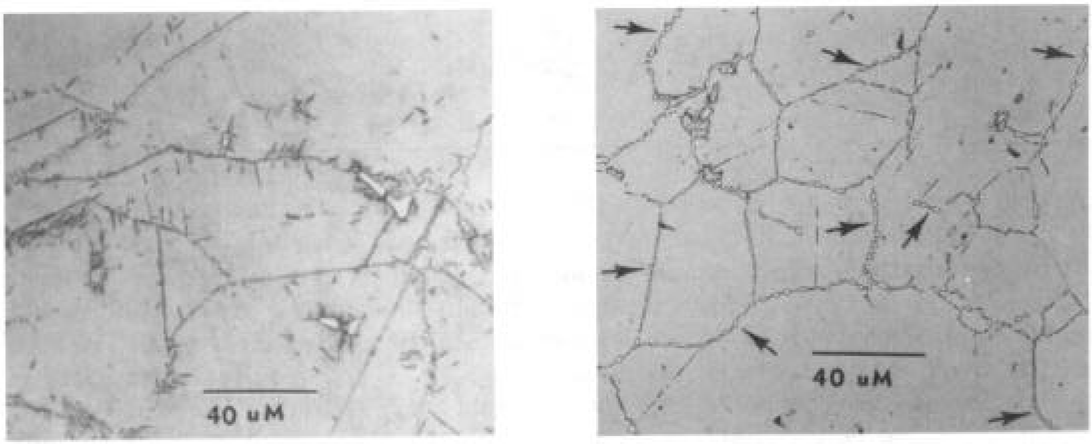
Due to the large amounts of Nb required for the phase, Laves usually forms in heavily segregated regions and is typically observed as large globular particles in cast Inconel 718. It is possible to develop the phase in wrought product when composition, primary ingot solidification and subsequent thermal–mechanical processing are not carefully controlled. The phase can form as a result of exposures to temperatures in excess of 982 °C. Because of the sensitivity of the mechanical properties of Inconel 718 to the presence of Laves, and the propensity of the phase to form (primarily in cast structures) in large Inconel 718 product forms, several test programs were conducted to evaluate the effect of Laves phase on the structural properties of Inconel 718. The test programs were conducted for both wrought and cast + HIP forms of the alloy. In the wrought program, test specimens were machined from commercially available products while the cast/HIP program was conducted using specially processed cast bars. To facilitate presentation of the results, each test program is discussed separately in this paper. Finally, it should be noted that although the amount of Laves phase evaluated in these test programs should not be considered typical for aerospace components, it is possible to produce it if alloy composition and processing are not controlled and carefully monitored.

Laves Phase Effects in Wrought (AMS 5663) Inconel 718

Three heats/configurations of AMS 5663 were selected for evaluation. All three heats conformed to AMS 5663 compositional requirements (Table I) and were procured in the form of rolled rings approximately 0.6 meter in height by 1.5 meters in diameter (requiring an input weight of 1,361 kg). Figure 1 shows typical microstructures for each of the heats. Heat A exhibits a microstructure routinely observed for AMS 5663 consisting of a fully recrystallized grain size of ASTM 3 to 5 and grain boundaries decorated with delta (orthorhombic Ni_3Nb) platelets. Heat B shows a similar grain size; however, the grain boundaries are decorated with a semicontinuous network of Laves phase (arrows). Heat C is similar to Heat B except the grain size is slightly coarser and the Laves phase network is more continuous. Heats B and C are enriched in Si and Fe relative to Heat A (see Table I). This, combined with the thermal mechanical processing, resulted in the Laves phase being present. Microprobe analysis of the Laves phase (average of 5 readings) in Heat C showed the phase to be enriched in Mo, Nb and Si and depleted in Ni, Fe and Cr relative to the grain center (average of 9 readings).

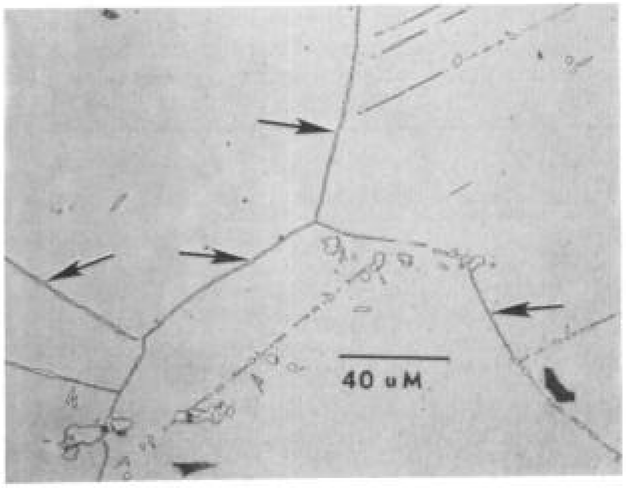
Composition (weight percent)

	Ni	Fe	Cr	Ti	Mo	Nb	Si
Laves	32.5	13.9	12.7	0.7	12.5	27.3	2.5
Matrix	52.1	20.4	18.8	1.0	3.1	5.2	0.35



Heat A
Average Grain Size ASTM 3.1

Heat B
Average Grain Size ASTM 4.2



Heat C
Average Grain Size ASTM 2.1

Figure 1 Typical microstructures of AMS 5663 test heats. Laves phase is indicated by arrows in Heats B and C. Hardness ranged from 43.5 to 45 Rc which is typical for AMS 5663.

Table I Composition of Test Heats and AMS 5663 Specification Requirements

	Composition (weight percent)			
Element	Heat A	Heat B	Heat C	AMS 5663
Ni	54.11	52.49	52.2	50 to 55
Co	0.01	0.02	0.02	- to 1
Fe	18.11	19.15	20.01	Bal.
Cr	17.56	17.97	17.53	17 to 21
Al	0.62	0.57	0.59	0.2 to 0.8
Ti	0.93	0.94	0.93	0.65 to 1.15
Mo	3.06	3.06	2.97	2.8 to 3.3
Mn	0.13	0.17	0.24	- to 0.35
Nb+Ta	5.3	5.24	5.13	4.75 to 5.5
Si	0.11	0.25	0.3	- to 0.35
B	0.002	0.002	0.003	- to 0.006
C	0.04	0.04	0.04	- to 0.08

Tensile testing was conducted for each of the heats at both room temperature (RT) and 649°C. On average (see Table II), the heats exhibited a wide range of properties with only Heat A meeting AMS 5663 minimum requirements. Both Heats B and C failed to meet AMS 5663 requirements. Analysis of the data (Figure 2) shows that room temperature yield strength is not affected by the presence of Laves while ductility and ultimate tensile strength are substantially reduced. The ductilities of Heats B and C are significantly improved at 649°C (relative to room temperature), indicating that Laves phase exhibits increased ductility with increasing temperature. At room temperature, scanning electron microscope (SEM) analysis of a Heat C tensile specimen showed the fracture to be completely intergranular. This is illustrated in the SEM fractograph (Figure 3) which also shows the fracture surface to be decorated with Laves phase.

Table II Average Tensile Properties of Wrought Inconel 718 Containing Various Amounts of Laves Phase

	Average Value			
Property	Heat A	Heat B	Heat C	AMS 5663 min.
RT .2 Yield Strength (MPa)	1135	1132	1157	1034
RT Ultimate Tensile Strength (MPa)	1338	1248	1245	1276
RT Elongation (%)	18.7	4.9	2.1	12
RT RA (%)	30.9	11	4.4	15
649°C .2 Yield Strength (MPa)	938	901	944	862
649°C Ultimate Tensile Strength (MPa)	1070	985	1057	1000
649°C Elongation (%)	25.8	10.1	6.0	12
649°C RA (%)	43.8	19.9	11.3	15

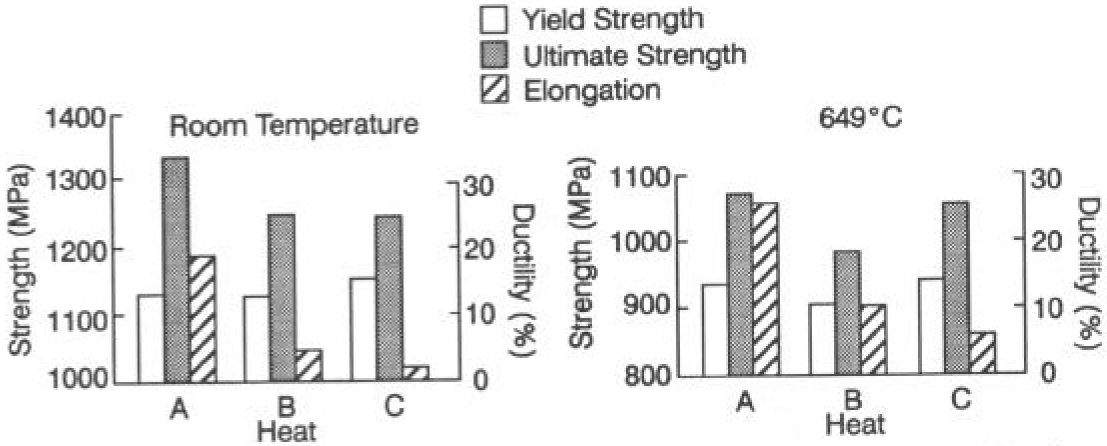


Figure 2 Room and elevated temperature tensile results for wrought Inconel 718 with various amounts of Laves

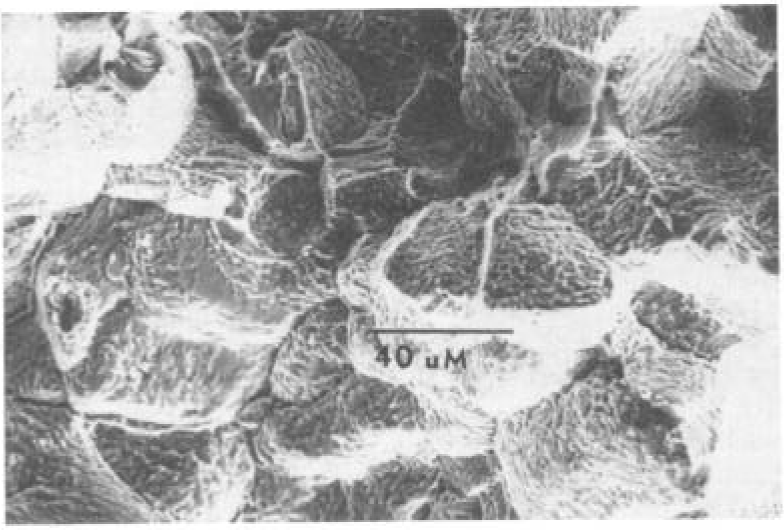
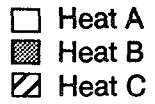
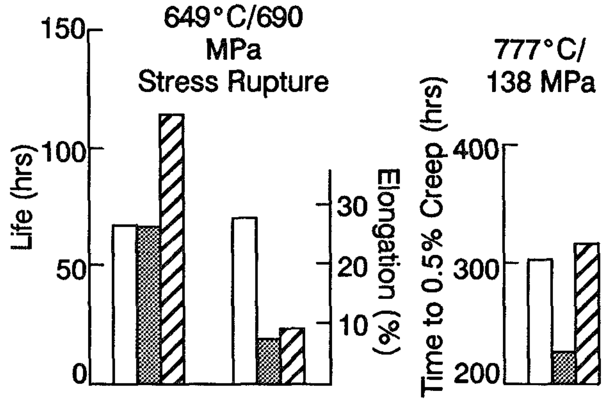


Figure 3 SEM fractograph of room temperature tensile specimen from Heat C showing intergranular fracture through Laves phase

Smooth stress rupture and creep testing was also conducted at conditions of 649°C/690 MPa and 777°C/138 MPa, respectively. Both rupture and creep (time to 0.5 percent) life were not affected by the presence of Laves phase and appear to be more strongly related to grain size. However, a comparison of Heats A and B of similar grain size indicates that Laves may reduce creep life slightly. The brittle behavior of Laves even at elevated temperature is again demonstrated by the reduced ductility (rupture elongation) of Heats B and C. Creep and rupture test results are presented in Figure 4.

Charpy impact and fracture toughness (modified three–point bend) testing was conducted at room temperature for each of the heats. Both Heats B and C exhibited dramatic reductions in property levels due to the very brittle nature of Laves at room temperature. Metallographic sections made through failed specimens showed the fractures to be predominantly intergranular through Laves phase in Heats B and C and transgranular in Heat A. The Charpy impact and fracture toughness test results are presented in Figure 5.





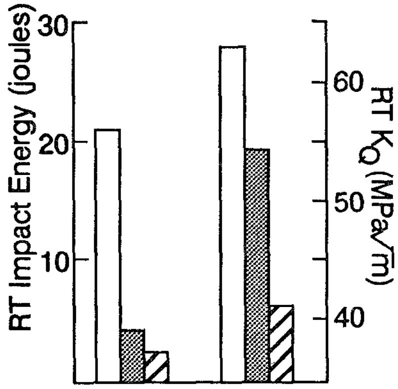


Figure 4
Smooth stress rupture and creep results for wrought Inconel 718 with various amounts of Laves phase

Figure 5
Room temperature (RT) Charpy impact and fracture toughness test results for wrought Inconel 718 with various amounts of Laves phase

Notch LCF testing was conducted on Heats B and C at 371°C, with fatigue crack propagation testing being conducted at 371 and 593°C. Although notch LCF testing was not conducted for Heat A, baseline data existed for AMS 5663 at similar test conditions for comparison purposes. Low cycle fatigue testing was conducted at a nominal stress of 741 MPa and specimens inspected for cycles to a crack indication. The results (Figure 6) are not conclusive but suggest that the presence of a continuous Laves phase network (Heat C) results in reduced notch fatigue crack initiation resistance. This is not surprising since the brittle Laves phase would be expected to act as a preferred crack initiation site. Metallographic sections made through tested notch LCF specimens in Heat B did not show preferred crack initiation and propagation through Laves phase (Figure 7) which is consistent with the observation that notch LCF properties were not reduced. A metallographic section made through the Heat C specimen was inconclusive in identifying Laves as the preferred initiation and propagation site. Additional work is required to better understand the effect of Laves phase on LCF initiation life.

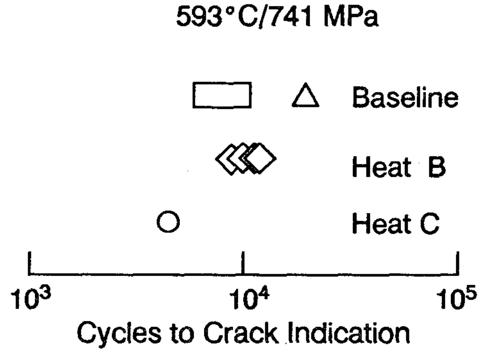


Figure 6 Notch LCF test results (cycles to crack indication) for wrought Inconel 718 with various amounts of Laves phase

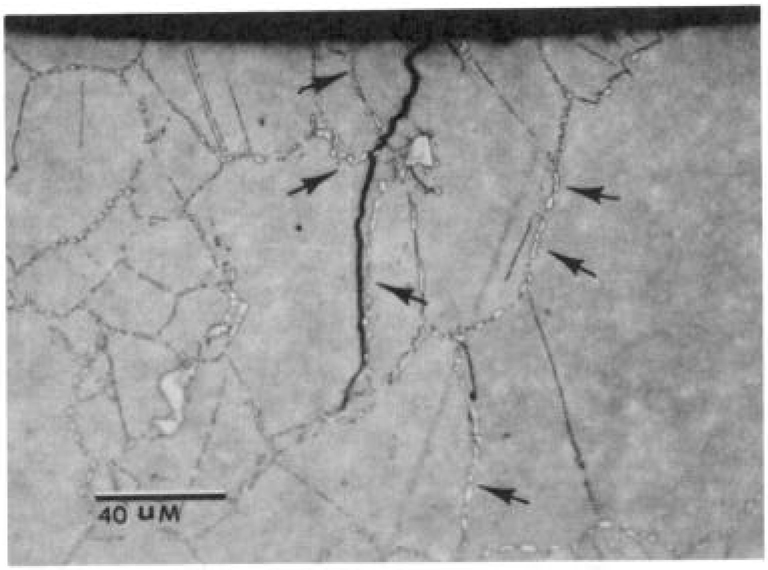


Figure 7 Metallographic section through a notch LCF specimen from Heat B. The fracture mode is transgranular and the crack is not growing preferentially through Laves.

Fatigue crack growth testing was conducted for Heats A, B and C at 371 and 593°C. Baseline AMS 5663 data already existed at 427, 538 and 593°C. All testing was conducted using centercrack panels under R=.1 and 10 cpm conditions. Test results are plotted in Figure 8 as residual life (cycles from a stress intensity of approximately 15 MPa$\sqrt{m}$ to 35 MPa$\sqrt{m}$) against temperature and show that all three heats generally exhibited fatigue crack growth behavior similar to the AMS 5663 baseline. At 593°C Heat C showed a substantial increase in fatigue crack propagation rate. Metallographic sections made through the tested specimens showed the crack to preferentially follow Laves in both Heat B specimens and the 593°C Heat C specimen. The crack in the 371°C Heat C propagated transgranularly, not through Laves. This indicates that Laves present as a semicontinuous network (Heat B specimens) does not significantly affect the elevated temperature crack growth properties of wrought Inconel 718. When Laves is present as a more continuous network (Heat C/593°C specimen), it can behave as a preferred crack propagation path and dramatically increase the fatigue crack growth rate.

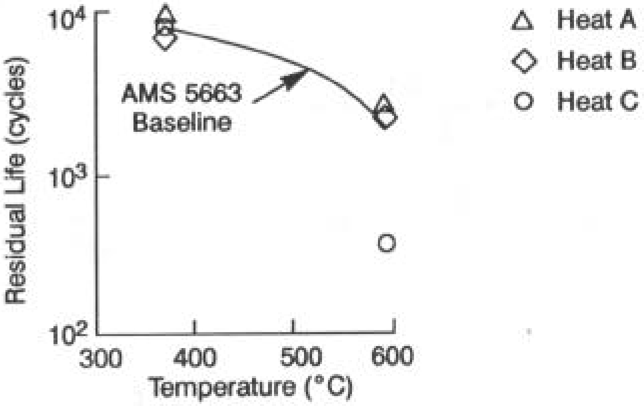
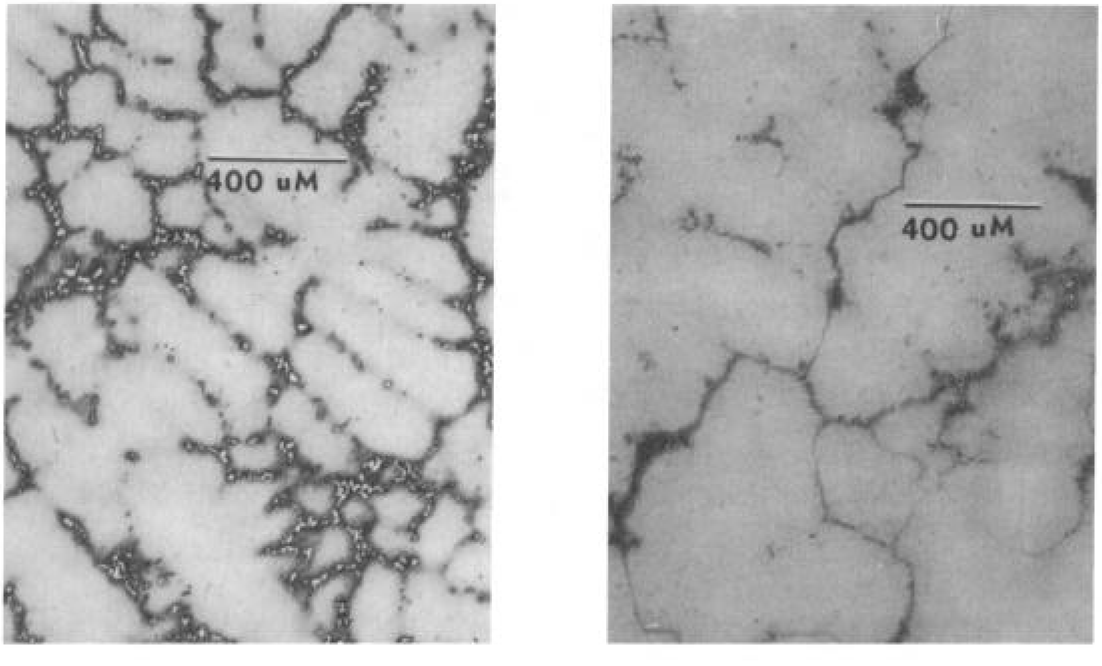


Figure 8 Fatigue crack growth behavior of wrought Inconel 718 containing various amounts of Laves phase

In summary, Laves phase present as a continuous or semicontinuous network in wrought Inconel 718 can result in significant reductions in mechanical properties, especially at room temperature. This is due to the very brittle behavior of the phase at room temperature acting as a preferred fracture path. At elevated temperature, the improved ductility of the Laves results in less of a reduction in mechanical properties, with elongation at fracture (tensile and stress rupture) showing the greatest reduction. Limited testing suggests that fatigue initiation life is reduced; however, this area must be studied further. Fatigue crack propagation behavior can be affected when Laves is present as a continuous network.

Laves Phase Effects in Cast+HIP Inconel 718

To attain gross levels of Laves phase, cast bars were slowly solidified (2°C/minute) over the range of 1371 to 1177°C and then processed through a 1107°C/103 MPa/2 hour HIP cycle. Additional bars were processed per one of the currently used industry practices of a 24 hour (1135°C/8 hours + 1149°C/16 hours) pre–HIP homogenization heat treatment, followed by a 1191°C/103 MPa/4 hour HIP cycle. Both sets of bars were then processed through a 871°C/10 hour stabilization cycle, followed by a 954°C/1 hour solution heat treatment and a 732°C/8 hour + 663°C/8 hour precipitation heat treatment (also a current process used in the industry). As illustrated in Figure 9, the microstructure of the 1107°C HIP material contains gross levels of Laves phase with the 1191°C HIP material essentially Laves–free. The heat (P9979) used in the test program conformed to PWA 1469 specification compositional requirements as illustrated in Table III. A range of mechanical property testing was conducted on specimens machined from the cast bars.



(a) (b)

Figure 9 Typical microstructures resulting from solidifying Inconel 718 at 2°C/minute from 1371° to 1177°C, and then processing through the following thermal cycles: (a) 1107°C/2 hours HIP, and (b) 1135°C/8 hours + 1149°C/16 hours pre–HIP heat treat + 1191°C/4 hours HIP

Table III
Composition of Heat P9979 Used to Evaluate the Effect of Laves Phase on Cast + HIP Inconel 718 Mechanical Properties.
PWA 1469 is an industry standard.

	Composition (weight percent)	
Element	Heat P9979	PWA 1469 Req.
C	0.05	0.03 to 0.08
Si	0.1	- to 0.35
Mn	0.02	- to 0.35
Co	0.19	- to 1.0
Ni	52.33	50 to 55
Cr	18.92	17 to 21
Fe	Bal.	Bal.
Mo	3.06	2.8 to 3.3
Ti	0.94	0.65 to 1.15
Al	0.5	0.4 to 0.8
Nb + Ta	5.09	4.75 to 5.5
B	0.006	- to 0.006
S	0.003	- to 0.015

Tensile testing was conducted at room temperature and 649°C. On average (see Figure 10) the high Laves material exhibited approximately 103 MPa lower strength and about 20 percent the ductility of the low Laves material. At 649°C, there was little or no difference in strength and the high Laves material continued to exhibit reduced ductility (Figure 10). Metallographic sections made through failed high Laves tensile specimens showed the fracture to be predominantly through the Laves phase consistent with results previously published (Ref. 4).

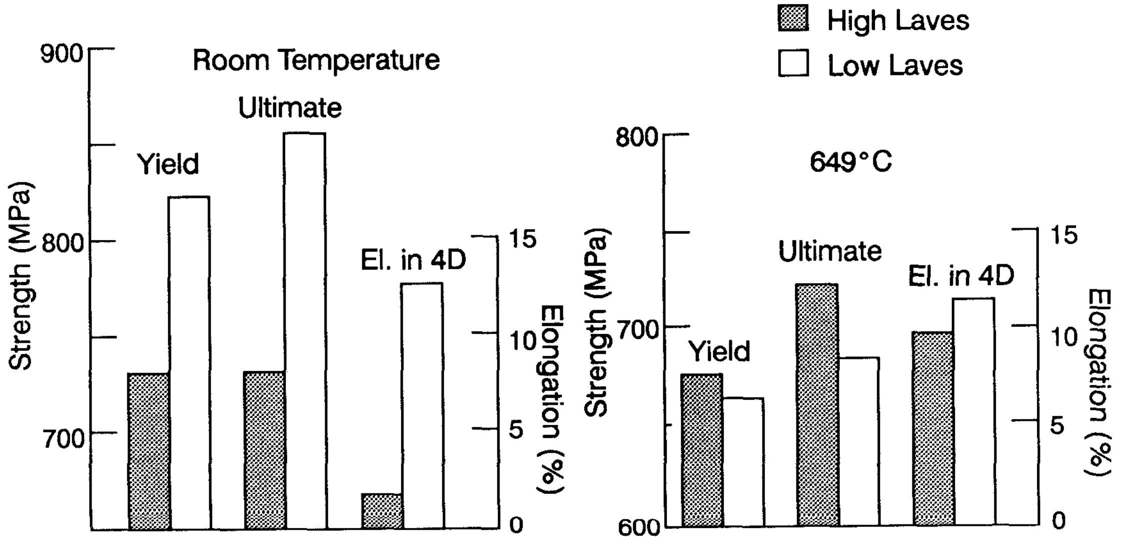


Figure 10 Room temperature and 649°C tensile properties of cast + HIP Inconel 718 with low and high levels of Laves phase

Smooth stress rupture testing was conducted under 649°C/552 MPa conditions. The results (Figure 11) show the high Laves material to exhibit a 2.4X reduction in rupture life and a 1.6X reduction in rupture elongation. Again, metallographic sections made through failed high Laves test specimens showed the fracture to be predominantly through Laves phase.

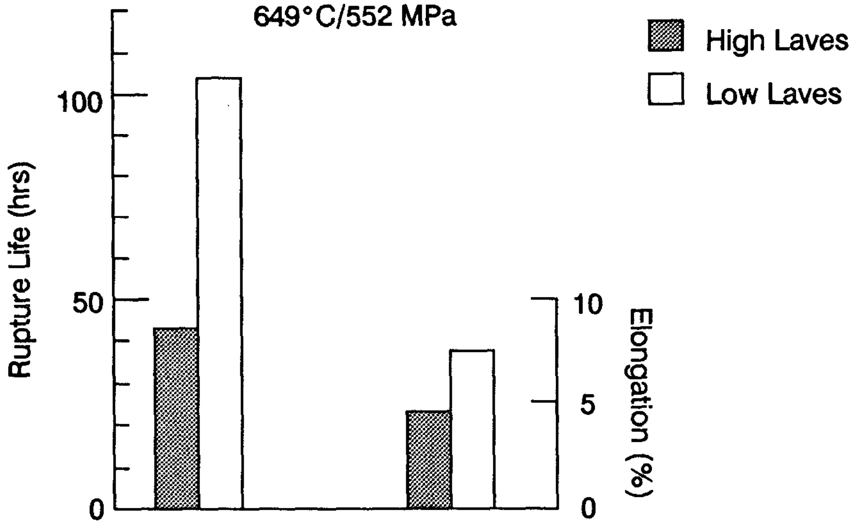


Figure 11 Stress rupture properties of cast + HIP Inconel 718 with low and high levels of Laves phase

Both smooth and notch LCF testing were conducted at 593°C. Smooth LCF testing was run to specimen failure while the notch specimens were run until a crack indication was detected. Results showed the smooth LCF properties (Figure 12) to be reduced by a factor of 3 (on average) and the notch LCF (Figure 13) properties to be reduced by a factor of 4 (on average). Post test SEM and metallographic analysis of failed high Laves specimens verified that the fracture initiated in and propagated through Laves phase (see Figures 14 and 15).

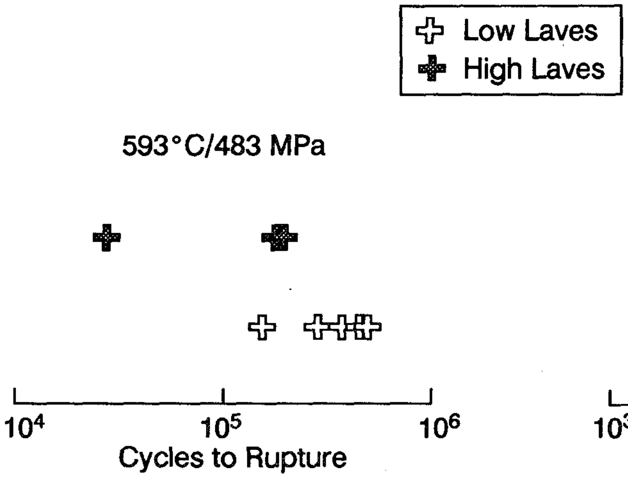


Figure 12
Smooth LCF properties of cast + HIP Inconel 718 with low and high levels of Laves

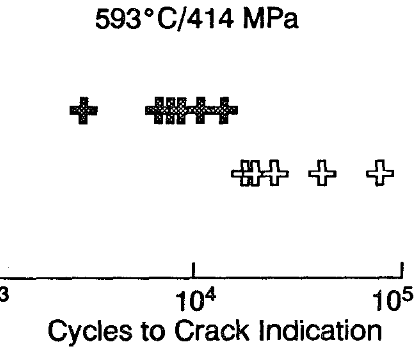


Figure 13
Notch LCF properties of cast + HIP Inconel 718 with low and high levels of Laves

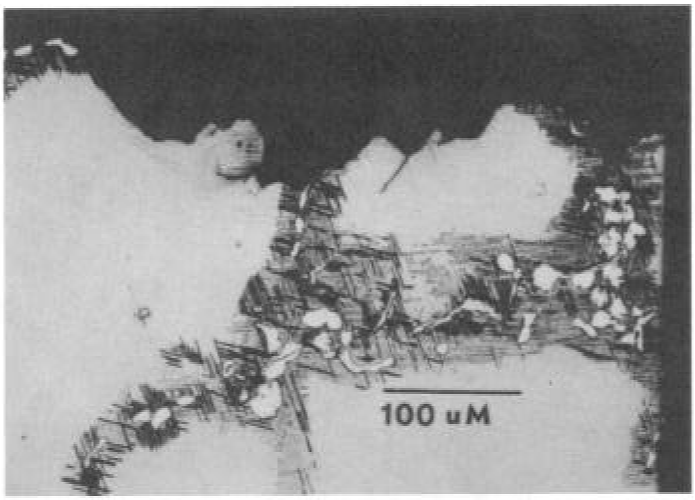


Figure 14 Smooth LCF specimen showing preferential crack initiation and propagation through Laves phase

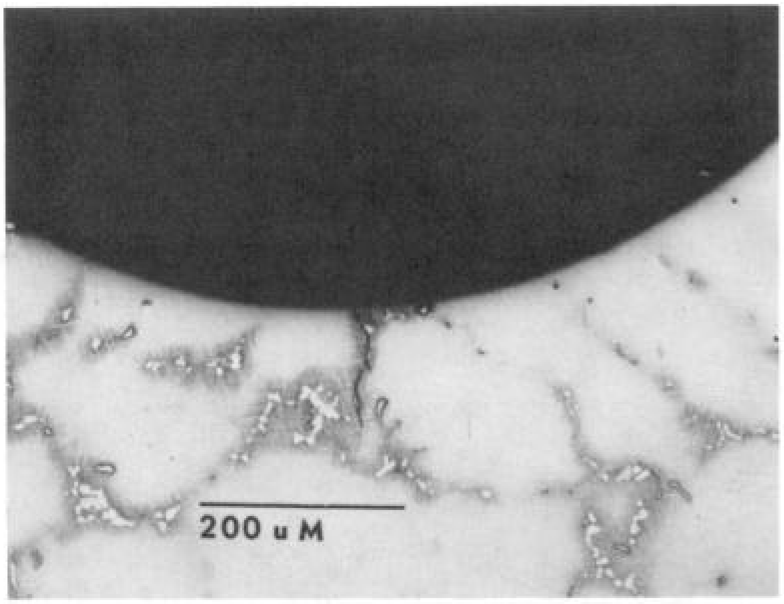


Figure 15 Notch LCF specimen showing preferential crack initiation and propagation through Laves phase

Fatigue crack growth testing was conducted under 593°C/10 cpm/$R=0.1$ conditions. In general, similar crack growth rates were observed (Figure 16) for both low and high Laves material. The high Laves material exhibited a substantially different slope than the low Laves material. Residual life calculations were made for both materials over the stress intensity range 12 MPa$\sqrt{m}$ to 36 MPa$\sqrt{m}$, and the high Laves material exhibited a fivefold reduction in damage tolerance (55,000 cycles versus 250,000 cycles). The reduced damage tolerance is due to the faster crack growth rate of the high Laves material at low stress intensities (<23 MPa$\sqrt{m}$). A metallographic section through the high Laves specimen showed the crack to be growing predominantly through Laves phase (see Figure 17).

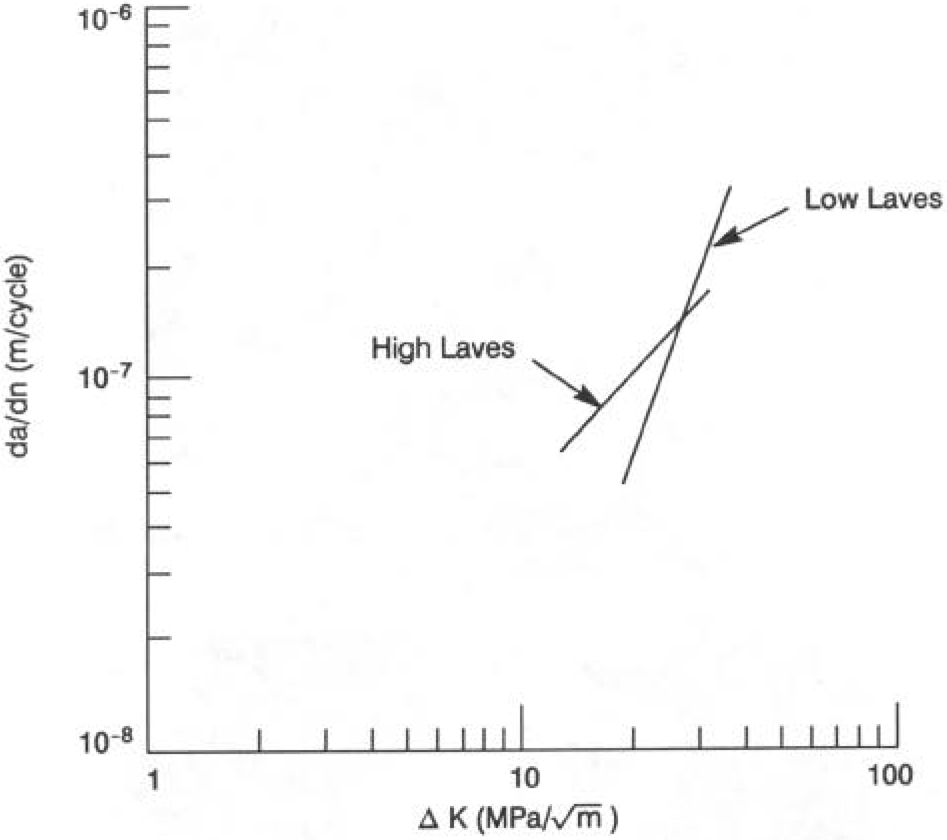


Figure 16 593°C fatigue crack growth properties of cast + HIP Inconel 718 with low and high levels of Laves

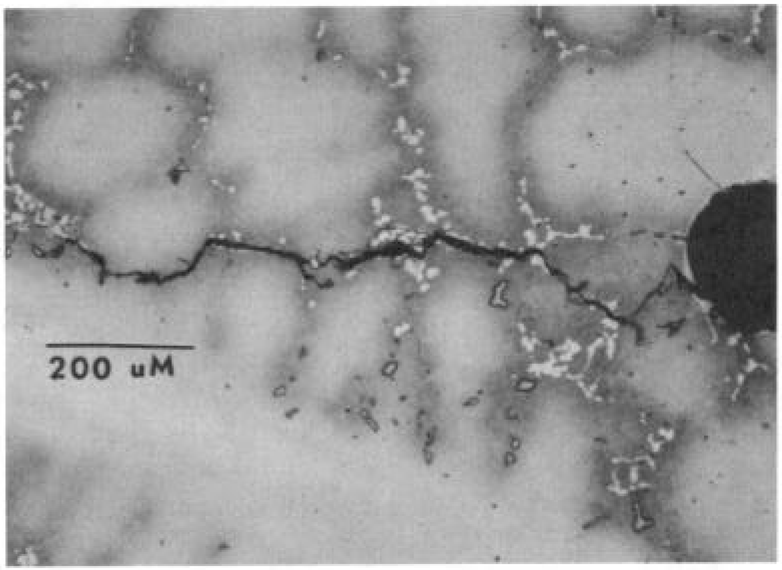


Figure 17 Metallographic section through tested high Laves crack growth specimen showing preferential propagation through Laves

In summary, the presence of gross Laves in cast+HIP Inconel 718 resulted in substantial reductions in room temperature tensile properties. At elevated temperature, tensile ductility was reduced slightly with strength unaffected. Both smooth stress rupture life and ductility were reduced. Laves acted as a preferred initiation and propagation site resulting in substantial reductions in smooth and notch LCF capability and an accelerated fatigue crack growth rate.

Discussion

It is interesting to note that both wrought and cast+HIP Inconel 718 exhibit similar responses when substantial amounts of Laves phase are present. Room temperature properties are substantially reduced with elevated temperature tensile ductility also reduced. The difference in the effect of Laves phase on rupture life suggests that rupture life in HIP Inconel 718 is more dependent on composition (grain size is already very coarse) while the wrought material is more strongly affected by grain size. Although phase volume fraction analysis was not conducted, the HIP material appears to contain a greater volume fraction of Laves phase than the wrought, which would result in greater Nb depletion of the matrix (relative to the wrought) reducing the precipitation hardening response. This would also explain why the cast+HIP material with gross Laves showed reduced tensile yield strength while the wrought material was not affected.

In previous work (Ref. 4), it was reported that as grain size becomes finer the effect of Laves phase on LCF properties should become more pronounced. It was also reported that the LCF behavior of conventionally cast Inconel 718 was not affected by Laves phase although no substantiating data was presented. In contrast, the results of this test program indicate that Laves phase has a direct influence on the behavior of conventionally cast material. Even at an elevated temperature, Laves is still brittle enough to act as a preferred early fatigue crack initiation site. As grain size becomes finer (i.e., the wrought material), Laves seems to have a much smaller and perhaps even negligible effect on LCF behavior. Limited testing, however, was performed on the wrought material, and additional work should be undertaken to further investigate and verify this trend.

The differences in fatigue crack growth behavior between the wrought and cast+HIP product may again reflect the probable difference in the amount of Laves phase present in the microstructure. The greater volume fraction present in the cast+HIP material presents a higher probability for the crack to grow through the brittle phase. Metallographic sections made through tested crack growth specimens showed more of the crack propagating through Laves in the cast+HIP material compared to the wrought material.

Due to the potentially catastrophic results if gross amounts of Laves phase are present, controls and processes have been developed to minimize or eliminate Laves in wrought and cast+HIP Inconel 718. Regression analysis of multiple heats of wrought Inconel 718 indicated that keeping Fe and Si on the low end of the specification requirements should result in little or no Laves phase being present. In cast+HIP Inconel 718, Pratt & Whitney has developed two approaches to control Laves phase. The first (U.S. Patent No. 4,662,951) is to use a pre-HIP homogenization heat treatment in conjunction with a 1191°C HIP cycle to eliminate the Laves phase without melting it. The other approach (U.S. Patent No. 4,750,944) is to reduce the Cr content to a level outside the current cast Inconel 718 specification requirements. This effectively suppresses the formation of Laves phase during solidification.

Conclusions

Laves phase present as a continuous or semicontinuous grain boundary network in wrought Inconel 718 results in significant reductions in:

- room temperature tensile ductility and ultimate tensile strength
- room temperature impact and fracture toughness properties
- elevated temperature ductility.

When acting as a preferred crack propagation site, a continuous grain boundary network of Laves results in an accelerated fatigue crack propagation rate in wrought Inconel 718.

The effect of continuous and semicontinuous networks of Laves phase on the LCF capability of wrought Inconel 718 is not clear and needs to be studied further. Limited testing suggests that LCF capability is reduced.

Control of iron and silicon to the low end of the AMS 5663 specification levels should minimize Laves phase levels in wrought Inconel 718.

Laves present as large, interdendritic aggregates in cast + HIP Inconel 718 results in significant reductions in:

- room temperature tensile properties
- elevated temperature smooth stress rupture properties
- elevated temperature smooth and notch LCF capability
- elevated temperature fatigue crack growth resistance.

Laves phase in cast + HIP Inconel 718 can be minimized through use of a homogenization heat treatment or reduction of chromium to levels below current specification limits.

The deleterious effect of Laves phase on the structural properties of wrought and cast + HIP Inconel 718 has been demonstrated and methods to control and/or minimize the phase proposed.

References

1. H. L. Eiselstein, "Metallurgy of a Columbium-Hardened Nickel-Chromium-Iron Alloy" (ASTM Special Technical Publication No. 369, 1965).

2. H. J. Wagner and A. M. Hall, "Physical Metallurgy of Alloy 718" (DMIC Report 217, June 1, 1965).

3. R. C. Hall, "The Metallurgy of Alloy 718," Journal of Basic Engineering, (September 1967), 511-516.

4. G. K. Bouse and M. R. Behrendt, "Mechanical Properties of Microcast-X® Alloy 718 Fine Grain Investment Castings," Superalloy 718: Metallurgy and Applications, ed. Edward Loria (TMS 1989), 319–329.

5. E. Campo, C. Turco, and V. Catena, "The Correlation Between Heat Treatment, Structure, and Mechanical Characteristics in Inconel 718," Metallurgical Sciences Technology 3 (1) (April 1985), 16–21.

6. L. A. James, "Fatigue Crack Growth in Inconel 718 Weldments," Welding Journal 57(1) (January 1978), 175–235.