Fatigue-Crack Growth in Inconel 718 Weldments at Elevated Temperatures

A "modified" vs. "conventional" postweld heat treatment results in lower crack growth rates and higher toughness that are thought to be associated with a more complete dissolution of the "brittle" Laves phase which forms during welding

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ABSTRACT. The techniques of linear-elastic fracture mechanics were used to characterize the fatigue-crack growth behavior of Inconel 718 gas tungsten arc (GTA) weldments over the temperature range 24-649 C (75-1200 F). Two different postweld heat treatments were employed: the "conventional" (ASTM A637) treatment, and a "modified" heat treatment designed to eliminate the brittle Laves phase that forms during the welding process.

Weldment specimens given the modified postweld heat treatment consistently exhibited superior fatigue-crack growth behavior relative to conventionally-treated weldments. In addition, weldment specimens treated by either process exhibited higher crack growth rates than plate specimens similarly heat treated.

Introduction

Inconel* 718 is a precipitation-hardenable nickel-base alloy that is utilized extensively where high strength and corrosion resistance are required at elevated temperatures. For these reasons, the alloy is employed in some nuclear reactor structural components, particularly where strength, swelling behavior, and creep resistance are important. Such structural components are often subjected to cyclic loadings in service, and hence the potential exists for subcritical extension of cracks or crack-like flaws during service.

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The techniques of linear-elastic fracture mechanics are particularly useful for estimating in-service crack extension,[1] and considerable progress has been made in characterizing the effect of various parameters upon the crack growth behavior of structural alloys. The present paper addresses the fatigue-crack growth behavior of Inconel 718 base metal and weldments at several temperatures, and with two different postweld heat treatments.

Experimental Procedure

Several heats of material were utilized in this study and are designated as heats A-F in Table 1. The chemical compositions of these heats are given in Table 2. Two different heat treatments were employed: the "conventional" heat treatment,[2] and the "modified" heat treatment developed at the Idaho National Engineering Laboratory (INEL).[3] The heat treatments were as follows:

1. "Conventional"—annealed at 954 C (1750 F), and air-cooled to room temperature. Aged 8 h at 718 C (1325 F), furnace-cooled to 621 C (1150 F) and held at 621 C (1150 F) for a total aging time of 18 h, and air-cooled to room temperature.
2. "Modified"—solution-annealed 1 h at 1093 C (2000 F), cooled to 718 C (1325 F) at 56 C/h (100 F/h), aged 4 h at 718 C (1325 F), cooled to 621 C (1150 F)

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Table 1—Identification of Material Heats

Heat identification	Producer heat no.	Product form	Melt practice[a]	Purchase specification
A	Haynes 2810-9-9104	0.5 in. plate	VIM-VAR	AMS 5597
B	Haynes 2180-1-9345	0.5 in. plate	VIM-ESR	AMS 5596C
C	Haynes 2180-4-9478	0.5 in. plate	VIM-ESR	AMS 5596C
D	Huntington 52C9EK	0.5 in. plate	VIM-EFR	AMS 5596C
E	Huntington 60C7E	0.062 in. diam. filler metal	—	AMS 5832A
F	Huntington 5280E	0.045 in. diam. filler metal	—	AMS 5832A

[a]VIM-VAR—vacuum induction melted, followed by vacuum arc remelting; VIM-ESR—vacuum induction melted, followed by electroslag remelting; VIM-EFR—vacuum induction melted, followed by electro-flux remelting; VIM-ESR and VIM-EFR are essentially the same process.

Table 2—Chemical Composition, Wt-%

Heat identification	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Co	P	Mo	B	Cb&Ta	Cb	Ta
A	.05	.19	Bal.	.003	.09	<.01	53.00	17.95	.46	.95	.07	.003	3.16	.003	5.17	[a]	[a]
B	.06	.08	Bal.	<.005	.07	.04	52.88	18.06	.51	1.11	.22	<.005	2.89	.004	5.04	[a]	[a]
C	.05	.21	Bal.	.005	.10	.02	52.63	18.21	.54	.97	.30	.005	3.05	.002	5.08	[a]	[a]
D	.07	.08	18.19	.007	.17	.11	53.44	18.11	.49	1.08	.03	[a]	3.00	[a]	5.10	[a]	[a]
E	.04	.09	17.97	.007	.18	.10	53.84	18.04	.55	1.01	.03	.010	3.00	.0042	5.12	5.11	.01
F	.04	.04	17.60	.007	.19	.05	54.58	17.91	.49	.99	.04	.011	2.96	.0031	5.08	5.07	.01

[a]Not determined.

at 56 C/h (100 F/h), aged 16 h at 621 C (1150 F), and air-cooled to room temperature.

Weldments were made with the material in the annealed condition and then given either the conventional or modified heat treatments following gas-tungsten arc welding. All weldments were of double V groove design.

The ASTM "Compact Type" specimen was employed in the fatigue tests. The width (W) and thickness (B) were approximately 50.8 mm (2.0 in.) and 11.4 mm (0.45 in.), respectively, for all specimens, except for those numbered 835 and above, which had W and B dimensions of approximately 29.3 mm (1.154 in.) and 7.8 mm (0.31 in.), respectively. The specimens were tested on an MTS servo-controlled testing machine employing load as the control parameter. The cyclic frequency was 40 cpm (0.667 Hz) except at room temperature where frequency is not expected to be an important variable. Sinusoidal loading waveforms with a stress ratio ($R = K_{min}/K_{max}$) of 0.05 were employed on all tests. Cracks in weldment specimens were centered in the weld deposit, and were oriented parallel to the direction of welding. Specimen identification is given in Table 3.

Elevated temperature tests were conducted in an air-circulating furnace, and temperatures were controlled to within about ±1 C (±2 F). Crack lengths were determined periodically throughout each test using a travelling microscope.

Crack growth rate (da/dN) was calculated by dividing each increment of crack extension (Δa) by the number of cycles producing that increment (ΔN). The stress intensity factor (K) was calculated from a determined relationship[4] using the average crack length for each growth increment. The results were then plotted as log (da/dN) as a function of log (ΔK), where ΔK is the stress intensity factor range.

Results and Discussion

Tests were conducted at temperatures of 24 C (75 F), 427 C (800 F), 538 C (1000 F), and 649 C (1200 F), with the emphasis being placed on the 427 C and 538 C temperatures where both the conventional and modified heat treatments were studied. The results are plotted in Figs. 1-6 where the behavior of a weldment at a given temperature is compared to the behavior of base metal given the same heat treatment. Although not shown in the present paper, additional results for plate material at other temperatures and with other heat treatments, were reported in the literature.[5]

Tensile tests were conducted on some of the material/heat treatment combinations employed in this study, and the results are given in Table 4. More extensive results are contained in the literature.[5]

The crack in each weldment specimen was approximately centered in the weld deposit and oriented parallel to the direction of welding. As crack extension occurred during each test, the cracks remained roughly normal to the direction of applied loading (i.e., parallel to the direction of welding). This is in contrast to the behavior observed[6] for bimetallic weldment specimens (Inconel 718 welded to either Inconel 600 or Type 316 stainless steel, using Inconel 82 filler metal in both cases) where crack extension directions deviated considerably from the normal to the loading time.

Figures 1-6 reveal that somewhat greater data scatter is generally observed for the weldment specimens relative to that in the plate specimens. This is in agreement with similar observations for weldments in ferritic[7] and austenitic[8] steels. Considerable scatter in the crack growth behavior of Inconel 718 weldments has also been noted at 538 C (1000 F),[9] but in this case approximately the same degree of scatter was also noted in the results for base metal.

In general, Inconel 718 has very good weldability. However, in some cases difficulties have been encountered achieving adequate ductility and impact strength, especially when the weldments are given the "conventional" heat treatment following welding.[3,10] These difficulties are apparently associated with the formation of a "brittle" Laves phase in the weld fusion zone, and the inability of the 954 C (1750 F) annealing temperature in the conventional postweld heat treatment to eliminate the Laves

Table 3—Specimen Identification

Specimen no.	Material	Heat treatment	Heat identification[a]	Test temperature
128	Plate	Conventional	A	24 C (75 F)
158	Plate	Conventional	D	24 C (75 F)
862	Weldment	Conventional	C/E	24 C (75 F)
162	Plate	Conventional	D	427 C (800 F)
255	Plate	Modified	D	427 C (800 F)
835	Weldment	Conventional	D/F	427 C (800 F)
852	Weldment	Conventional	C/E	427 C (800 F)
840	Weldment	Modified	D/F	427 C (800 F)
864	Weldment	Modified	C/E	427 C (800 F)
130	Plate	Conventional	A	538 C (1000 F)
131	Plate	Conventional	A	538 C (1000 F)
165	Plate	Conventional	D	538 C (1000 F)
250	Plate	Modified	D	538 C (1000 F)
251	Plate	Modified	D	538 C (1000 F)
368	Weldment	Conventional	B/E	538 C (1000 F)
369	Weldment	Conventional	B/E	538 C (1000 F)
487	Weldment	Modified	D/F	538 C (1000 F)
841	Weldment	Modified	D/F	538 C (1000 F)
252	Plate	Modified	D	649 C (1200 F)
486	Weldment	Modified	D/F	649 C (1200 F)

[a]Designations incorporating a slash mark mean: base metal heat/filler metal heat.

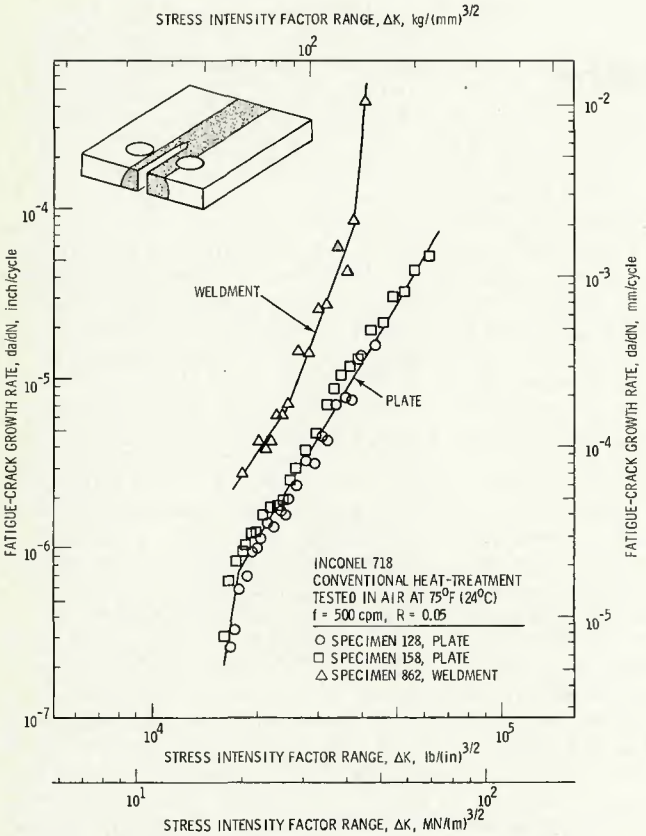

Fig. 1—Fatigue-crack growth behavior of Inconel 718 plate and weldments tested in an air environment at room temperature (conventional heat treatment)

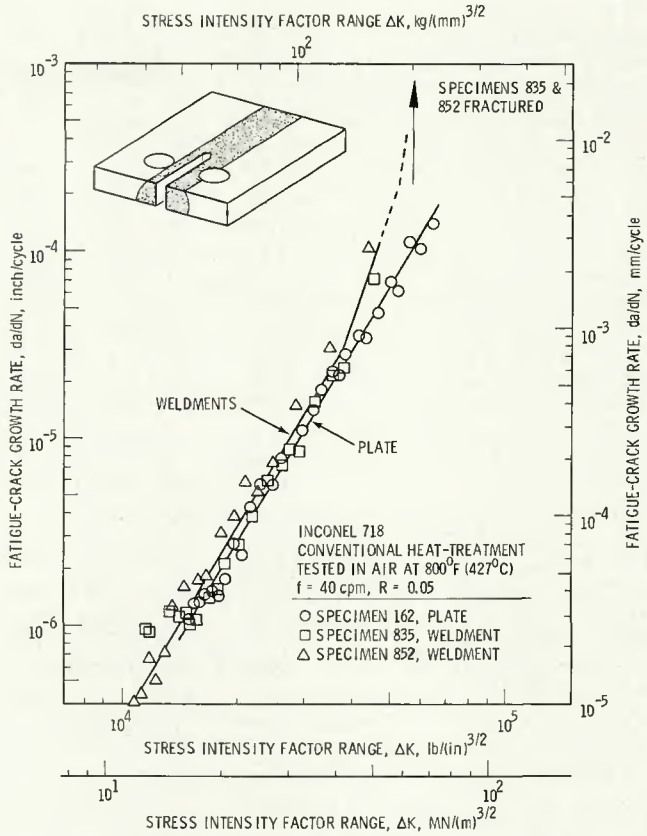

Fig. 2—Fatigue-crack growth behavior of Inconel 718 plate and weldments tested in an air environment at 427 C (conventional heat treatment)

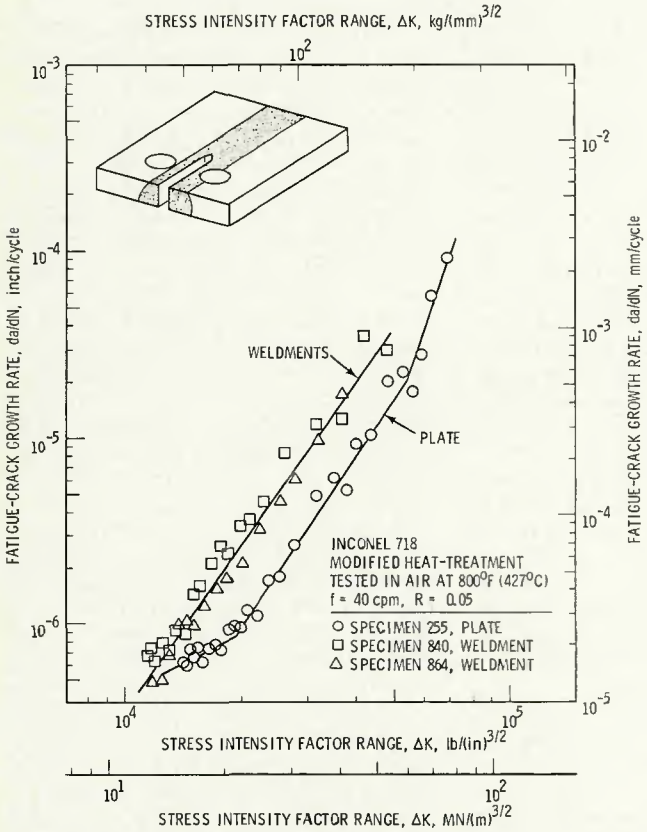

Fig. 3—Fatigue-crack growth behavior of Inconel 718 plate and weldments tested in an air environment at 427 C (modified heat treatment)

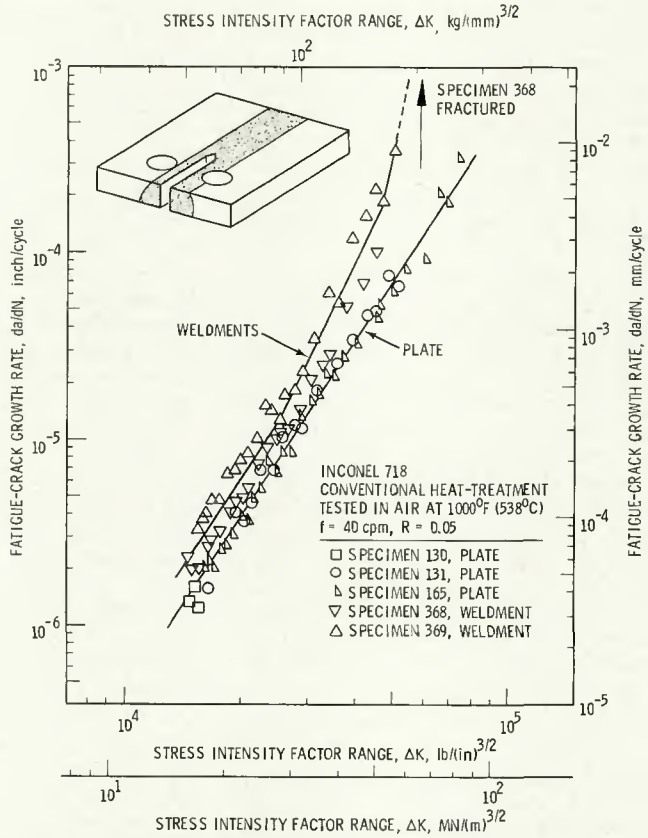

Fig. 4—Fatigue-crack growth behavior of Inconel 718 plate and weldments tested in an air environment at 538 C (conventional heat treatment)

phase. For this reason, the "modified" heat treatment was developed at the INEL.[3] The 1093 C (2000 F) postweld annealing temperature and subsequent modified heat treatment restores adequate ductility and impact strength to the weldments by dissolution of the Laves phase. Similar conclusions were reached in Canada.[10]

Since the nuclear applications of Inconel 718 are mainly in the temperature range 427–538 C (800–1000 F), the present study emphasized this region. Both conventional and modified heat treatments on plate material and weldments were studied in this temperature range. The results, shown in Figs. 2–5, reveal several trends in the data. Least-squares regression analyses were conducted for each group of data (e.g., weldments in a given heat treated condition at a given test temperature), and are shown as linear or bi-linear lines in the Figs. 2–5.

It will be seen that, at each test temperature/heat treatment combination, the crack growth rates are somewhat higher in the weldments than in the plate material. In some cases (e.g., Fig. 2) the differences are minimal and may not be statistically significant,* while in other cases (e.g., Figs. 1 and 3) the differences are appreciable. This observation of higher crack growth rates in weldments than in base metal is in contrast to most observations on the behavior of weldments in ferritic[7] and austenitic[8] steels.

Comparing the results for both heat treatments at a given temperature (e.g., comparing Figs. 2 and 3, or Figs. 4 and 5) reveals that in all cases the modified heat treatment produces lower crack growth rates in a given material than does the conventional treatment. In other words, crack growth rates in weldments given the modified treatment following welding are lower than those in weldments given the conventional postweld heat treatment; also, growth rates in plates given the modified treatment are lower than those in plates given the conventional treatment. In fact, the differences between differing heat treatments on the same product form (e.g., weldments) are often greater than the difference between different product forms given the same heat treatment. It is apparent, then, that postweld heat-treatment is a parameter that must be given careful consideration. It is likewise apparent that the modified treatment appears to give superior results in both weldments and plate material.

The limited results at 24 C (75 F) and 649 C (1200 F) also show the same trend of somewhat higher crack growth rates in the weldments relative to those in plate. These results, however, are of less practical interest since the lower temperature is below that of most reactor applications, while the higher temperature is slightly above the final precipitation temperature, and hence overaging could result.

As mentioned earlier, previous studies[3,10] had suggested that the higher annealing temperature in the modified postweld heat treatment produced a greater dissolution of the Laves phase, and that this in turn produced the improvement in ductility and impact strength. The dissolution of the Laves phase is dramatically illustrated by comparing the photomicrographs of Figs. 7 and 8 for the conventional and modified heat treatments, respectively. The Laves phase (the small white-etching areas surrounded by the dark-etching areas) present in the conventionally-treated weldment (Fig. 7) is almost completely absent in the weldment given the modified treatment (Fig. 8). Very similar photomicrographs may also be seen in the literature.[10] It is therefore reasonable to speculate that the improvement in fatigue-crack growth resistance noted in the weldments given the modified treatment may at least in part be due to the dissolution of the "brittle" Laves phase.

Three of the "conventionally" treated weldment specimens (specimens 368, 835 and 852) failed during fatigue testing. The fracture surfaces of these specimens were flat and devoid of shear lips, indicating a low-energy fracture. Taking specimen 368 as an example and assuming that the failure occurred at the maximum fatigue load, and using the final crack length (taken from the fracture faces), an approximate final value of K may be calculated to be 62.5 MPa$\sqrt{m}$ (56,900 psi $\sqrt{in.}$).

There are a number of reasons why the K value should not be construed as K_{Ic} since many of the criteria of ASTM E399-74 were not met:

1. Since this was a fatigue test, no crack opening deflection transducers were installed as would be necessary in a facture toughness test.
2. The final fatigue crack length was longer than that specified in E399 and "precracking" occurred at approximately the same load as the failure load, rather than at the lower precracking loads required in E399.
3. The load rise time (one-half the fatigue cyclic period for a sine wave) was faster than allowed by E399.

Nevertheless, it is interesting to make the calculation (per E399) to see if specimen 368 was sufficiently thick to produce a "plane-strain" fracture:

$$B > 2.5 \left(\frac{K}{\sigma_{ys}}\right)^2$$

where B = the specimen thickness, and σ_{ys} = the material yield strength at that temperature. Substituting K = 62.5 MPa$\sqrt{m}$ (56,900 psi$\sqrt{in.}$) and σ_{ys} = 928.7 MPa (134,700 psi) the above relationship predicts that a thickness of 11.33 mm (0.446 in.) would have been sufficient to produce a "valid" plane-strain fracture, provided of course, that all of the other requirements of E399-74 were met. Specimen 368 had a thickness of 11.53 mm (0.454 in.), slightly greater than that required by E399. This is a surprisingly low toughness for a test temperature as high as 538 C (1000 F).

Specimens 835 and 852, which were tested at 427 C (800 F), also fractured during fatigue testing. Both failed at final K levels of approximately 57.7 MPa$\sqrt{m}$ (52,500 psi$\sqrt{in.}$). The yield strength of the deposited weld metal at 427 C (800 F) was 933.6 MPa (135,400 psi), and hence a thickness of 9.55 mm (0.376 in.) would have been necessary to produce "plane-strain" fracture. The thicknesses were slightly less, approximately 8.13 mm (0.32 in.), but the fracture surfaces were nevertheless flat and devoid of shear tips.

It is apparent from the above discussion that conventionally-treated weldments can possess relatively low values of toughness, even at temperatures in the range 427–538 C (800-1000 F). In addition, other results[10] show that such weldments have low impact toughness at room temperature. In contrast, none of the weldment specimens given the modified heat treatment fractured during fatigue testing, even through the tests were carried to higher K-levels. The toughness of modified weldments is not presently known quantitatively, but J-integral toughness tests of weldments with both heat treatments are presently in progress at Westinghouse Hanford Company.

Some tests have been conducted at Westinghouse Hanford Company comparing the fracture toughness of Inconel 718 plate given both heat treatments.[12] At room temperature, conventionally-treated plate had a J_{Ic} toughness of 72.5 mm-N/(mm)^2 (414 in.-lb/(in.)^2), while plate given the modified treatment had a toughness of 146.9 mm-N/(mm)^2 (839 in.-lb/(in.)^2). These correspond to approximate K_{Ic} values of 120.5 MPa$\sqrt{m}$ (109.6 ksi$\sqrt{in.}$) and 171.4 MPa$\sqrt{m}$ (156.0 ksi$\sqrt{in.}$), respectively.

At 427 C (800 F), conventionally-

An ASTM round-robin test program[11] has established that a factor of two scatter on da/dN can be expected for intralaboratory tests on a single heat of material, and a factor of three for interlaboratory tests.

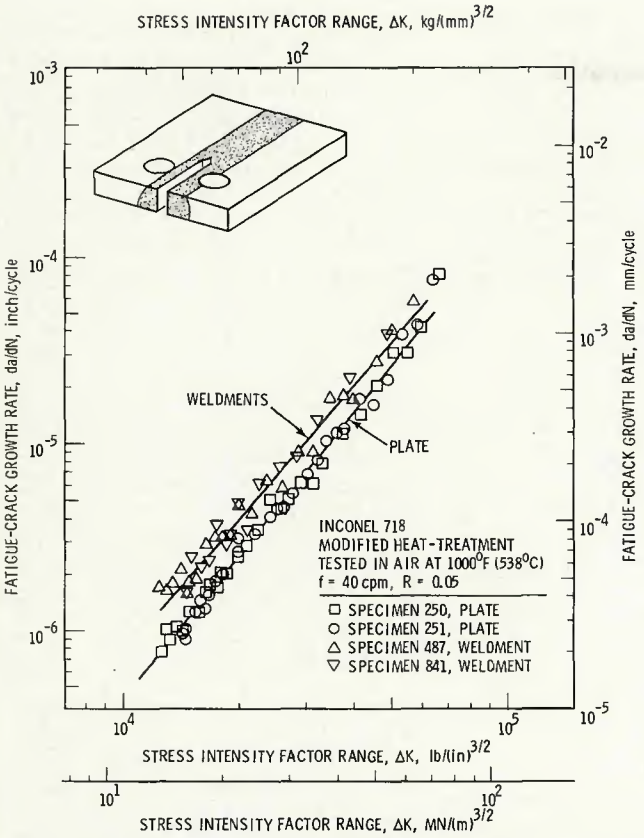

Fig. 5—Fatigue-crack growth behavior of Inconel 718 plate and weldments tested in an air environment at 538 C (modified heat treatment)

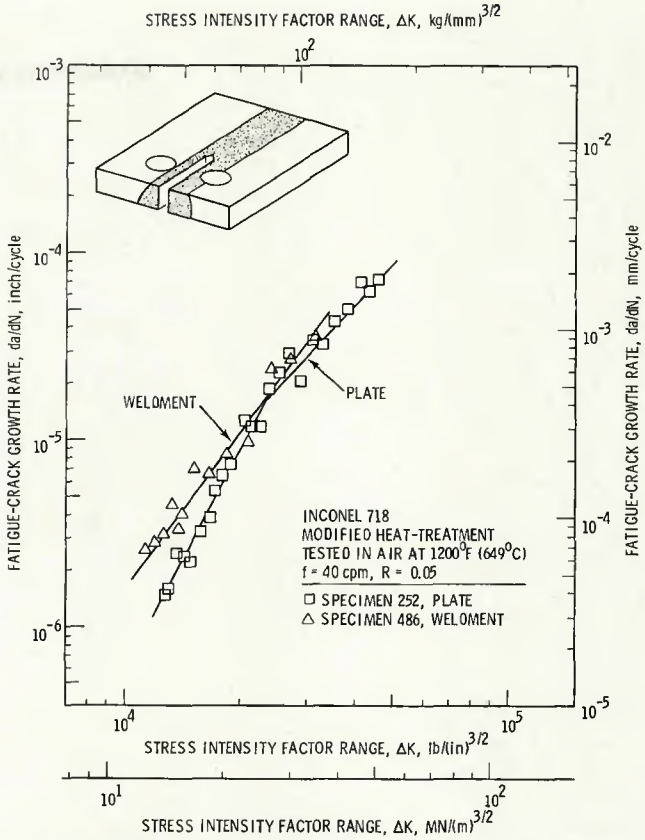

Fig. 6—Fatigue-crack growth behavior of Inconel 718 plate and weldments tested in an air environment at 649 C (modified heat treatment)

Table 4—Mechanical Properties[a]

Heat identification	Heat treatment	Test temperature	0.2% yield strength	Ultimate strength	Total elongation, %	Uniform elongation, %	Reduction in area, %	Notations
A	Conv.	24 C 75 F	1110.7 MPa 161.1 ksi	1366.5 MPa 198.2 ksi	20.5	[b]	[b]	
D	Conv.	24 C 75 F	1037.7 MPa 150.5 ksi	1319.0 MPa 191.3 ksi	18.7	17.6	32.1	[c]
D	Conv.	427 C 800 F	925.3 MPa 134.2 ksi	1139.7 MPa 165.3 ksi	17.7	14.0	30.9	[c]
D	Conv.	538 C 1000 F	893.6 MPa 129.6 ksi	1112.1 MPa 161.3 ksi	15.8	13.9	27.7	[c]
D	Mod.	24 C 75 F	1011.5 MPa 146.7 ksi	1325.2 MPa 192.2 ksi	11.2	10.8	18.0	
D	Mod.	427 C 800 F	889.4 MPa 129.0 ksi	1209.3 MPa 175.4 ksi	13.0	11.9	17.7	
D	Mod.	538 C 1000 F	866.0 MPa 125.6 ksi	1182.4 MPa 171.5 ksi	14.8	12.9	24.4	
D	Mod.	649 C 1200 F	828.7 MPa 120.2 ksi	907.4 MPa 131.6 ksi	10.3	6.2	17.7	
E	Conv.	24 C 75 F	1017.0 MPa 147.5 ksi	1269.3 MPa 184.1 ksi	14.9	14.5	17.1	[d]
E	Conv.	427 C 800 F	933.6 MPa 135.4 ksi	1119.7 MPa 162.4 ksi	17.6	12.7	23.6	[d]
E	Conv.	538 C 1000 F	928.7 MPa 134.7 ksi	1129.4 MPa 163.8 ksi	14.6	13.3	22.8	[d]
F	Mod.	24 C 75 F	970.1 MPa 140.7 ksi	1323.8 MPa 192.0 ksi	20.3	[b]	24.3	[c,d,e]
F	Mod.	427 C 800 F	872.2 MPa 126.5 ksi	1182.5 MPa 171.5 ksi	13.2	[b]	18.6	[c,d,e]

[a] Strain rate = $3 \times 10^{-5}\ s^{-1}$
[b] Not determined.
[c] Average of multiple tests.
[d] Specimens oriented parallel to direction of welding and were comprised entirely of deposited filler metal.
[e] From the literature.[14]

treated plate had a J_{Ic} toughness of 76.2 mm-N/(mm)^2 (435 in.-lb/(in.)^2), and the modified treatment plate had a toughness of 126.1 mm-N/(mm)^2 (720 in.-lb/(in.)^2), again corresponding to approximate K_{Ic} values of 116.4 MPa$\sqrt{m}$ (105.9 ksi$\sqrt{in.}$) and 149.8 MPa$\sqrt{m}$ (136.3 ksi$\sqrt{in.}$). The above value of equivalent K_{Ic} of 120.5 MPa$\sqrt{m}$ (109.6 ksi$\sqrt{in.}$) for conventionally-treated plate at room temperature compares favorably with the value of 109.9 MPa$\sqrt{m}$ (100 ksi$\sqrt{in.}$) that has been given for plate material.[13] It has also been found that K_{Ic} of Inconel 718 weld metal at room temperature was 54.9 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$).[13]

It will be noted that at each of the temperatures where conventionally-treated weldments were studied (Figs. 1, 2, and 4), fatigue-crack growth rates tend to accelerate at the higher levels of ΔK. Fatigue-crack growth curves over wide ranges of ΔK are often observed to be sigmoidal in nature, tending downward toward a vertical asymptote at low values of ΔK as the crack growth threshold is approached, and tending upward toward a vertical asymptote at high values of ΔK as the onset of instability is approached. Therefore, the upward slope transitions observed in Figs. 1, 2 and 4 at the higher values of ΔK probably reflect the rapid acceleration in crack growth rates as K_{max} in the fatigue test approaches the material fracture toughness.

One possible explanation for the increased crack growth rates in conventionally-treated weldments relative to those in modified weldments, could be that the "brittle" Laves particles could be fracturing in the highly-deformed area ahead of the crack tip. The fractured Laves particles could, in turn, initiate microcracks in the matrix material which could then interact with the main fatigue crack. Such a mechanism has indeed been observed microscopically by Barnby[15] studying the role of carbide particles in the fatigue behavior of thermally-aged austenitic steels, and the same mechanism has also been suggested as responsible for the degraded fatigue-crack growth behavior of thermally-aged austenitic steels at room temperature.[16]

The tensile properties of the as-heat treated weld filler metals are shown in Table 4. Comparing the two heat treatments, it will be seen that slightly lower strengths are obtained with the modified treatment. However, perhaps the most significant observation is that although the ductility parameters (elongation and reduction of area) of the conventionally-treated weldments appear to be quite satisfactory in the tensile specimens, these results mask

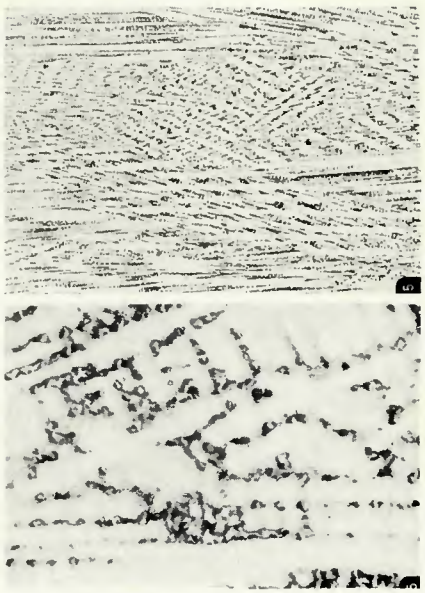

Fig. 7—Photomicrograph of weld deposit in specimen 368 showing Laves phase (small white-etching areas surrounded by the dark areas). A (top)—×100; B (bottom)—enlargement of an area in A, ×750. 10% oxalic acid etch (reduced 50% on reproduction)

the relatively low toughness possessed by these weldments in the presence of a sharp crack. Hence, it is wise to also consider properties other than tensile tests when attempting to evaluate in-service behavior of these weldments.

Two different heats of filler metal were employed with both postweld heat treatments studied at 427 C (800 F). Although the number of tests and heats involved is much too small to make general observations concerning heat-to-heat variations, Figures 2 and 3 show little or no difference in the behavior of the weldments employing the different filler metals. Similarly, there is no apparent difference in the behavior of plate specimens at 24 C (75.2 F) in Fig. 1 and 538 C (1000 F) in Fig. 5 fabricated from different plates. The potential for heat-to-heat and/or melt practice variations is currently being examined in the author's laboratory.

Finally, the observation may be made in comparing the results in Figs. 1-6, that fatigue-crack growth rates generally increase with increasing temperature. This general observation has been noted in numerous previous studies on a wide variety of different alloy systems tested in an air environment.

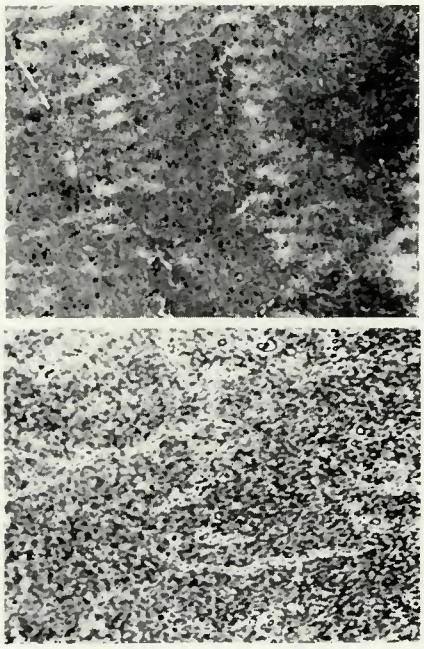

Fig. 8—Photomicrograph of weld deposit in specimen 487 showing almost complete dissolution of the Laves phase. A (top)—×100; B (bottom)—enlargement of an area in A, ×750. 10% oxalic acid etch

Conclusion

The fatigue-crack growth behavior of Inconel 718 plate and weldments given either a "conventional" (ASTM A637) heat treatment or a "modified" (INEL designed to minimize the presence of Laves phase) heat treatment was studied. The results of this study may be summarized as follows:

1. In general, fatigue-crack growth rates in Inconel 718 plate and weldments tested in an air environment increase with increasing test temperature.
2. For the two heat treatments studied, crack growth rates are generally somewhat higher in weldments than in plate material.
3. For a given product form (e.g., weldments or plate), crack growth rates are generally higher in material given the conventional heat treatment than in material given the modified treatment.
4. Conventionally treated weldments apparently exhibit relatively low toughness in the range 427-538 C (800-1000 F), while weldments given the modified treatment apparently have a higher (but unknown) toughness.
5. The improvement in the crack growth and fracture toughness behavior of weldments given the modified heat treatment is thought to be associated with the more complete dissolution of the "brittle" Laves phase obtained with that treatment.

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