Development of a Improved Heat Treatment for Investment Cast Inconel 718 (PWA 649)

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Abstract

An improved, modified heat treat was developed for investment cast Inconel 718 using the Taguchi design of experiments approach. The objectives of the heat treat modifications were to reduce process cycle time, reduce local areas of high hardness and maintain specification property requirements. The heat treat modifications identified resulted in a 30% reduction in processing cycle time, 7 R_c (Rockwell C) drop in local hardness and equivalent or superior mechanical properties. The key process modifications incorporated include the use of an increased temperature / time homogenization cycle, application of a controlled cooling rate from solution heat treat and use of a higher temperature / shorter time precipitation heat treatment.

Superalloys 718, 625, 706 and Various Derivatives
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Introduction

Investment cast Inconel 718 offers many advantages relative to other metal processing techniques. These include improved material usage ("buy to fly" ratios), the ability to produce relatively complex configurations and reduced component cost. However the process has disadvantages; including susceptibility to metallurgical defects such as porosity, segregation and very coarse grain sizes. These result in reduced design capability and difficulty in subsequent processing steps. For structural applications, investment cast Inconel 718 is frequently HIP'ed (hot isostatically pressed) to minimize shrinkage porosity and casting segregation. The HIP step however adds cost to the finished component. For non-structural applications the material is used in the cast + heat treated condition. One manufacturing concern with processing of investment cast Inconel 718 is that areas of local segregation (typically Niobium) produce regions of high local hardness during heat treatment. These regions of high hardness result in increased tool wear and occasional catastrophic tool failure and concomitant increased manufacturing cost (or deviant / scrap parts in the case of tool failure). The detrimental effect of hard, coarse MC carbides on the machinability of Inconel 718 has been previously documented (ref 1) and the regions of high local hardness behave in a similar fashion.

Traditionally, heat treat process optimization has been a time consuming effort as studies were undertaken evaluating the effect of process parameters on material capability. Statistically designed experimental matrix approaches have recently demonstrated their utility as an efficient technique for material process development (ref 2). This approach permits the screening of a large number of process variables and when combined with a confirmation step, result in identification and control of the critical processing variables. The Taguchi based approach to experimental design has proven to be extremely valuable. To identify the process parameters for inclusion in the experimental matrix, the PWA 649 (investment cast Inconel 718) specification heat treat was reviewed. The steps in the heat treat cycle are presented in Table I together with the modifications used in the experimental matrix design and justification. Hardness (Rockwell C and Vickers microhardness of segregated and non segregated regions) was selected as the response variable.

Table I
Heat Treat Processing Steps for PWA 649 (Investment Cast Inconel 718) Selected for Evaluation Together with the Modifications Explored and the Justification for Including Them.

Heat Treat Step	PWA 649	Modifications	Reason
Homogenization	1093°C/1 hour	1163°C/4 hrs	better homogenization
Solution Temp	954°C	1052°C	parts are brazed at 1052°C
Cooling Rate	Air Cool (>1333°C/hr)	111°C / hr	reduces IN718 hardness[1]
Age Cycle	718°C/8 hrs + 635°C/8 hrs	760°C/5 hrs + 649°C/1 hr	reduce cycle time

1. Reduces the hardness of wrought Inconel 718 (ref 4).

Upon completion of the heat treat matrix and verification of the processing trends, typical cast Inconel 718 components were processed through the modified heat treat cycle and properties characterized to verify that specification minimum properties were achieved and the balance of properties was maintained.

Details

A segment of a PW4000 diffuser case in the as cast condition was used for the heat treatment matrix. A Taguchi L8 experimental matrix was selected and the variables and levels presented in Table 1 utilized. In addition to screening the main effects, the experiment was also designed to assess the effect of the cooling rate/age cycle, homogenization cycle/age cycle and homogenization cycle/cooling rate interactions. The experimental runs are listed in Table II.

Table II
Experimental Matrix (L8) Runs for Investment Cast Inconel 718 Process Development

Run #	Homogenization Cycle	Solution Cycle	Cooling Rate	Age Cycle
1	1093°C/1 hr	1052°C/1 hr	111°C/1 hr	760°C/5 hrs + 649°C/1 hr
2	1163°C/4 hrs	954°C/1 hr	111°C/1 hr	760°C/5 hrs + 649°C/1 hr
3	1093°C/1 hr	954°C/1 hr	111°C/1 hr	718°C/8 hrs + 635°C/8 hrs
4	1163°C/4 hrs	1052°C/1 hr	111°C/1 hr	718°C/8 hrs + 635°C/8 hrs
5	1093°C/1 hr	954°C/1 hr	1333°C/1 hr	760°C/5 hrs + 649°C/1 hr
6	1163°C/4 hrs	1052°C/1 hr	1333°C/1 hr	760°C/5 hrs + 649°C/1 hr
7	1093°C/1 hr	1052°C/1 hr	1333°C/1 hr	718°C/8 hrs + 635°C/8 hrs
8	1163°C/4 hrs	954°C/1 hr	1333°C/1 hr	718°C/8 hrs + 635°C/8 hrs

Flange segments were processed through the heat treatments listed in Table II. After heat treatment the samples were prepared using standard metallographic techniques and then evaluated using optical metallography and Vickers microhardness and Rockwell C hardness testing. Typical microstructures observed for each of the heat treat runs are presented in Figure 1. Each of the runs exhibited varying degrees of segregation with the 1163°C cycle generally resulting in greater homogenization than the 1093°C cycle. Vickers microhardness (10 kg) tests were conducted on the segregated and matrix regions of the microstructure with direct Rockwell testing conducted to measure bulk hardness. Hardness results are presented in Table III.

Table III
Hardness Test Results for Material Processed Through the Matrix in Table II

Run #	Matrix Hardness[1]	Segregated Hardness[1]	Bulk Hardness[2]	Δ Hardness[3]
1	33.8 R_C	48.0 R_C	33.8 R_C	14.2 R_C
2	36.0 R_C	45.5 R_C	33.3 R_C	9.5 R_C
3	35.0 R_C	45.5 R_C	36.4 R_C	10.5 R_C
4	39.8 R_C	48.0 R_C	36.5 R_C	8.2 R_C
5	28.5 R_C	50.0 R_C	32.4 R_C	21.5 R_C
6	30.5 R_C	30.5 R_C	34.1 R_C	0.0 R_C
7	37.6 R_C	52.7 R_C	35.7 R_C	15.1 R_C
8	40.0 R_C	50.8 R_C	36.8 R_C	10.8 R_C

1) Converted to R_C from 10 kg Vickers microhardness test results. 2) Direct Rockwell testing.
3) Difference in hardness between segregated and matrix areas.

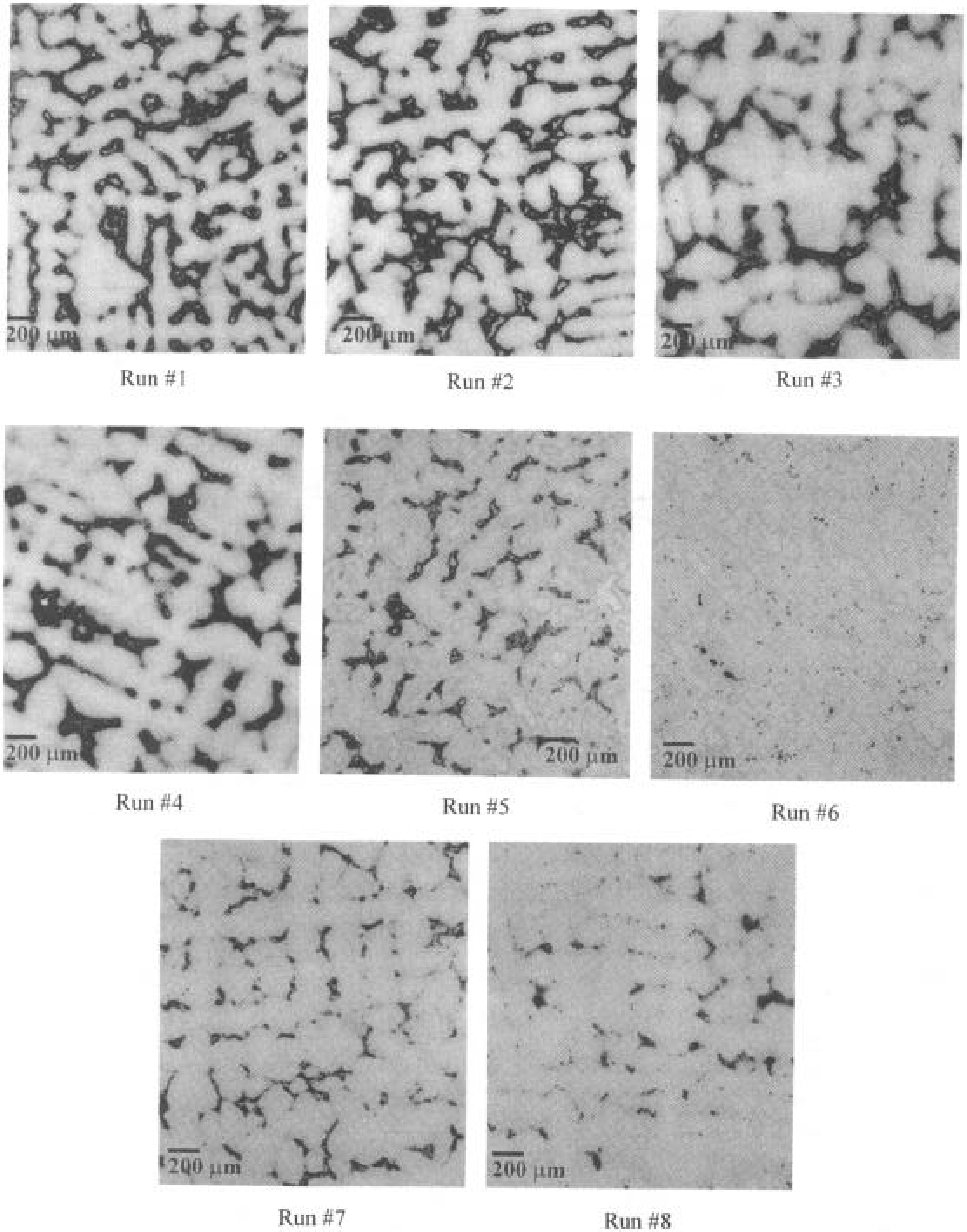
Review of the results show little variation in the bulk hardness with much greater variation in the hardness of the segregated and matrix areas. Hardness values ranging from 31 R_C to 53 R_C were measured for the segregated areas with hardness differentials between the matrix and segregated areas of up to 22 R_C observed. Analysis of the results showed that each of the experimental variables and interactions had statistically significant (> 95 % confidence) effects on one or more of the hardness values measured. The results of the analysis are presented in Table IV.

Table IV
Summary of the Effect of Heat Treatment Processing Variables on Cast Inconel 718 Hardness. Variable Levels Identified are the Statistically Significant Effects and Show the Desired Level to Reduce Hardness

Factors and Interactions	Matrix Hardness[1]	Segregated Hardness[1]	Bulk Hardness[2]	Δ Hardness[3]
Cooling Rate	Fast			
Age Cycle	Short	Short	Short	
Homogenization Cycle	1093°C	1163°C	1093°C[4]	1163°C
Solution Temperature		1052°C		1052°C
Age Cycle/Cooling Rate	Short / Fast	Short / Fast		
Homogenization Cycle/Aging Cycle		1163°C / short		1163°C / short
Homogenization Cycle/Cooling Rate		1163°C / Fast	1163°C / slow	1163°C / Fast

1) Converted to R_C from 10 kg Vickers microhardness test results. 2) Direct Rockwell testing.
3) Difference in hardness between segregated and matrix areas. 4) Marginally significant.

The results indicate that the use of an increased homogenization temperature and shortened age cycle significantly reduce the hardness difference between the segregated and matrix regions, primarily by reducing the hardness of the segregated areas. To verify the results additional segments of the cast diffuser were processed through the confirmation heat treat runs listed below. The objectives were to verify the effect of homogenization cycle and cooling rate on hardness together with establishing a baseline value (run 3b). Similar to the above, Vickers microhardness and direct Rockwell hardness testing was conducted and the results are presented in Table V.



Run #1 Run #2 Run #3

Run #4 Run #5 Run #6

Run #7 Run #8

Figure 1
Typical Microstructures Observed in Investment Cast Inconel 718 Processed Through Experimental Heat Treatments Listed in Table II. Etch 10% Oxalic Acid

Experimental Heat Treatment Confirmation Runs

Run 1 : 1163°C/4 hrs + Air Cool (AC) followed by 954°C/1 hr + AC then sectioned in half
1a) : aged 760°C/5 hrs + 649°C/1 hr 1b) : 760°C/8 hrs + 635°C/8 hrs
Run 2 : 1163°C/4 hrs + AC followed by 954°C/1 hr + cool 111°C/hr then sectioned in half
2a) : aged 760°C/5 hrs + 649°C/1 hr 2b) : 760°C/8 hrs + 635°C/8 hrs
Run 3 : 1093°C/1 hr + AC followed by 954°C/1 hr + AC then sectioned in half
3a) : aged 760°C/5 hrs + 649°C/1 hr 3b) : 760°C/8 hrs + 635°C/8 hrs

Table V
Hardness Test Results for Investment Cast Inconel 718 for Material Processed through the Confirmation Runs.

Run #	Matrix Hardness[1]	Segregated Hardness[1]	Bulk Hardness[2]	Δ Hardness[3]
1a	43.0 R_C	53.0 R_C	31.2 R_C	10.0 R_C
1b	41.0 R_C	51.0 R_C	36.6 R_C	10.0 R_C
2a	40.5 R_C	45.5 R_C	34.3 R_C	5.0 R_C
2b	38.5 R_C	44.0 R_C	37.4 R_C	5.5 R_C
3a	< 20 to 37 R_C[4]	50.5 R_C	25.8 R_C	13.5 to >20 R_C
3b	35.0 R_C	54.5 R_C	34.8 R_C	19.0 R_C

1)Converted to R_C from 10 kg Vickers microhardness test results.2) Direct Rockwell testing. 3) Difference in hardness between segregated and matrix areas. 4). Significant hardness variation observed in matrix areas.

Comparing the results for runs 1 and 3, the results show that the increased homogenization cycle temperature reduced the hardness difference between the matrix and segregated areas by increasing the matrix hardness. The effect of controlling the cooling rate from solution heat treatment to 111°C/hr further reduced the hardness difference, by reducing the hardness of both the segregated and matrix areas (compare runs 1 and 2). The results from the above runs verified the trends observed in the original experimental matrix. To summarize the effect of the major processing step modifications:

- o Increase homogenization to 1163°C / 4 hrs from 1093°C / 1 hr resulted in a slight increase in the bulk hardness. The hardness difference between the matrix and segregated areas was reduced by increasing the hardness of the matrix regions.
- o Incorporating a cooling rate of 111°C/hr from the solution temperature results in a slight increase in bulk hardness with a reduction in the hardness of the segregated areas and hardness difference between the matrix and segregated areas.
- o Changing the age cycle to 760°C/5 hrs + 649°C/1 hr reduced the bulk hardness and eliminated about 10 hours from the processing cycle.

A specimen test program was then initiated to define the impact of the processing modifications on the balance of properties of investment cast Inconel 718. Two production castings (a bearing support and bearing housing) scrapped for dimensional deviations were obtained in the as cast condition. Each casting was sectioned in half with one segment being processed through the baseline heat treat process with the remaining segment processed through the modified heat treatment. A comparison of the microstructures resulting from the two processes is presented in Figure 2. Consistent with the development work, both processes failed to completely eliminate casting segregation, however the modified process appears to reduce it significantly. Tensile, creep rupture, high cycle fatigue (fully reversed bending) and fatigue crack growth specimens were machined for material characterization. A summary of the source of test material, specimen configuration and test conditions is presented in Table VI. Results for each test type conducted will be discussed in the following sections.

Table VI
Mechanical Property Test Matrix for Inconel 718 Heat Treatment Modifications

Test	Test Conditions	Specimen Type	Component
Tensile	20°C, 468°C, 649°C	FML96478-201	bearing support
Creep Rupture	649°C / 552 MPa 704°C / 448 MPa	FML96478-201	bearing support
High Cycle Fatigue	468°C / R = -1 / 1800 cpm	MT 36 (Krouse bending)	bearing support
Fatigue Crack Growth	371°C & 593°C / 10 cpm / R=.1	MT 52 (compact tension)	bearing housing

Multiple tensile tests were conducted at each temperature for both heat treat processes and two data distributions observed. Typically the modified heat treatment exhibited higher strengths and lower ductility's than the baseline material. On average, tensile strengths were increased 10% for the modified heat treatment. A comparison between the baseline and modified heat treat results is presented in Table VII. Both processes achieved specification property requirements.

Table VII
Comparison of the Tensile Properties of Investment Cast Inconel 718 Processed
With a Standard (Baseline) and Modified Heat Treatment.

	.2 % Yield (MPa)		Ultimate (MPa)		Elongation (%)		Reduction in Area (%)	
Temperature	Base[1]	Mod[2]	Base[1]	Mod[2]	Base[1]	Mod[2]	Base[1]	Mod[2]
20°C	803.5	852.2	986.7	1041.8	22	16.3	28.5	26.8
468°C	653	748.1	768.1	852.2	18.8	15.3	29.6	33.4
649°C	644.7	708.1	747.4	823.3	19.6	13.2	29.2	31.2
Spec[3] 20°C	758.5		861.9		5		10	

1) Baseline (PWA 649) Heat Treatment
2) Modified Heat Treatment
3) PWA 649 Specification Requirements

Multiple creep rupture tests were also conducted with the majority of the testing concentrated at the specification conditions 704°C/448 MPa. Extensometry was attached to the specimen grips enabling measurement of specimen creep during the stress rupture test. Similar to the tensile results, two distributions of data were observed with the modified heat treatment exhibiting significantly improved creep rupture life relative to the baseline process. Both of the modified heat treat specimens tested at 649°C / 552 MPa were discontinued after 1000+ hours in test having just reached .5 % creep. All the baseline specimens tested at the same conditions ruptured in 500 hours or less. Average creep rupture lives are presented in Table VIII. Both heat treat processes met specification property requirements.

Table VIII
Comparison of the Creep Rupture Properties of Investment Cast Inconel 718 Processed
With a Standard (Baseline) and Modified Heat Treatment.

	.5% Creep Life (hrs)		Rupture Life (hrs)		Elongation (%)		RA (%)	
Test Conditions	Base[1]	Mod[2]	Base[1]	Mod[2]	Base[1]	Mod[2]	Base[1]	Mod[2]
649°C/552 MPa	77.6	1175+[3]	260.7	disc[4]	7	disc[4]	14.7	disc[4]
704°C/448 MPa	52	191.8	151.9	284.7	5.9	6	20.8	14.2
Specification[3] 704°C/448 MPa			23		3			

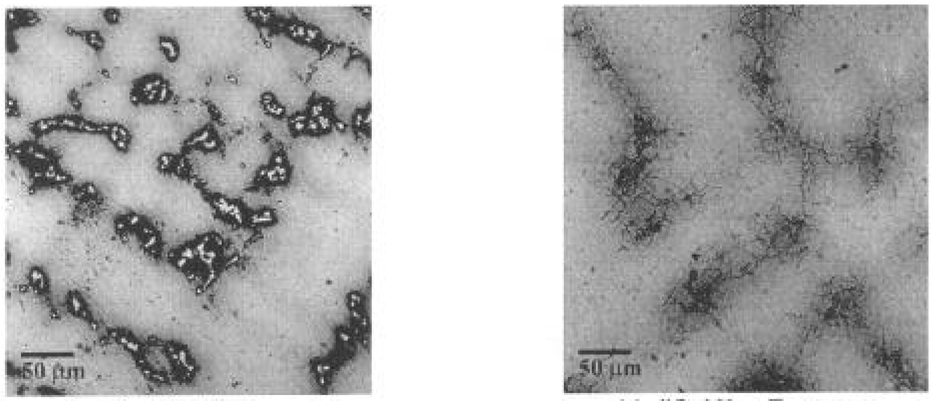
1) Baseline (PWA 649) Heat Treatment
2) Modified Heat Treatment
3) PWA 649 Specification Requirements
4) Specimens discontinued after ~1200 hours in test. Post test creep elongation was ~.5 %.

Fully reversed (R=-1) high cycle fatigue (HCF) testing was conducted at a temperature of 468°C and 1800 cpm using the Krouse bending test setup. Specimens not failing after $1x10^7$ cycles were discontinued and treated as run outs. The test results are presented in Figure 3 and indicate that the modified heat treatment has HCF capability equivalent to or better than the baseline process. Analysis of the data suggests that the modified heat treatment has a runout stress ~ 10 % higher than the baseline process.

Fatigue crack growth tests were conducted under R=.1 / 10 cpm conditions at both 371°C and 593°C. The results are presented in Figure 4 and indicate that both heat treat processes resulted in equivalent fatigue crack growth rates.

Discussion

The results of this study identified a series of heat treat modifications to P&W's standard process for investment cast Inconel 718 that result in a more uniform microstructure while retaining mechanical properties equivalent to the baseline material. The key process modifications and their probable effects are:



Baseline Heat Treatment

Modified Heat Treatment

Figure 2

Microstructure of Investment Cast Inconel 718 used for the Specimen Test Program Processed with a Baseline, Standard (left) and Modified (right) Heat Treatment. Etched with 10% Oxalic Acid

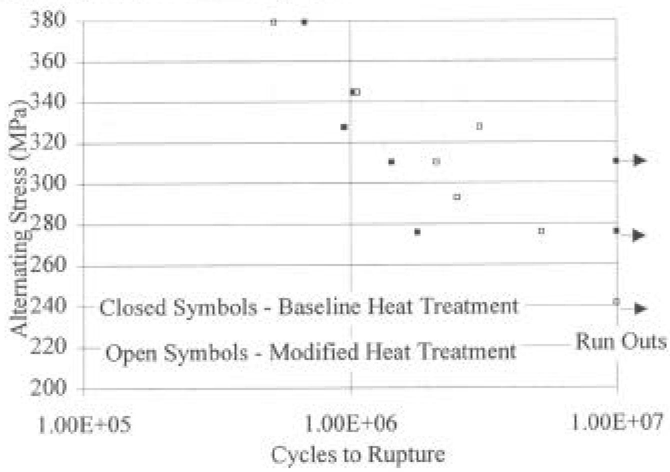


Figure 3

High Cycle Fatigue Properties of Cast Inconel 718 Processed with a Standard and Modified Heat Treatment

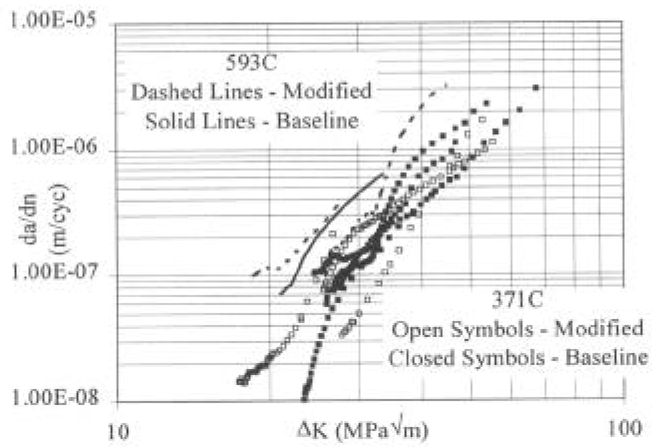


Figure 4

Fatigue Crack Growth Rate of Cast Inconel 718 Processed with a Standard and Modified Heat Treatment

- o increasing homogenization temperature reduces the degree of segregation observed and increases the hardness of the matrix (probably due to the homogenizing effect). The improved homogenization enables use of the 760°C short age cycle which overages material processed with a lower temperature homogenization resulting in reduced properties. (ref 3)

- o incorporating a controlled cool from solution results in slight overaging of the segregated regions reducing their hardness without affecting the hardness of the matrix. Use of the controlled cool should also eliminate the development of high residual stresses due to aggressive cooling or quenching after the solution cycle.

- o the use of a higher temperature, shorter age cycle further reduces the hardness of the segregated regions while slightly improving both the bulk and matrix hardness. The short age cycle reduces the total heat treat time by approximately 25%.

The P&W investment cast Inconel 718 specification has been revised to permit use of the modified heat treatment.

References:

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4) J. J. Schirra; "Effect of Heat Treatment Variations on the Hardness and mechanical Properties of Wrought Inconel 718"; Superalloys 718, 625, 706 and Various Derivatives; (1997)