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EVALUATION OF THERMAL TREATMENTS FOR NICKEL-BASE INCONEL 718 ALLOY IN BELLOWS AND GIMBAL APPLICATIONS

by

P. J. Valdez

Prepared for

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FINAL REPORT

EVALUATION OF THERMAL TREATMENTS FOR NICKEL-BASE INCONEL 718 ALLOY IN BELLOWS AND GIMBAL APPLICATIONS

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FOREWORD

This report was prepared in the Research Laboratories of the Solar Division of International Harvester Company, under contract NAS-8-11282, Task Order R-ME-1V-S4. The work is administered under the National Aeronautics and Space Administration, Manufacturing Engineering Laboratory, Huntsville, Alabama, with C. N. Irvine, W. K. Davis, and P. G. Parks serving as project engineers.

This report covers work conducted from August 1965 through May 1967.

Engineering and Research personnel supervising the several phases of the program and contributing to the compilation of this report were Paul J. Valdez, Principal Investigator; H. T. Mischel, Program Manager; C. P. Davis, Weld Development; D. Jones, Mechanical Testing; G. Jones, Metallography; J. Steinman, Electron Microscopy Study; and C. Saucer, Electron Microprobe Evaluation.

This report is the final report under contract NAS-8-11282, Task Order R-ME-1V-S-4. Solar's report number is RDR 1460-1.

The helpful assistance of Mr. John V. Long, Director of Research; G. B. Pritchett, Staff Metallurgist; and J. W. Welty, Metallurgical Consultant, is gratefully acknowledged.

Acknowledgement is also extended to Mr. E. Raymond, metallurgist with Huntington Alloy Products, Division of International Nickel Company, for his advice in helping to identify and classify microconstituents of the Inconel 718 alloy.

ABSTRACT

An investigation has been conducted to establish a thermal treatment for the Inconel 718 alloy for use in bellows and gimbal structures. Because of the likelihood that the nickel-base alloy would be welded in the fully heat-treated condition, variations in thermal treatments and the relationship of the thermal treatments to heat-affected zone cracking and strength properties were studied.

The scope of the program was enlarged to determine the effect of cold work and subsequent variations in aging treatments on strength properties. In addition, the effects of time-temperature variations on crack susceptibility, strength, and fatigue properties were also determined.

The results indicated that the weld heat-affected zone cracking susceptibility of the aged Inconel 718 alloy increased as the annealing temperature was raised to the maximum investigated, 1950 F. The Pratt & Whitney-developed thermal treatment in accordance with AMS 5596 (low anneal, 1750 F, followed by an 18-hour double-aging cycle), resulted in the least amount of heat-affected zone cracking for the two thicknesses evaluated. The next best thermal treatment, relative to reduced cracking susceptibility, is the Solar developed thermal treatment which consists of an 1800 F anneal, followed by a short double-aging cycle of approximately 8.5 hours.

Test on cold worked Inconel 718 material, simulating bellows forming operations, have indicated that interstage annealing may be eliminated if an abbreviated aging cycle is used. Material with five percent cold work subjected to a short, double-aging treatment of 2.5 hours resulted in an average ultimate strength of 195.8 ksi, a yield strength of 160.4 ksi, and good ductility corresponding to 22.5 percent on 0.040-inch Inconel 718 material.

Time-temperature variations indicated that heat-affected zone cracking sensitivity increased as the energy input increased to 1155 Joules/inch. Strength properties were not degraded by variations in heat input when welding the Inconel 718 alloy in the annealed condition. Welding of specimens in the age-hardened condition resulted in strength degradation as the energy input was increased. There does,

however, appear to be a threshold beyond which a further increase in energy input will result in a slight reversal in yield strength values.

Annealing and aging after weld planishing is essential for long fatigue life of bellows manufactured from the Inconel 718 nickel-base alloy. In addition, annealing at 1850 F offers increased life over a 1750 or 1950 F interstage anneal.

Evaluation of the results from the viewpoint of fabricability, fatigue life, and mechanical properties showed that the Inconel 718 alloy annealed in the range of 1750 to 1850 F, and double aged offers the greatest potential for bellows and ducting application. Further, it was found that the use of an annealing cycle above 1900 F which resulted in solutioning of carbides and Laves phase had an adverse effect on weldability and mechanical properties.

SUMMARY

A study was conducted to investigate the effects of thermal treatments on the Inconel 718 nickel-base alloy, and the effects of these thermal treatments on the subsequent fabrication processes. Of primary concern was the effect of welding the Inconel 718 alloy in the hardened condition because of welding difficulties being experienced by several major subcontractors to NASA. Difficulties were encountered in welding heavy sections to thin sections and in welding heavy sections under high restraint for use in gimbal and ducting sections for the Saturn missile. The major problem was related to hot cracking in the weld heat-affected zone during welding. It was evident that if successful application of this alloy is to be made, the underlying causes of cracking and methods to prevent cracking must be determined. An effort was made to reach a solution and to find a suitable means for determining the crack susceptibility of the Inconel 718 alloy in various thicknesses, heats, and variations in thermal treatments and primary processes. Attempts to determine crack susceptibility from heat to heat with variations in thermal treatments by the use of the Varestraint test developed by Savage of RPI have been relatively successful. Varestraint test results on various heats have shown that there is considerable difference in the heat-affected zone cracking behavior of the heats tested. It was also established that the cracking sensitivity of the age-hardened Inconel 718 alloy increases as the annealing temperature is raised from 1750 to 1950 F. In addition, some difference in cracking sensitivity was also noted in the material supplied by various producers. The increase in cracking susceptibility of one as-received material over another has been attributed to increased amounts of grain boundary segregation, particularly, in areas of titanium-columbium carbo-nitride stringer formations. Microcracking in the heat-affected zone followed the general pattern of the stringer formations.

The result of one hour of abbreviated aging cycles was to reduce the effect of the higher annealing temperature on the cracking sensitivity of the Inconel 718 alloy.

However, strength properties and, in particular, yield strength values are degraded by the abbreviated aging cycles. Typical yield strength values range from 110.0 to 126.0 ksi.

The thermal treatment which resulted in the least heat-affected zone cracking in the two thicknesses evaluated is the Pratt & Whitney-developed thermal treatment (AMS 5596). This cycle consists of an annealing treatment at the relatively low temperature of 1750 F followed by a double aging cycle. The next best treatment is Solar's cycle which consists of an 1800 F anneal followed by an abbreviated double aging cycle.

Variations in welding parameters resulted in an increase in the cracking sensitivity of Varestraint test specimens as the heat energy input was increased.

Variations in welding parameters did not show any particular effect in strength values on specimens welded in the annealed condition. However, considerable scatter in strength properties was noted on specimens welded in the age-hardened condition.

Axial fatigue tests of simulated bellows specimens indicated that an increase in heat energy input increased rather than decreased the fatigue life. In addition, annealing after welding planishing is necessary for long fatigue life. However, annealing at 1850 F results in a substantial increase in fatigue life over a 1750 F anneal and a 20 percent increase over a 1950 F anneal.

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1

EXPERIMENTAL PROCEDURE

1.1 MATERIAL

The material evaluated in this program consisted of two thicknesses, 0.040- and 0.209-inch material. Five heats of each thickness with specified restricted chemical compositions were ordered. The chemical variations relative to the titanium and aluminum contents studied were within the broad range of various specifications covering the alloy (Ref. 1).

The bulk of the material for this evaluation was produced by Huntington Alloy Products (Huntington). In addition, Eastern Stainless Steel (Eastern) supplied two heats for evaluation. Material was supplied in the cold-rolled and pickled condition, unless otherwise indicated, with Solar performing the required high-temperature annealing treatments.

A special request by the NASA project engineer to include material melted by the Hopkins process resulted in a limited amount of crack susceptibility testing of 0.125- and 0.250-inch thick Inconel 718 material supplied by Firth Sterling, Inc. In addition, two sample pieces of double vacuum melted material produced by Armco Steel Corporation (Armco) were also evaluated for weld cracking susceptibility.

Table I shows the target composition range of the aluminum and titanium content as well as the reported values of the titanium and aluminum contents on heats ordered and supplied for this study. Table II shows the reported chemical composition of the heats supplied by all producers. Since most producers tend to melt to a particular aluminum-titanium ratio, Solar's restricted requirements on these two elements caused considerable difficulty in acquiring materials for evaluation. Of particular difficulty was the acquisition of a heat with high-aluminum low-titanium composition. This particular composition was never acquired for this evaluation. Since producers do not melt to this particular titanium-aluminum ratio, acquisition of a special heat was not pursued.

TABLE I

INCONEL 718 MATERIALS FOR EVALUATION

Target Composition		Reported Composition and Supplier				
Composition	Percent	Aluminum (%)	Titanium (%)	Heat Number	Gage (in.)	Supplier
Low aluminum	0.20 to 0.40	0.41	0.88	6790	0.040 and 0.209	Huntington
Low titanium	0.65 to 0.80					
Low aluminum	0.20 to 0.40	0.46	1.15	6394	0.040 and 0.209	Huntington
High titanium	1.00 to 1.20					
High aluminum	0.65 to 0.80	0.68 0.75 0.70	1.14 1.10 1.00	95224 95221 6300	0.209 0.040 0.040	Eastern Eastern Huntington
High titanium	1.00 to 1.20					
High aluminum	0.65 to 0.80	718 alloy is not normally produced to this Ti-Al ratio. Consequently, material with this Al-Ti ratio was not evaluated.				
Low titanium	0.65 to 0.80					
Average aluminum	0.55 to 0.65	0.60	0.92	6518	0.040 and 0.209	Huntington
Average titanium	0.80 to 0.95					

TABLE II

REPORTED CHEMICAL COMPOSITION OF ALL HEATS USED IN THIS EVALUATION

Heat Number	C	Mn	S	Si	Cr	Ni	Cu	Ti	Al	Cb+Ta	Mo	B	Co	Fe	P
6300E(1)	0.04	0.23	0.007	0.29	18.41	53.05	0.04	1.0	0.70	5.45	3.20	0.0028	0.06	17.56	
6394E(1)	0.05	0.24	0.007	0.30	18.45	52.95	0.06	1.15	0.46	5.63	3.13	0.0033	0.08	17.55	
6518E(1)	0.05	0.21	0.007	0.30	18.28	52.67	0.06	0.92	0.60	5.09	3.13	0.0030	0.07	18.66	
6790E(1)	0.04	0.22	0.007	0.34	18.76	52.51	0.04	0.88	0.41	4.91	3.10	0.0025	0.06	18.76	
95221(2)	0.09	0.02	0.005	0.03	18.74	51.97	0.02	1.10	0.75	5.40	3.30	0.0034	0.06	BAL	0.011
95224(2)	0.04	0.02	0.005	0.05	18.60	51.77	0.03	1.14	0.68	5.07	3.25	0.0037	0.07	BAL	0.005
D-562(3)	0.06	0.01	0.007	0.05	19.15	51.93	<.10	1.16	0.48	5.00	3.21	0.0042	0.04	BAL	0.006
A-786(3)	0.08	0.08	0.005	0.01	20.18	52.78		0.80	0.42	5.17	3.01	0.002	0.05	17.35	0.007
IV0016(4)	0.034	0.09	0.002	0.10	18.56	52.30	0.03	0.97	0.58	5.19	3.04	0.005	0.19	BAL	0.007

Producer:
1. **Huntington Alloy Products**
2. **Eastern Stainless**
3. **Firth Sterling**
4. **ARMCO Steel Corporation**

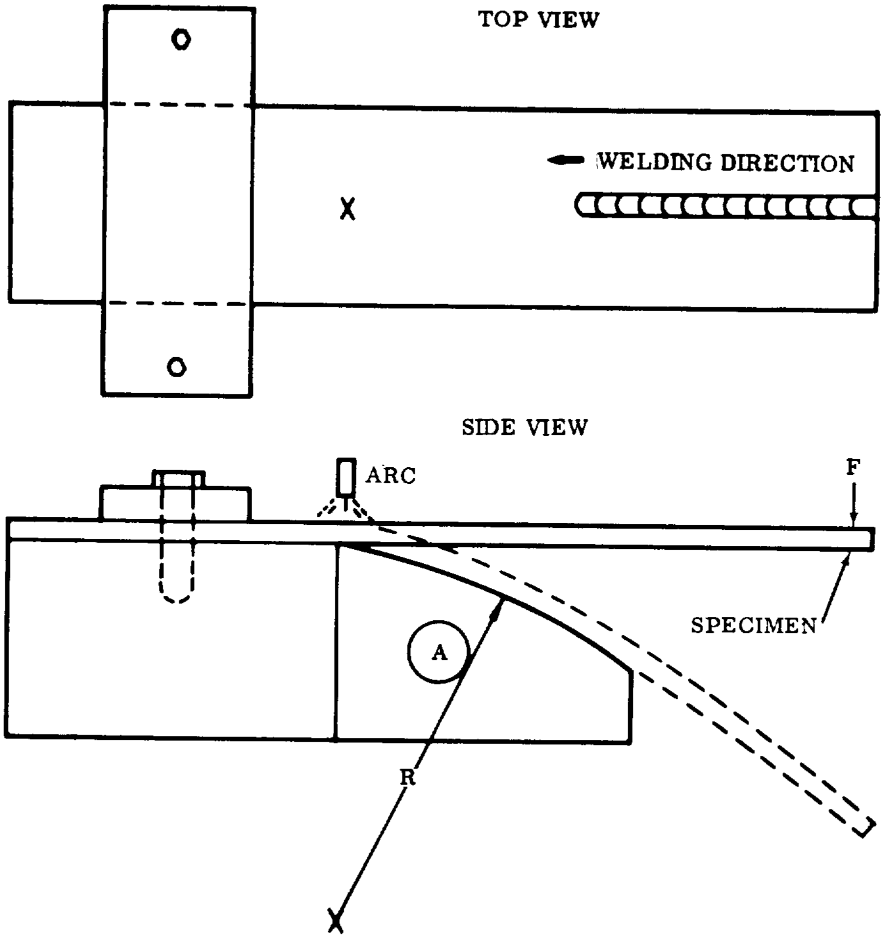


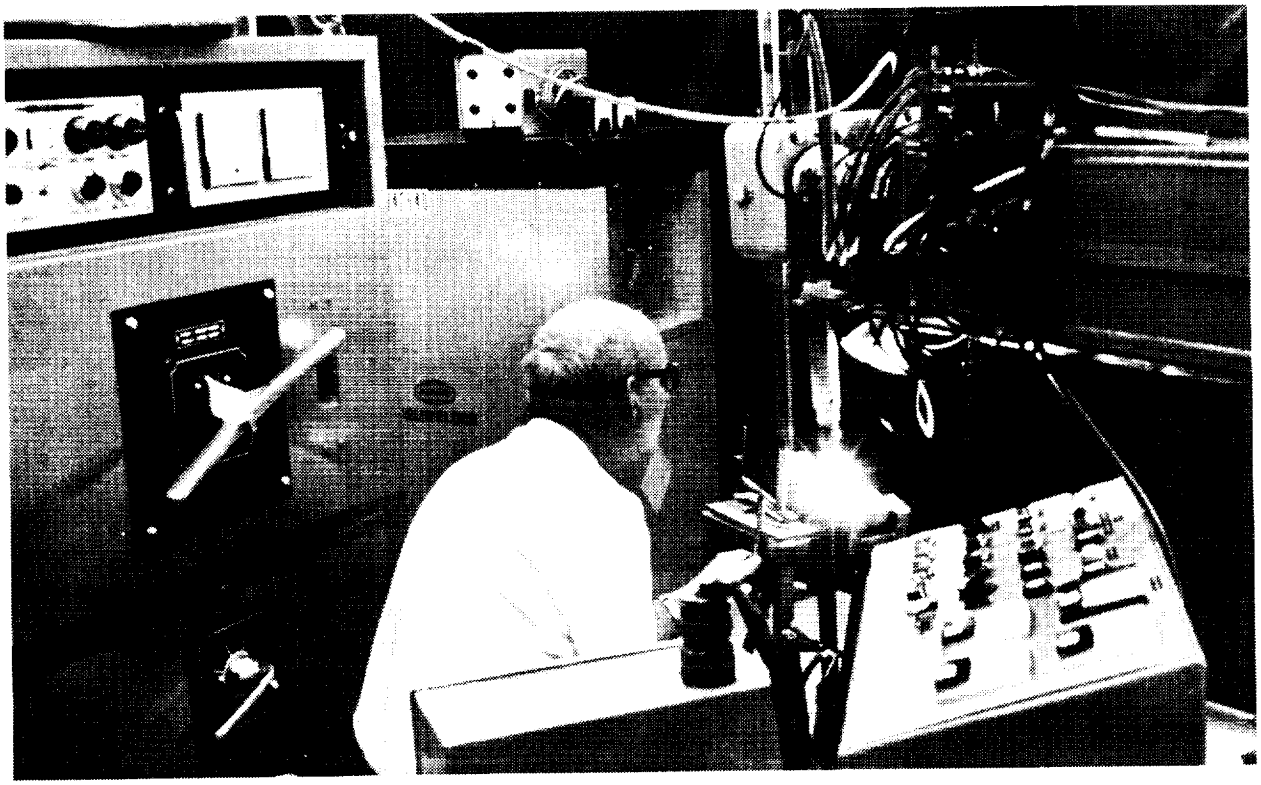
FIGURE 1. OPERATION OF THE VARESTRAINT TEST

Primary information from Huntington Alloy Products shows that their Inconel 718 material is air melted, hot forged, then vacuum-arc remelted. Material supplied by Eastern and Armco is vacuum-induction melted, followed by consumable electrode vacuum-arc remelting. Hopkins-processed material supplied by Firth Sterling is vacuum-induction melted and then consumable electrode remelted using a protective flux blanket. Complete primary processing sequences of the materials acquired for this study are contained in Appendix A.

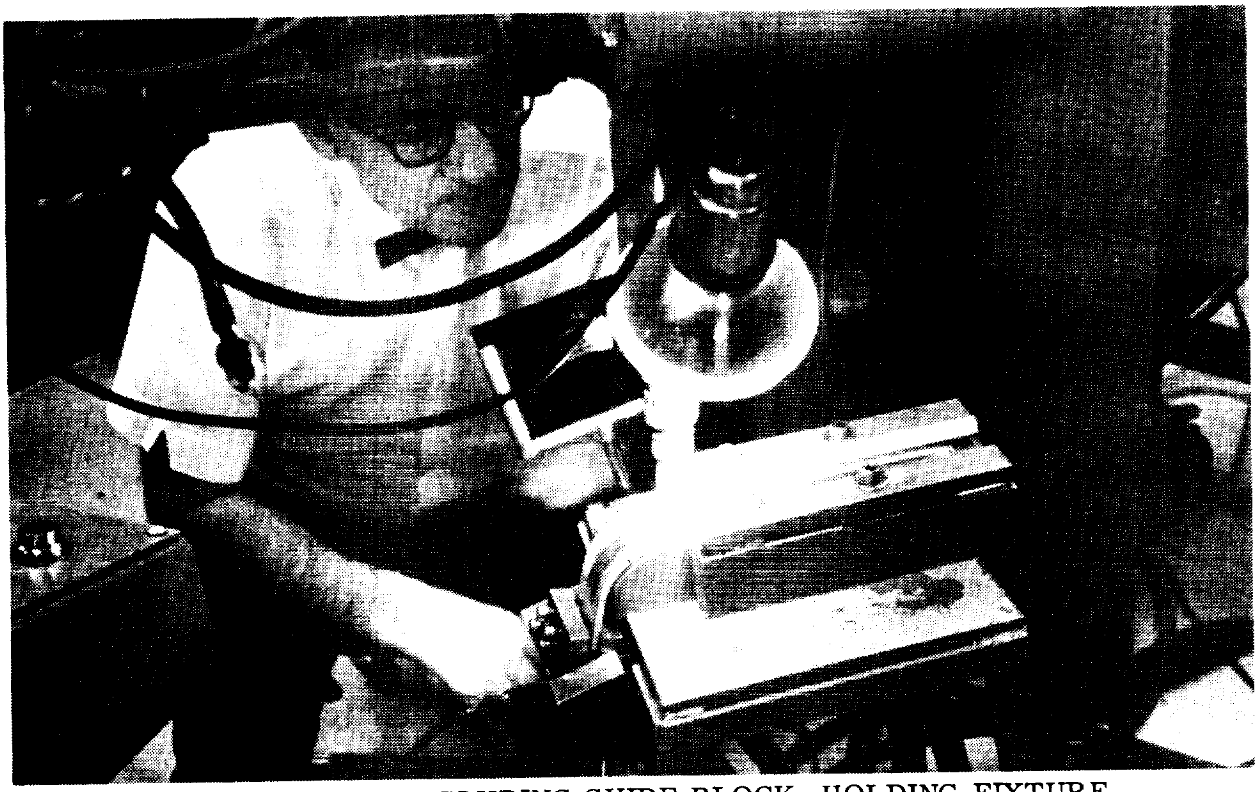
1.2 PHASE I - HEAT TREATING AND WELD CRACKING SENSITIVITY STUDY

1.2.1 Varestraint Test Apparatus

A Varestraint testing facility, similar to the test equipment developed by Dr. Warren Savage of Rensselaer Polytechnic Institute (Ref. 2), was designed and built. The test uses a small specimen supported as a cantilever beam (Fig. 1 and 2).



A. OVERALL/ VIEW



B. CLOSE VIEW INCLUDING GUIDE BLOCK, HOLDING FIXTURE, AND LOADING RAM

FIGURE 2. VARESTRAINT TESTING AND RECORDING EQUIPMENT

A loading yoke is located near the overhanging end of the specimen. When the weld bead reaches point X at the left end of the guide block A, the specimen is quickly bent by force F to conform to the curvature of the guide block. Knowing the physical dimensions of the test specimen and the guide block, the nominal value of the applied augmented-tangential strain in the outer fibers of the test specimen can be calculated as follows:

Augmented-tangential strain = $\epsilon_t = t/2R$

where t = specimen thickness, and R = radius of curvature of guide block.

At the instant of application of the augmented strain, all temperatures from the melting point to slightly above room temperature exist in the temperature gradient surrounding the weld.

The operation of the Varestraint Test Apparatus is quite simple once welding parameters have been established. A technician has only to press a button to initiate the following sequence:

- Purge gas flows to torch
- High-voltage impulse arc is started
- Arc is established - automatic voltage control is in effect
- Weld travel is initiated
- Force is applied to the test specimen at a predetermined point
- Weld continues for approximately one inch beyond bend tangent and stops
- Arc is extinguished
- Apparatus deenergized

The Varestraint apparatus built at Solar is designed so that only minor adjustments are necessary to weld and bend materials of varying thicknesses.

Cracking sensitivity of a particular alloy subjected to the Varestraint test can be revealed by:

- Cracking threshold
- Number of cracks
- Maximum crack length
- Total combined crack length either in the fusion zone and/or in the heat-affected zone.

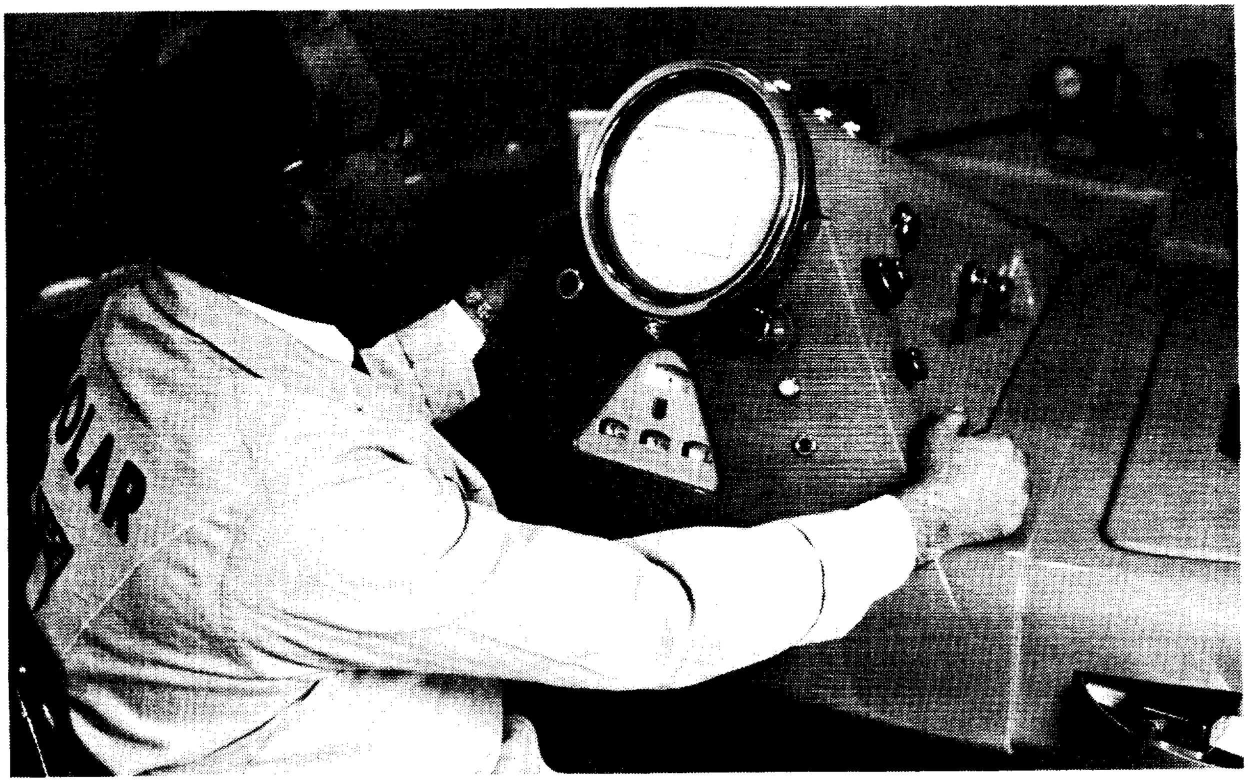


FIGURE 3. ELECTRON MICROSCOPE

Because the effect of thermal treatments on the cracking sensitivity of the Inconel 718 alloy was one of the objectives of this study, it was decided that the total combined crack length produced in the heat-affected zone would be the quantitative index to be used in the evaluation. Varestraint tested specimens were manually cleaned with Oakite alkaline cleanser, rinsed, and etched with Marbles reagent prior to examination with a metallurgical microscope. The cleaning and etching procedure eliminates possible errors in evaluation of the as-welded surface by exposing cracks at the edge of the fusion zone which could otherwise be obscured by surface roughness and oxidation. Thus, the rating procedure is greatly simplified over a rating which would involve sectioning, mounting, and polishing for metallographic examination.

1.2.2 Electron Microscope and Electron-Probe Microanalyzer Studies

A Norelco electron microscope (Fig. 3) and a Norelco AMR3 electron beam microanalyzer (Fig. 4) were used during this program to help identify microconstituents and phases which may be associated with the cracking tendency of the Inconel 718 alloy. The microprobe analyzer employed a one micron diameter spot and has the

FIGURE 4. MICROPROBE ANALYZER

capability of identifying the composition of intermetallic compounds and phases with elements of atomic numbers 5 through 92. This includes boron, carbon, and nitrogen, the elements that form a large number of the phases normally found in superalloys.

1.2.3 MTS Load Control Cyclic Tester

A MTS closed-loop electrohydraulic cyclic tester, Model No. 483.01, S/N 21, was used for axial fatigue testing of simulated bellows test specimens. The system shown in Figure 5 is capable of dynamic tension, compression, or tension-compression testing. Essentially, the unit is comprised of standard modular programing and control units, with solid-state circuitry. This system allows load, strain, and cycling to be established as direct primary control parameters and automatically maintains the command environment upon the specimen irrespective of disturbing effects such as coefficient of thermal expansion and relaxation.

FIGURE 5. MTS AXIAL FATIGUE CLOSED LOOP TESTING MACHINE

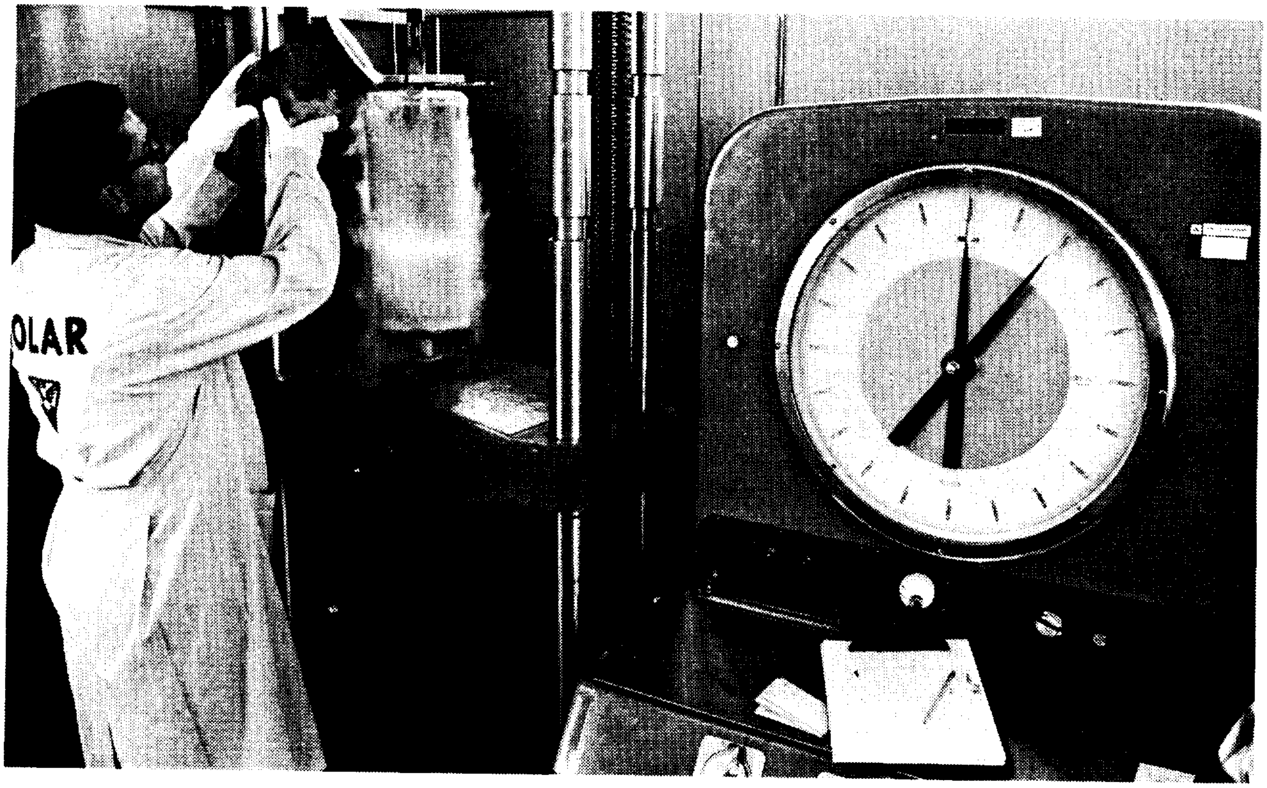


FIGURE 6. CRYOSTAT AND RIEHLE TENSILE TEST MACHINE

1.2.4 Ambient and Cryogenic Tensile Testing

All tensile tests were performed on a Riehle screw power tensile testing machine, Model No. FS120. Tensile specimens were strained at a rate of 0.005 in./in./min to approximately 0.6 percent offset, and a strain of 0.05 in./in./min was then used to fracture.

A photograph of the cryostat used for cryogenic temperature tests is shown in Figure 6. The cryostat was constructed so that it was not necessary to empty the cryostat after each test. It was only necessary to unlock the gripping mechanism to remove the broken tensile specimen and install an unbroken one. Yield strength determinations were made with an extension arm attached to the reduced section. A Riehle DAR 20 extensometer was attached to the extension arm. Load-strain curves were plotted on a Riehle Model RD5 recorder.

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EXPERIMENTAL RESULTS AND DISCUSSION

Tensile tests were conducted at ambient and cryogenic temperature of -320 F on specimens cycled through:

- Standard heat treatments
- Variations in thermal treatments
- Controlled amounts of cold work

Varestraint tests were conducted on specimens cycled through standard and abbreviated aging cycles. These tests were conducted to determine heat-affected zone cracking sensitivity relative to variations in thermal treatments of the Inconel 718 alloy.

2.1 STANDARD HEAT TREAT EVALUATIONS

Because of numerous application and fabrication problems encountered with the Inconel 718 alloy, individual companies have issued their own specifications for the alloy. Each specification was established for the achievement of the desired goals in properties and/or fabricating characteristics. The number of company specifications prepared, therefore, involved the thoughts and ideas of a large number of individuals, and as might be expected reflect differences of opinion among the specification writers. During the present program, the following most common thermal treatments were used to establish baseline properties:

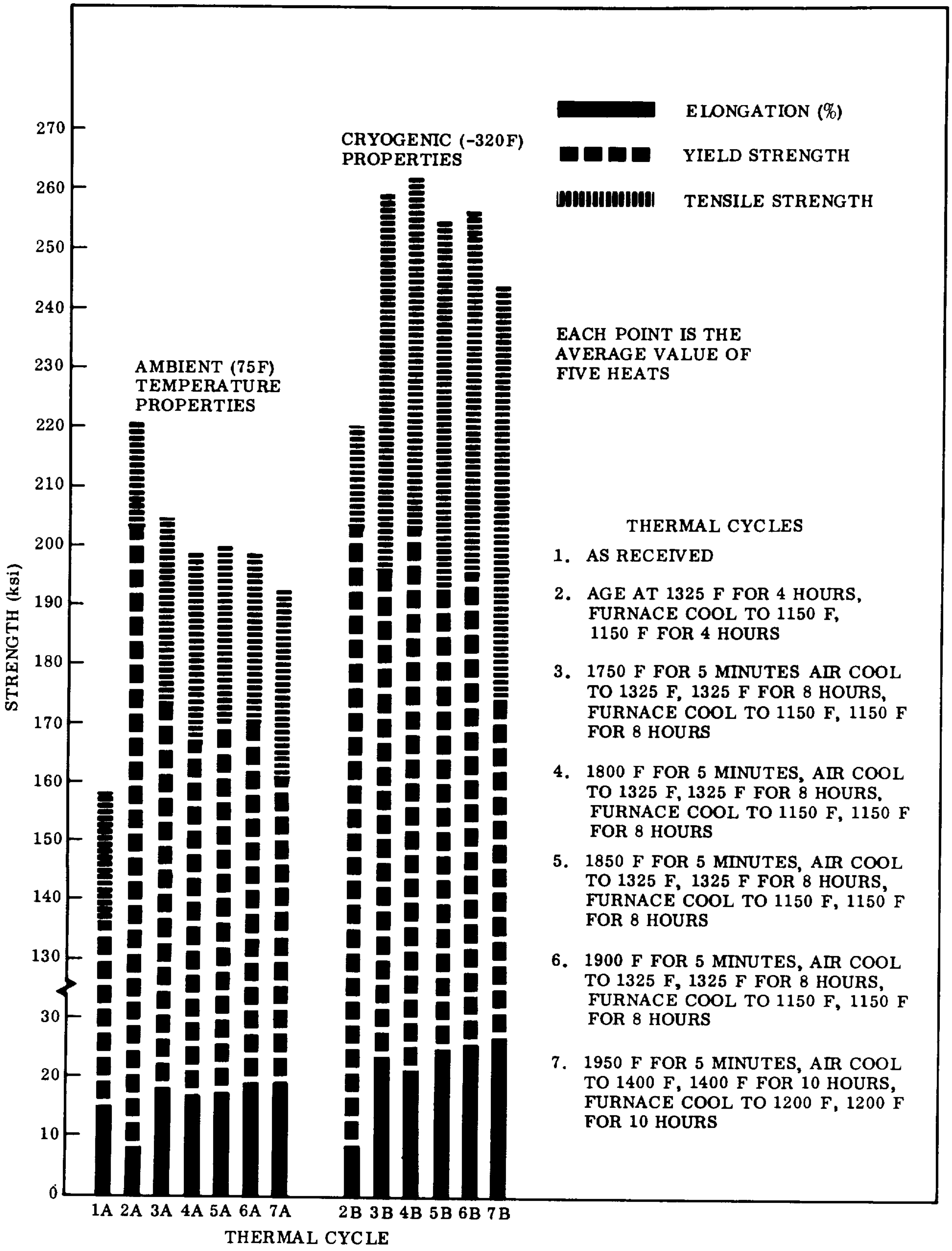
Cycle Number	Annealing Temperature (F)	Aging Cycle
A	1750	1325 F 8 hr - furnace cool 100 degrees F/hr to 1150 F - 1150 F 8 hr
B	1800	1325 F 4 hr - furnace cool to 1150 F - 1150 F 4 hr
C	1850	1325 F 8 hr - furnace cool to 1150 F - 1150 F 8 hr
D	1900	1325 F 8 hr - furnace cool to 1150 F - 1150 F 8 hr
E	1950	1400 F 10 hr - furnace cool to 1200 F - 1200 F 10 hr

TABLE III

EFFECT OF BASELINE THERMAL TREATMENTS ON MECHANICAL PROPERTIES OF 0.040-INCH MATERIAL

As-Received Condition					As Received and Aged at 1325 F for 4 Hours Furance Cool to 1150 F Held 4 Hours			
Heat Number	Test Temperature (F)	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches	Test Temperature (F)	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches
6300	Ambient	171.5	150.0	11.5	Ambient	237.0	227.0	5.0
6300	Ambient	172.0	140.0	10.0	Ambient	234.2	225.0	5.0
6790	Ambient	161.2	141.5	15.0	Ambient	219.8	206.0	10.0
6790	Ambient	160.0	141.0	15.0	Ambient	219.0	205.5	10.0
6518	Ambient	146.0	125.0	18.0	Ambient	210.8	196.5	10.5
6518	Ambient	146.9	123.5	20.5	Ambient	211.0	197.0	8.0
6394	Ambient	158.0	138.5	17.5	Ambient	228.2	218.2	7.5
6394	Ambient	159.0	140.0	18.0	Ambient	226.0	216.0	7.5
95221	Ambient	151.0	142.0	16.5	Ambient	206.0	187.0	13.5
95221	Ambient	148.0	136.0	17.5	Ambient	206.0	188.0	12.5
As Received + 1750 F for 5 Minutes - Air Cooled to 1325 F Held 8 Hours - Furnace Cool to 1150 F Held for 8 Hours								
6300	Ambient	212.5	179.0	16.5	-320	266.0	201.5	21.0
6790	Ambient	207.0	174.0	18.5	-320	255.5	190.5	27.0
6518	Ambient	194.5	161.5	25.0	-320	252.0	187.5	27.5
6394	Ambient	211.0	185.5	18.0	-320	270.0	210.0	21.5
95221	Ambient	201.0	169.0	16.0	-320	255.0	193.5	21.0
As Received + 1800 F for 5 Minutes - Air Cooled to 1325 F Held 4 Hours - Furnace Cool to 1150 F Held for 4 Hours								
6300	Ambient	211.0	177.0	20.0	-320	273.0	210.5	21.0
6790	Ambient	193.0	158.5	17.5	-320	261.0	201.5	21.0
6518	Ambient	190.0	155.5	22.0	-320	253.0	188.3	27.0
6394	Ambient	196.0	164.5	13.5	-320	268.0	204.0	19.0
95221	Ambient	196.0	163.5	16.0	-320	262.5	216.0	21.0
As Received + 1850 F for 5 Minutes - Air Cooled to 1325 F Held 8 Hours - Furnace Cool to 1150 F Held for 8 Hours								
6300	Ambient	208.5	177.5	16.0	-320	267.0	198.0	24.5
6790	Ambient	202.5	172.5	18.5	-320	260.0	202.0	28.5
6518	Ambient	190.5	157.0	21.5	-320	245.5	180.5	31.0
6394	Ambient	207.0	182.0	15.0	-320	250.0	205.0	16.0
95221	Ambient	196.0	166.5	16.5	-320	251.5	188.5	26.0
As Received + 1900 F for 5 Minutes - Air Cooled + 1325 F for 8 Hours - Furnace Cool to 1150 F Held for 8 Hours								
6300	Ambient	208.0	188.0	19.0	-320	266.0	205.0	27.5
6790	Ambient	204.0	175.0	20.0	-320	258.0	196.0	26.5
6518	Ambient	188.5	156.0	22.5	-320	243.5	180.5	25.0
6394	Ambient	205.5	182.0	18.0	-320	264.5	205.0	27.0
95221	Ambient	193.0	166.0	17.5	-320	252.0	194.5	23.0
As Received + 1950 F for 5 Minutes - Air Cooled + 1400 F for 10 Hours - Furnace Cool to 1200 F Held 10 Hours								
6300	Ambient	199.0	167.5	21.0	-320	254.0	176.0	26.5
6790	Ambient	190.0	161.5	17.0	-320	238.0	166.5	29.0
6518	Ambient	185.5	148.0	22.5	-320	234.0	159.0	31.0
6394	Ambient	200.0	174.0	15.0	-320	252.0	186.0	26.5
95224	Ambient	194.0	156.5	20.0	-320	245.0	191.0	22.0

Baseline strength data for the 0.040- and 0.209-inch Inconel 718 material is shown in Table III, Figure 7 and Table IV, Figure 8, respectively. Examination of Tables III and IV shows that aging response varies from heat to heat. It is believed that the difference in properties may be the result of variations in primary processing as well as compositional effects. Although primary processing information supplied by the producers shows hot-rolled and cold-rolled dimensions, these figures are only approximate. It is likely that some heats received more cold work than others. This variation in cold work can thus partially account for the scatter in mechanical properties.



EACH POINT IS THE AVERAGE VALUE OF FIVE HEATS

THERMAL CYCLES

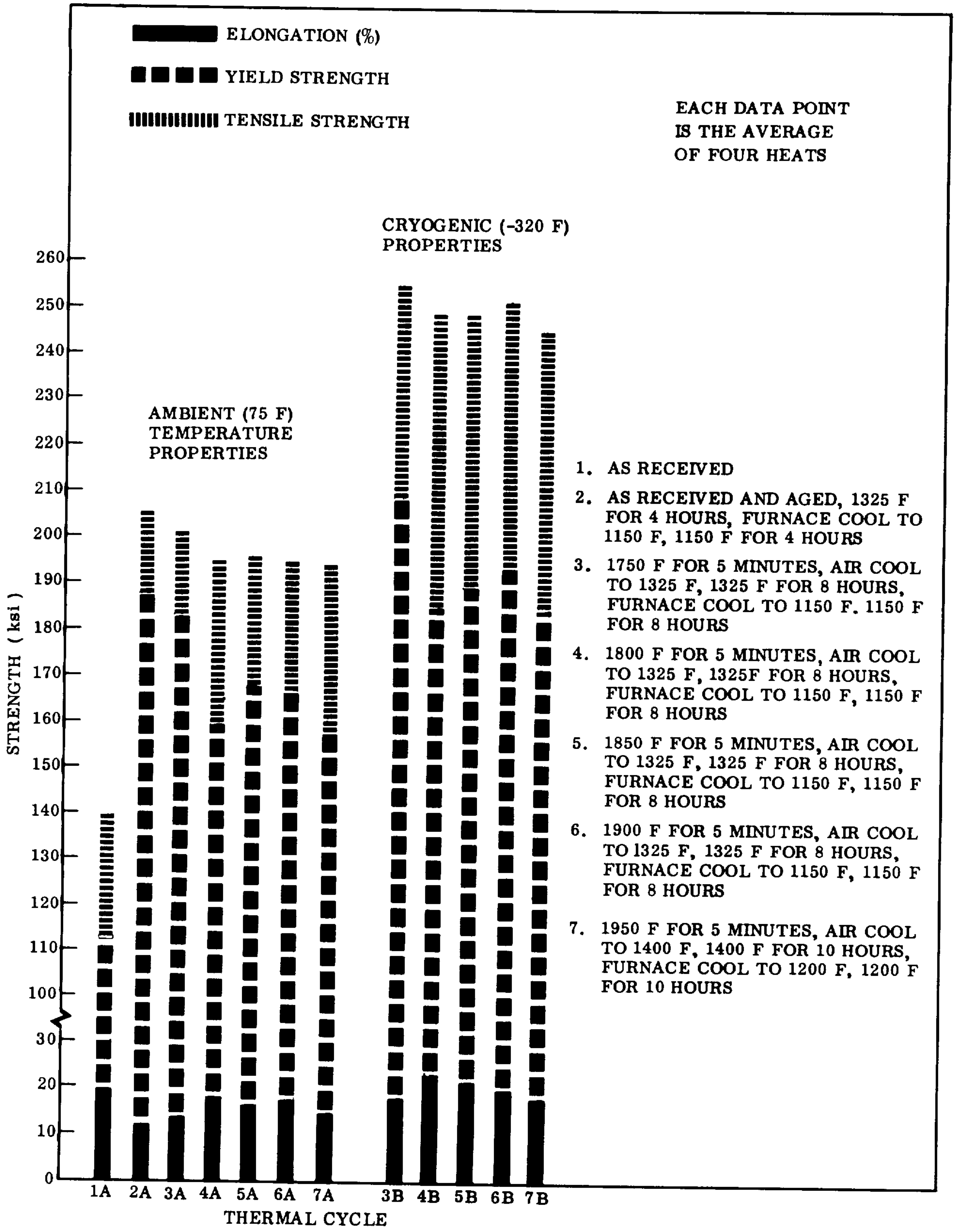
1. AS RECEIVED
2. AGE AT 1325 F FOR 4 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 4 HOURS
3. 1750 F FOR 5 MINUTES AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
4. 1800 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
5. 1850 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
6. 1900 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
7. 1950 F FOR 5 MINUTES, AIR COOL TO 1400 F, 1400 F FOR 10 HOURS, FURNACE COOL TO 1200 F, 1200 F FOR 10 HOURS

FIGURE 7. TENSILE STRENGTH VERSUS STANDARD THERMAL TREATMENTS; 0.040-Inch Inconel 718 Alloy

TABLE IV

EFFECT OF BASELINE THERMAL TREATMENTS ON MECHANICAL PROPERTIES OF 0.209 INCH MATERIAL

As Received								
Heat Number	Test Temperature (F)	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches	Test Temperature (F)	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches
6518	Ambient	134.0	106.7	27.5				
6394	Ambient	144.0	114.5	28.0	—	—	—	—
6790	Ambient	131.2	100.7	22.0				
95224	Ambient	147.0	122.0	18.0				
As Received and Aged 1325 F for 4 Hours - Furnace Cool to 1150 F Held 4 Hours								
6518	Ambient	198.0	179.0	13.0				
6394	Ambient	211.0	196.5	9.0	—	—	—	—
6790	Ambient	199.5	176.0	15.5				
95224	Ambient	211.0	189.0	9.5				
As Received and Aged 1400 F for 10 Hours - Furnace Cool to 1200 F Held 10 Hours								
6518	Ambient	199.3	166.6	17.0				
6394	Ambient	213.0	180.0	13.5	—	—	—	—
6790	Ambient	194.5	157.5	13.5				
95224	Ambient	213.0	181.6	11.5				
As Received and Aged 1350 F for 8 Hours - Furnace Cool to 1200 F Held 8 Hours								
6518	Ambient	200.0	183.5	9.5				
6394	Ambient	212.2	195.5	11.0	—	—	—	—
6790	Ambient	200.3	176.0	13.5				
95224	Ambient	212.2	195.0	12.5				
As Received and Aged 1325 F for 8 Hours - Furnace Cool to 1125 F Held 8 Hours								
6518	Ambient	199.0	184.5	8.5				
6394	Ambient	214.5	201.0	7.0	—	—	—	—
6790	Ambient	201.0	184.0	13.0				
95224	Ambient	215.0	199.5	9.0				
1750 F for 5 Minutes - Air Cooled Aged 1325 F for 8 Hours - Furnace Cool to 1150 F Held 8 Hours								
6518	Ambient	194.5	170.5	16.0	-320	245.0	195.0	25.0
6394	Ambient	212.5	198.0	10.0	-320	264.0	224.0	13.5
6790	Ambient	190.5	176.0	13.5	-320	250.0	201.0	18.0
95224	Ambient	206.5	190.5	13.0	-320	262.0	214.5	17.5
1800 F for 5 Minutes - Air Cooled Aged 1325 F for 4 Hours - Furnace Cool to 1150 F Held 4 Hours								
6518	Ambient	188.0	158.0	17.0	-320	240.0	174.5	26.5
6394	Ambient	203.0	171.0	16.5	-320	261.0	199.5	17.5
6790	Ambient	190.5	160.5	18.5	-320	247.0	180.5	22.5
95224	Ambient	197.0	158.5	19.0	-320	254.0	183.0	27.0
1850 F for 5 Minutes - Air Cooled Aged 1325 F for 8 Hours - Furnace Cool to 1150 F Held 8 Hours								
6518	Ambient	190.0	157.5	20.0	-320	243.0	184.5	26.0
6394	Ambient	203.0	174.0	13.0	-320	259.0	201.0	19.0
6790	Ambient	193.5	167.5	13.5	-320	242.0	182.5	21.5
95224	Ambient	197.0	170.5	18.0	-320	254.0	193.0	20.0
1900 F for 5 Minutes - Air Cooled Aged 1325 F for 8 Hours - Furnace Cool to 1150 F Held 8 Hours								
6518	Ambient	188.5	157.0	19.0	-320	241.0	182.0	23.5
6394	Ambient	204.0	180.0	12.5	-320	263.0	206.0	16.0
6790	Ambient	193.5	165.0	15.0	-320	250.0	194.5	19.0
95224	Ambient	195.0	167.5	22.5	-320	253.0	193.0	23.5
1950 F for 5 Minutes - Air Cooled Aged 1400 F for 10 Hours - Furnace Cool to 1200 F Held 10 Hours								
6518	Ambient	190.5	152.0	16.5	-320	238.0	177.0	22.0
6394	Ambient	207.0	177.0	11.5	-320	257.0	199.0	14.5
6790	Ambient	181.0	145.5	14.5	-320	232.0	170.0	18.0
95224	Ambient	200.0	168.0	16.5	-320	254.0	192.5	20.0



EACH DATA POINT IS THE AVERAGE OF FOUR HEATS

1. AS RECEIVED
2. AS RECEIVED AND AGED, 1325 F FOR 4 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 4 HOURS
3. 1750 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F. 1150 F FOR 8 HOURS
4. 1800 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
5. 1850 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
6. 1900 F FOR 5 MINUTES, AIR COOL TO 1325 F, 1325 F FOR 8 HOURS, FURNACE COOL TO 1150 F, 1150 F FOR 8 HOURS
7. 1950 F FOR 5 MINUTES, AIR COOL TO 1400 F, 1400 F FOR 10 HOURS, FURNACE COOL TO 1200 F, 1200 F FOR 10 HOURS

FIGURE 8. TENSILE STRENGTH VERSUS STANDARD THERMAL TREATMENTS; 0.209-Inch Inconel 718 Alloy

TABLE V

EFFECT OF TITANIUM-ALUMINUM RATIO ON TENSILE PROPERTIES

Heat Number	Thickness (in.)	Titanium (%)	Aluminum (%)	Ti/Al Ratio	Cb + Ta (%)	F_{ty} (ksi)	F_{tu} (1) (ksi)	% Elongation (in 2 inches)
6394	0.040 and 0.209	1.15	0.46	2.50	5.63	164.5	196.0	13.5
6790	0.040 and 0.209	0.88	0.41	2.15	4.91	158.5	193.0	17.5
6518	0.040 and 0.209	0.82	0.60	1.53	5.09	155.5	190.0	22.0
6300 (2)	0.040	1.00	0.70	1.43	5.45	177.0	211.0	20.0
95221	0.040	1.10	0.75	1.46	5.40	163.5	196.5	16.0
95224	0.209	1.14	0.68	1.70	5.07	158.5	197.0	19.0

1. Solar's Specification on heat treatment - 1800 F, 1325 F 4 hours, furnace cool to 1150 F, 1150 for 4 hours
2. Heat 6300 shows the lowest titanium-aluminum ratio, it received the greater amount of cold work.

In addition, a personal communication (Ref 3) from Huntington indicates that the titanium-aluminum ratio has an effect on the aged properties of the Inconel 718 alloy. Reportedly, the greater the titanium-aluminum ratio, the greater the strength.

Table V contains a summation of the titanium-aluminum ratio of the heats evaluated in this program.

The effects of the titanium-aluminum ratio can possibly be explained by the relative amounts of aluminum, titanium, and columbium in the gamma prime. The aluminum in any precipitation-hardened nickel-base alloy is normally present as part of the gamma prime, the major strengthening phase, which for the Inconel 718 alloy has the general formula Ni_3 (Al, Ti, Cb). The higher the aluminum content, the greater the aluminum concentration in the gamma prime. Aluminum has an atomic diameter of approximately 2.85 Å, while titanium and columbium have larger atomic diameters, approximately 3.00 Å. If the aluminum is replaced by a substitution of either columbium or titanium, the larger atomic diameter of the titanium or columbium should produce an increase in gamma prime lattice parameter. This substitution will result in an increase in the coherency strain between the gamma prime and the matrix accounting for an increase in strength. Thus, heats with a high aluminum content are generally lower in strength. An exception is Heat 6300, with a relative high aluminum content of 0.70 percent and also the highest strength values of the heats evaluated. Since this particular heat received the greatest amount of cold work, it appears that cold work exerts a more powerful influence on strength values than the titanium-aluminum ratios. It is also noteworthy that the high ambient strength properties of Heat 6300 carried over into the cryogenic region of -320 F. Strangely, ductility (as measured by percent elongation) is also better at -320 F in spite of the increased tensile strength.

2.2 VARIATIONS IN THERMAL CYCLES

Because the principal hardening phase of the Inconel 718 alloy differs from other superalloys (Ref. 4), precipitation behavior during variations in heat-treating cycles was studied. The effects of abbreviated aging treatments on the precipitate morphology and its effect on strength and weldability was of primary concern. In addition, annealing studies were conducted to determine the effect of temperature levels on the subsequent precipitation behavior during age-hardening cycles. It had previously been shown (Ref. 5, 6, and 7), that when the Inconel 718 alloy is annealed at temperatures greater than 1900 F, grain growth can be expected. In addition, precipitation behavior during subsequent aging is altered enough to deleteriously affect weldability and mechanical properties.

Test specimens were annealed at 1750, 1850, and 1950 F. Specimens were subsequently exposed to abbreviated aging cycles consisting of the following:

Cycle Number	Aging Cycle
F	1150 F 1 hour
G	1250 F 1 hour
H	1325 F 1 hour
I	1350 F 1 hour
J	1450 F 1 hour
K	1325 F 0.5 hour - furnace cool to 1150 F - 1150 F 0.5 hour

Figures 9 and 10 and Tables VI and VII compare the mechanical properties developed by different annealing cycles in relation to the abbreviated cycles used in this study. Test data developed indicate that fairly high tensile strengths are obtainable with abbreviated aging cycles of only one-hour duration. The highest tensile properties obtained on the 0.040-inch Inconel 718 specimens resulted from annealing at 1750 F, followed by using an abbreviated aging cycle of 1350 F for one hour. Typical strength values at ambient (75 F) and cryogenic (-320 F) temperatures are:

	Ambient (75 F)	Cryogenic (-320 F)
F_{tu} (ksi)	188.0	241.0
F_{ty} (ksi)	139.0	163.0
Percent Elongation	21.0	30.0

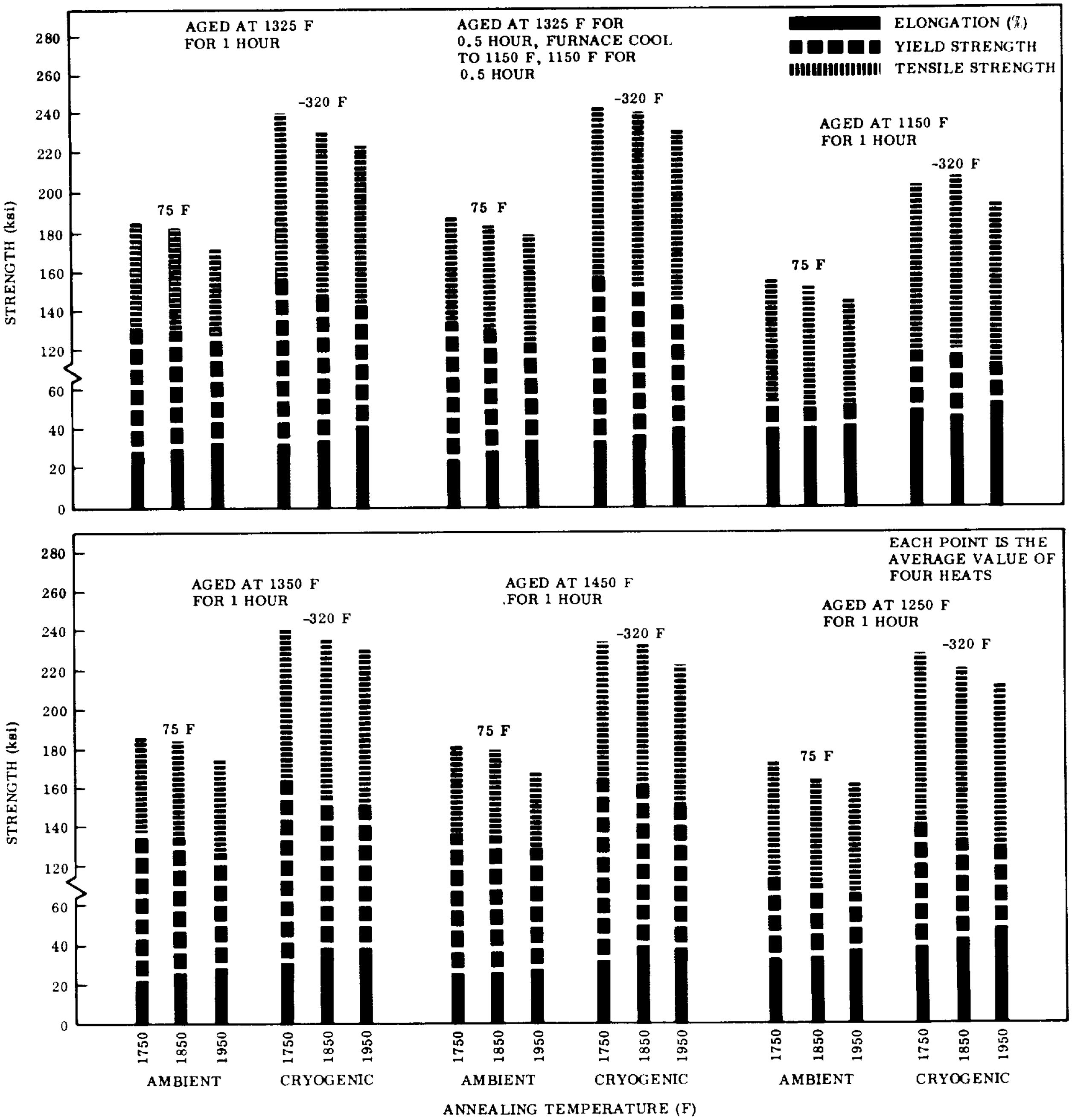


FIGURE 9. TENSILE STRENGTH VERSUS ABBREVIATED AGING CYCLES; 0.040-Inch Inconel 718 Alloy

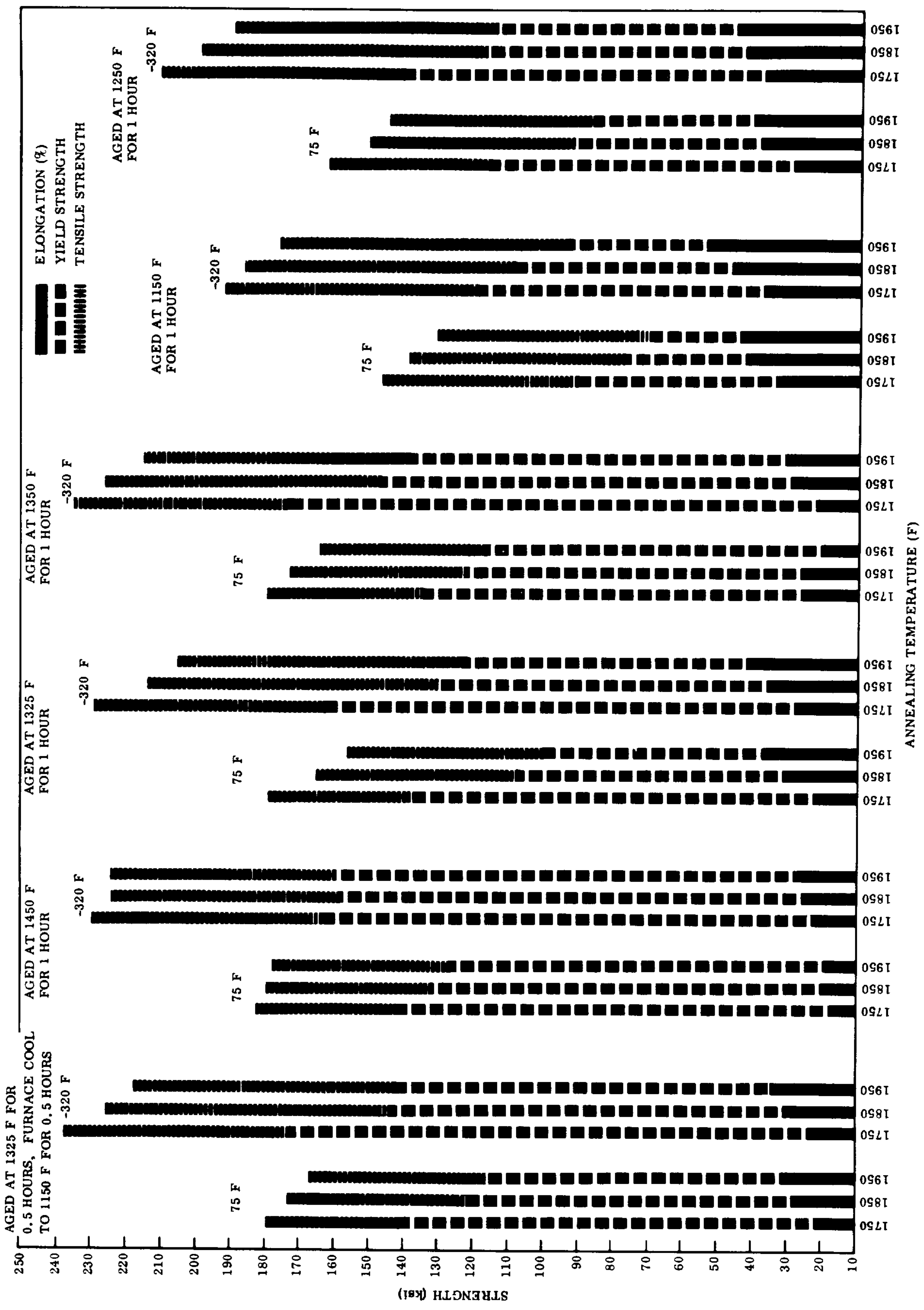


FIGURE 10. TENSILE STRENGTH VERSUS ABBREVIATED AGING CYCLES; 0.209-Inch Inconel 718 Alloy

TABLE VI

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
	As Received + 1750 F 5 Min, Air Cool, Aged at 1150 F 1 Hour							
6300	Ambient	165.5	103.0	37.0	-320 F	213.0	126.0	44.5
6790	Ambient	152.0	90.5	39.0	-320 F	204.0	118.0	47.5
6518	Ambient	143.0	81.0	45.0	-320 F	190.5	112.0	55.5
6394	Ambient	157.0	100.5	40.0	-320 F	200.0	117.0	53.0
	Average	154.4	93.8	40.3		201.9	118.3	50.1
	As Received + 1850 F 5 Min, Air Cool, Aged at 1150 F 1 Hour							
6300	Ambient	159.5	94.0	38.0	-320 F	216.0	129.0	42.5
6790	Ambient	150.0	87.5	40.5	-320 F	204.5	120.0	49.0
6518	Ambient	138.0	75.0	48.0	-320 F	192.5	107.5	56.5
6394	Ambient	156.0	102.0	39.0	-320 F	208.5	133.5	46.0
	Average	150.9	89.6	41.4		205.4	122.5	48.5
	As Received + 1950 F 5 Min, Air Cool, Aged at 1150 F 1 Hour							
6300	Ambient	154.5	108.5	39.0	-320 F	207.5	119.0	48.0
6790	Ambient	143.5	84.5	43.5	-320 F	193.5	111.0	55.5
6518	Ambient	134.0	75.0	50.0	-320 F	187.0	104.0	60.0
6394	Ambient	148.0	104.0	39.0	-320 F	196.0	117.0	51.5
	Average	145.0	93.0	42.9		196.0	112.8	53.8
	As Received + 1750 F 5 Min, Air Cool, Aged at 1250 F 1 Hour							
6300	Ambient	181.0	120.0	28.0	-320 F	234.5	147.0	32.0
6790	Ambient	173.0	114.0	31.0	-320 F	226.0	140.5	39.0
6518	Ambient	161.0	102.5	34.5	-320 F	213.0	127.5	43.5
6394	Ambient	178.0	123.0	30.0	-320 F	231.0	148.0	38.5
	Average	173.3	114.9	30.9		226.1	140.8	38.3
	As Received + 1850 F 5 Min, Air Cool, Aged at 1250 F 1 Hour							
6300	Ambient	176.0	117.0	32.0	-320 F	228.5	141.0	40.0
6790	Ambient	171.0	111.0	32.5	-320 F	220.0	135.5	42.5
6518	Ambient	154.5	96.5	41.5	-320 F	204.5	118.5	47.0
6394	Ambient	156.5	116.5	34.0	-320 F	223.5	137.0	45.0
	Average	164.5	110.3	35.0		219.1	133.0	43.6

TABLE VI (Cont.)

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
As Received + 1950 F 5 Min, Air Cool, Aged at 1250 F 1 Hour								
6300	Ambient	171.0	111.5	32.5	-320 F	225.0	138.5	41.0
6790	Ambient	160.0	103.0	35.5	-320 F	209.0	126.0	45.5
6518	Ambient	149.0	91.0	41.5	-320 F	197.0	114.0	53.5
6394	Ambient	166.5	111.5	33.5	-320 F	219.0	132.0	46.0
	Average	161.6	104.3	35.8		212.5	127.6	46.5
As Received + 1750 F 5 Min, Air Cool, Aged at 1325 F 1 Hour								
6300	Ambient	191.0	132.0	27.0	-320 F	248.0	162.0	27.5
6790	Ambient	191.0	138.0	27.0	-320 F	237.0	156.0	32.5
6518	Ambient	172.0	115.0	32.0	-320 F	226.0	139.0	40.0
6394	Ambient	190.0	141.0	25.5	-320 F	246.0	162.0	32.0
	Average	186.0	131.5	27.9		239.3	154.8	33.0
As Received + 1850 F 5 Min, Air Cool, Aged at 1325 F 1 Hour								
6300	Ambient	190.0	133.5	27.5	-320 F	231.0	153.5	23.0
6790	Ambient	185.0	133.5	27.0	-320 F	236.0	152.0	32.5
6518	Ambient	168.5	116.5	34.5	-320 F	221.0	135.0	45.0
6394	Ambient	186.0	136.5	27.5	-320 F	240.0	156.5	37.0
	Average	182.4	130.0	29.1		232.0	149.3	34.4
As Received + 1950 F 5 Min, Air Cool, Aged at 1325 F 1 Hour								
6300	Ambient	178.0	122.0	30.5	-320 F	236.0	147.5	38.0
6790	Ambient	170.0	123.0	32.5	-320 F	222.5	142.5	39.0
6518	Ambient	158.0	104.0	37.5	-320 F	209.0	127.0	50.5
6394	Ambient	177.0	127.0	30.5	-320 F	232.0	151.0	35.0
	Average	170.8	119.0	32.8		224.9	142.0	40.6
As Received + 1750 F 5 Min, Air Cool, Aged at 1350 F 1 Hour								
6300	Ambient	195.0	142.0	21.0	-320 F	250.5	166.0	28.0
6790	Ambient	187.0	139.0	22.0	-320 F	238.0	164.5	28.5
6518	Ambient	176.0	124.0	27.5	-320 F	230.0	150.0	35.5
6394	Ambient	194.0	152.0	19.5	-320 F	249.0	174.5	28.5
	Average	188.0	139.3	22.5		241.9	163.8	30.1

TABLE VI (Cont.)

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
			As Received + 1850 F 5 Min, Air Cool, Aged at 1350 F 1 Hour					
6300	Ambient	191.0	138.0	26.0	-320 F	247.5	166.0	33.0
6790	Ambient	185.0	139.0	23.0	-320 F	236.0	157.5	34.0
6518	Ambient	170.0	119.0	29.0	-320 F	219.0	139.5	38.0
6394	Ambient	191.0	146.0	25.0	-320 F	243.0	164.5	32.0
	Average	184.3	135.5	25.8		236.4	156.9	34.3
			As Received + 1950 F 5 Min, Air Cool, Aged at 1350 F 1 Hour					
6300	Ambient	185.0	133.0	25.0	-320 F	242.0	157.5	35.0
6790	Ambient	175.0	122.0	26.0	-320 F	227.0	152.0	35.0
6518	Ambient	162.0	112.0	33.0	-320 F	212.5	135.0	42.5
6394	Ambient	181.0	137.0	27.5	-320 F	240.5	158.0	36.5
	Average	175.8	126.0	27.9		230.5	150.6	37.3
			As Received + 1750 F 5 Min, Air Cool, Aged at 1450 F 1 Hour					
6300	Ambient	191.0	145.0	25.0	-320 F	243.5	172.5	29.0
6790	Ambient	177.0	134.0	24.0	-320 F	229.5	157.0	30.0
6518	Ambient	169.0	120.0	27.5	-320 F	216.0	148.0	33.0
6394	Ambient	189.0	149.0	22.5	-320 F	243.0	178.0	31.5
	Average	181.5	137.0	24.8		233.0	163.9	30.9
			As Received + 1850 F 5 Min, Air Cool, Aged at 1450 F 1 Hour					
6300	Ambient	190.0	144.0	24.0	-320 F	242.0	171.5	33.0
6790	Ambient	176.0	133.5	24.0	-320 F	227.0	160.0	37.0
6518	Ambient	165.0	119.0	30.0	-320 F	216.0	146.0	43.5
6394	Ambient	187.0	145.0	24.0	-320 F	241.5	172.5	34.5
	Average	179.5	135.4	25.5		231.6	162.5	37.0
			As Received + 1950 F 5 Min, Air Cool, Aged at 1450 F 1 Hour					
6300	Ambient	185.0	140.0	26.0	-320 F	234.5	162.0	31.5
6790	Ambient	164.0	129.0	26.5	-320 F	215.0	150.5	35.0
6518	Ambient	157.0	113.0	32.0	-320 F	204.0	135.0	48.5
6394	Ambient	172.0	134.0	24.0	-320 F	230.0	158.5	36.5
	Average	169.5	129.0	27.1		220.9	151.5	37.9

TABLE VI (Cont.)

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY

Heat No.	Test Temp	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong in 2 inches
As Received + 1750 F 5 Min, Air Cool, Aged at 1325 F 0.5 Hour, Furnace Cool to 1150 F, Hold 0.5 Hour								
6300	Ambient	194.0	138.2	26.0	-320 F	250.0	162.0	31.0
6790	Ambient	190.4	136.0	25.0	-320 F	244.0	159.0	35.0
6518	Ambient	175.5	120.1	30.0	-320 F	228.0	142.0	38.0
6394	Ambient	193.1	143.6	23.0	-320 F	250.0	165.0	33.0
	Average	188.3	134.5	26.0		243.0	157.0	34.3
As Received + 1850 F 5 Min, Air Cool, Aged at 1325 F 0.5 Hour, Furnace Cool to 1150 F, Hold 0.5 Hour								
6300	Ambient	190.4	134.5	25.0	-320 F	246.0	159.0	33.0
6790	Ambient	188.1	134.3	26.5	-320 F	247.0	160.5	36.5
6518	Ambient	170.4	115.3	34.0	-320 F	226.0	140.0	43.0
6394	Ambient	186.0	135.8	27.0	-320 F	242.0	159.0	29.0
	Average	183.7	130.0	28.1		240.3	154.6	35.4
As Received + 1950 F 5 Min, Air Cool, Aged at 1325 F 0.5 Hour, Furnace Cool to 1150 F, Hold 0.5 Hour								
6300	Ambient	183.2	127.2	28.5	-320 F	240.0	152.0	36.5
6790	Ambient	177.8	124.4	31.0	-320 F	233.0	147.0	39.0
6518	Ambient	163.1	108.5	38.0	-320 F	214.0	130.0	45.0
6394	Ambient	182.6	128.7	31.5	-320 F	236.0	152.0	38.0
	Average	176.7	122.2	32.3		230.8	145.3	39.6

TABLE VII

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
As Received, Annealed + 1750 F 5 Min, Air Cool, Aged at 1150 F 1 Hour								
6518	Ambient	141.0	78.8	39.0	-320 F	186.5	103.5	44.5
6394	Ambient	158.5	112.0	30.0	-320 F	207.5	141.0	34.0
6790	Ambient	144.0	91.2	36.0	-320 F	184.5	119.0	37.0
95224	Ambient	146.0	91.0	35.0	-320 F	193.0	118.5	38.0
	Average	147.4	93.3	35.0		192.9	120.5	38.4
As Received, Annealed + 1850 F 5 Min, Air Cool, Aged at 1150 F 1 Hour								
6518	Ambient	135.0	73.2	49.0	-320 F	181.5	126.5	51.5
6394	Ambient	149.0	87.2	36.5	-320 F	201.0	114.0	43.5
6790	Ambient	143.0	84.2	42.0	-320 F	165.0	93.2	47.5
95224	Ambient	132.0	68.5	45.5	-320 F	200.0	106.5	48.0
	Average	139.8	78.3	43.3		186.9	110.1	47.6
As Received, Annealed + 1950 F 5 Min, Air Cool, Aged at 1150 F 1 Hour								
6518	Ambient	131.0	70.8	48.0	-320 F	208.0	111.0	55.0
6394	Ambient	141.7	82.3	37.5	-320 F	187.0	105.0	49.5
6790	Ambient	134.8	80.5	43.0	-320 F	159.0	91.3	48.0
95224	Ambient	117.0	51.7	51.0	-320 F	154.0	73.0	67.0
	Average	131.1	71.3	44.9		177.0	95.1	54.9
As Received, Annealed + 1750 F 5 Min, Air Cool, Aged at 1250 F 1 Hour								
6518	Ambient	156.0	110.6	31.5	-320 F	208.0	145.0	37.5
6394	Ambient	175.5	143.5	24.0	-320 F	221.0	156.5	28.5
6790	Ambient	156.0	104.6	30.5	-320 F	207.0	132.0	38.5
95224	Ambient	161.6	111.0	34.0	-320 F	211.0	137.0	44.0
	Average	162.3	117.4	30.0		211.8	142.6	37.4
As Received, Annealed + 1850 F 5 Min, Air Cool, Aged at 1250 F 1 Hour								
6518	Ambient	146.5	87.0	41.5	-320 F	193.0	111.0	48.0
6394	Ambient	160.0	101.5	35.5	-320 F	210.0	133.0	38.0
6790	Ambient	155.5	97.0	40.0	-320 F	201.0	118.5	45.0
95224	Ambient	146.5	88.5	40.0	-320 F	194.5	111.0	43.5
	Average	152.1	93.5	39.3		199.6	118.4	43.6

TABLE VII (Cont.)

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
As Received, Annealed + 1950 F 5 Min, Air Cool, Aged at 1250 F Hour								
6518	Ambient	144.3	85.7	41.5	-320 F	189.5	107.5	49.0
6394	Ambient	156.0	98.4	35.0	-320 F	201.0	120.0	39.0
6790	Ambient	149.3	93.5	41.0	-320 F	194.5	123.0	45.5
95224	Ambient	131.0	69.7	47.5	-320 F	174.5	109.0	52.0
	Average	145.2	86.8	41.3		189.9	114.9	46.4
As Received, Annealed + 1750 F 5 Min, Air Cool, Aged at 1325 F 1 Hour								
6518	Ambient	173.5	139.5	23.0	-320 F	220.0	153.0	30.5
6394	Ambient	185.5	145.0	19.5	-320 F	243.0	185.0	25.0
6790	Ambient	175.0	126.0	26.0	-320 F	225.0	150.0	28.5
95224	Ambient	181.5	145.5	21.5	-320 F	230.0	167.0	28.5
	Average	178.9	139.0	22.5		229.5	163.8	28.1
As Received + 1850 F 5 Min, Air Cool, Aged at 1325 F 1 Hour								
6518	Ambient	162.0	102.5	36.5	-320 F	208.0	124.0	40.5
6394	Ambient	174.5	119.0	26.0	-320 F	227.0	142.5	30.5
6790	Ambient	166.0	111.0	27.0	-320 F	212.0	133.0	31.0
95224	Ambient	159.5	102.0	36.0	-320 F	210.0	127.0	42.5
	Average	165.5	108.6	31.4		214.3	131.6	36.1
As Received + 1950 F 5 Min, Air Cool, Aged at 1325 F 1 Hour								
6518	Ambient	153.5	95.5	39.0	-320 F	201.0	119.5	42.5
6394	Ambient	170.0	113.0	34.5	-320 F	235.0	144.5	34.5
6790	Ambient	159.5	107.0	36.5	-320 F	194.0	119.0	41.5
95224	Ambient	145.0	90.5	40.0	-320 F	195.5	112.5	49.0
	Average	157.0	101.5	37.5		206.4	123.9	41.9
As Received + 1750 F 5 Min, Air Cool, Aged at 1350 F 1 Hour								
6518	Ambient	171.5	128.5	33.0	-320 F	224.0	161.0	29.0
6394	Ambient	191.0	144.0	19.0	-320 F	247.0	197.0	17.0
6790	Ambient	178.0	138.0	26.0	-320 F	230.0	163.5	23.0
95224	Ambient	182.0	137.5	28.5	-320 F	242.0	182.5	21.5
	Average	180.6	137.0	26.6		235.8	176.0	22.6

TABLE VII (Cont.)

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
As Received + 1850 F 5 Min, Air Cool, Aged at 1350 F 1 Hour								
6518	Ambient	165.0	112.0	30.0	-320 F	216.0	142.5	34.5
6394	Ambient	184.0	135.5	23.5	-320 F	238.0	156.5	29.0
6790	Ambient	173.0	128.0	23.5	-320 F	224.0	151.0	26.5
95224	Ambient	172.0	118.5	31.0	-320 F	232.0	143.0	30.0
	Average	173.5	123.5	27.0		227.5	148.3	30.0
As Received + 1950 F 5 Min, Air Cool, Aged at 1350 F 1 Hour								
6518	Ambient	158.5	108.5	23.0	-320 F	209.0	131.0	36.0
6394	Ambient	177.5	129.5	20.0	-320 F	231.0	152.0	27.5
6790	Ambient	165.0	123.0	14.0	-320 F	215.0	153.0	29.0
95224	Ambient	159.5	107.0	26.5	-320 F	209.0	126.5	43.0
	Average	165.1	117.0	20.9		216.0	140.6	32.1
As Received + 1750 F 5 Min, Air Cool, Aged at 1450 F 1 Hour								
6518	Ambient	176.0	131.5	19.0	-320 F	222.0	156.5	27.0
6394	Ambient	192.0	159.0	16.5	-320 F	244.0	182.0	23.5
6790	Ambient	172.5	132.0	18.5	-320 F	218.0	152.5	24.5
95224	Ambient	189.5	153.5	17.0	-320 F	235.0	168.5	22.0
	Average	182.5	144.0	17.8		229.8	164.9	24.3
As Received + 1850 F 5 Min, Air Cool, Aged at 1450 F 1 Hour								
6518	Ambient	175.0	122.5	22.5	-320 F	220.0	165.5	28.5
6394	Ambient	193.5	147.0	19.0	-320 F	238.5	172.0	23.0
6790	Ambient	174.5	126.0	21.5	-320 F	212.0	142.5	24.5
95224	Ambient	179.5	134.0	19.5	-320 F	230.0	159.0	28.0
	Average	180.6	132.4	20.6		225.1	159.8	26.0
As Received + 1950 F 5 Min, Air Cool, Aged at 1450 F 1 Hour								
6518	Ambient	170.0	116.5	22.0	-320 F	217.0	150.5	27.0
6394	Ambient	188.5	142.0	19.0	-320 F	237.0	167.0	26.5
6790	Ambient	168.0	119.0	19.5	-320 F	219.0	173.5	30.0
95224	Ambient	178.5	135.5	19.5	-320 F	229.0	155.5	27.5
	Average	176.3	128.2	20.0		225.5	161.6	27.8

TABLE VII (Cont.)

EFFECT OF VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	in 2 inches
As Received + 1750 F 5 Min, Air Cool, Aged at 1325 F 0.5 Hour, Furnace Cool to 1150 F, Hold 0.5 Hour								
6518	Ambient	179.5	131.2	25.0	-320 F	232.0	162.0	25.0
6394	Ambient	172.0	144.0	25.0	-320 F	247.5	200.5	23.0
6790	Ambient	181.5	144.0	18.5	-320 F	232.0	158.0	22.5
95224	Ambient	186.0	145.5	21.5	-320 F	244.0	179.5	24.0
	Average	179.8	141.2	22.5		238.9	175.0	23.6
As Received + 1850 F 5 Min, Air Cool, Aged at 1325 F 0.5 Hour, Furnace Cool to 1150 F, Hold 0.5 Hour								
6518	Ambient	168.5	114.6	29.5	-320 F	222.0	139.5	34.0
6394	Ambient	185.0	131.0	23.5	-320 F	239.5	155.0	28.0
6790	Ambient	178.0	128.5	26.0	-320 F	223.5	143.5	30.0
95224	Ambient	167.0	112.0	33.0	-320 F	221.0	140.0	32.0
	Average	174.6	121.5	28.0		226.5	144.5	31.0
As Received + 1950 F 5 Min, Air Cool, Aged at 1325 F 0.5 Hour, Furnace Cool to 1150 F, Hold 0.5 Hour								
6518	Ambient	162.0	113.5	33.5	-320 F	211.0	132.0	34.0
6394	Ambient	180.5	128.0	26.5	-320 F	233.5	152.5	30.0
6790	Ambient	171.5	125.0	28.0	-320 F	221.0	163.0	36.0
95224	Ambient	154.5	101.0	37.0	-320 F	204.0	127.0	35.5
	Average	167.1	116.9	31.3		217.4	143.6	33.9

The effect of abbreviated aging cycles on the 0.209-inch Inconel 718 material at ambient and cryogenic temperatures is shown in Table VII and Figure 10. Examination of the test data shows that there is a slight degradation in strength as the annealing temperature is increased from 1750 to 1950 F, however, there is a tendency for the elongation to vary inversely as the strength is decreased. The highest strength was obtained on the 0.209-inch Inconel 718 material after annealing at 1750 F and subjected to the abbreviated aging cycle of 1450 F for one hour. Average strength values of the four heats evaluated as a result of this thermal treatment are:

	Ambient (75 F)	Cryogenic (-320 F)
F_{tu}	182. 5 (ksi)	229.8 (ksi)
F_{ty}	144.0 (ksi)	164.9 (ksi)
Percent Elongation	17.8	24.3

2.3 EFFECT OF COLD WORK PLUS AGING

The Inconel 718 alloy, like other age-hardenable alloys, is dependent on cold work to accelerate the aging reaction. An area of concern in the fabrication of the Inconel 718 alloy bellows, welded to such components as gimbal flanges, is the effect of annealing treatments on grain size and mechanical properties. Since bellows convolutions contain varying amounts of cold work, certain areas may be susceptible to excessive grain growth.

Reported data (Ref. 5, 6, and 7) as well as data previously developed by Solar have shown that annealing cycles greater than 1900 F will cause grain coarsening. In addition, the tensile properties of the aged material indicate a strength degradation.

In an effort to eliminate interstage annealing after forming, various abbreviated aging cycles were used on material cold worked 5, 10, 15, and 20 percent. Strength properties at ambient (75 F) and cryogenic (-320 F) temperature were determined. Aging cycles used for this evaluation consisted of the following:

Aging Cycles

1250 F 2 hours
1325 F 1 hour
1325 F 2 hours
1325 F 1 hour - furnace cool to 1150 F - 1150 F 1 hour
1325 F 2 hours - furnace cool to 1150 F - 1150 F 2 hours
1325 F 4 hours - furnace cool to 1150 F - 1150 F 4 hours
1350 F 8 hours - furnace cool to 1150 F - 1150 F 8 hours

Examination of the test data shown in Tables VIII and IX and Figures 11 and 12 shows that fairly high strength properties with good ductility are obtainable by limited amounts of cold work (5 to 20 percent) followed by short-time aging cycles. For example, specimens with 5 percent cold work given a short aging cycle of 1325 F for only two hours had the following strength properties:

- Material - 0.040-inch Inconel 718 alloy
- Condition - Annealed 1800 F - 5 percent cold worked - aged at 1325 F for 2 hours.

	Ambient (75 F)	Cryogenic (-320 F)
F_{tu}	195.0 (ksi)	247.0 (ksi)
F_{ty}	162.0 (ksi)	182.5 (ksi)
Percent Elongation	21.5	28.5

With just 10 percent cold work, most subsequent aging cycles evaluated resulted in room temperature yield strengths higher than 150.0 ksi. Ductility values ranged from 15.5 to 22.5 percent.

Room temperature yield strengths, 200.0 ksi and above, are obtained by cold working the Inconel 718 alloy 20 percent and using a double aging treatment. An abbreviated aging cycle consisting of 1325 F for one hour - furnace cool to 1150 F for one hour, resulted in the following high-strength properties:

	Ambient (75 F)	Cryogenic (-320 F)
F_{tu}	220.0 (ksi)	269.5 (ksi)
F_{ty}	201.4 (ksi)	231.6 (ksi)
Percent Elongation	12.6	19.3

TABLE VIII

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

(Material Annealed at 1800 F 5 Min. - Cold Worked and Aged as Indicated)

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 5%, Aged at 1250 F 2 Hours								
6300	Ambient	184.0	148.5	25.5	-320 F	235.5	180.5	29.0
6790	Ambient	178.5	138.0	26.0	-320 F	219.5	157.0	33.5
6518	Ambient	165.0	122.5	34.5	-320 F	204.0	139.5	41.0
6394	Ambient	176.5	139.0	28.5	-320 F	221.0	159.5	34.5
	Average	176.0	137.0	28.6		220.0	159.1	34.5
Cold Worked 5%, Aged at 1325 F 1 Hour								
6300	Ambient	194.0	158.5	20.0	-320 F	246.5	183.0	27.0
6790	Ambient	187.5	149.0	24.5	-320 F	237.0	174.0	28.5
6518	Ambient	170.5	129.0	28.0	-320 F	220.0	156.0	31.5
6394	Ambient	185.0	148.0	23.0	-320 F	241.0	176.5	28.0
	Average	184.3	146.1	23.9		236.1	172.4	28.8
Cold Worked 5%, Aged at 1325 F 2 Hours								
6300	Ambient	213.0	176.5	20.0	-320 F	256.0	193.5	24.5
6790	Ambient	194.0	161.0	20.0	-320 F	244.0	184.5	27.5
6518	Ambient	180.5	142.0	26.0	-320 F	231.0	163.0	34.0
6394	Ambient	197.0	168.0	20.5	-320 F	252.0	189.5	28.0
	Average	196.1	161.9	21.6		245.8	182.6	28.5
Cold Worked 5%, Aged at 1325 F 1 Hour, Furance Cool to 1150 F, 1150 F 1 Hour								
6300	Ambient	206.0	172.5	22.0	-320 F	251.0	193.5	26.5
6790	Ambient	197.0	160.0	21.5	-320 F	240.0	178.0	27.0
6518	Ambient	181.5	143.0	27.0	-320 F	222.0	157.5	35.0
6394	Ambient	198.5	166.0	19.5	-320 F	241.0	179.0	31.5
	Average	195.8	160.4	22.5		238.5	177.0	30.0
Cold Worked 5%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6300	Ambient	207.5	175.5	17.0	-320 F	269.0	203.5	24.0
6790	Ambient	203.5	169.5	18.5	-320 F	255.0	190.5	23.5
6518	Ambient	188.5	150.0	24.0	-320 F	239.5	172.5	34.0
6394	Ambient	201.0	170.5	17.5	-320 F	263.0	196.5	27.0
	Average	200.1	166.4	19.3		256.6	190.8	27.1

TABLE VIII (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

(Material Annealed at 1800 F 5 Min. - Cold Worked and Aged as Indicated)

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 5%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6300	Ambient	219.0	193.5	14.5	-320 F	272.5	220.0	18.0
6790	Ambient	206.0	182.0	16.0	-320 F	263.0	211.0	20.0
6518	Ambient	197.5	167.0	21.5	-320 F	254.0	198.0	25.0
6394	Ambient	210.0	188.0	17.0	-320 F	274.0	217.0	21.0
	Average	208.1	182.6	17.3		265.9	211.5	21.0
Cold Worked 5%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6300	Ambient	212.0	189.0	16.0	-320 F	271.0	224.0	17.0
6790	Ambient	198.0	165.0	19.0	-320 F	258.5	208.0	22.5
6518	Ambient	191.5	158.5	21.5	-320 F	248.0	196.0	25.5
6394	Ambient	205.5	177.0	20.0	-320 F	264.0	211.0	20.0
	Average	201.8	172.4	19.1		260.4	209.8	21.3
Cold Worked 10%, Aged at 1250 F 2 Hours								
6300	Ambient	196.0	169.0	17.0	-320 F	257.0	203.0	25.0
6790	Ambient	187.0	155.5	22.0	-320 F	238.5	182.5	29.0
6518	Ambient	169.0	134.0	28.0	-320 F	226.0	168.5	32.5
6394	Ambient	185.5	154.5	22.8	-320 F	241.0	189.0	24.5
	Average	184.4	153.3	22.5		240.6	185.8	27.8
Cold Worked 10%, Aged at 1325 F 1 Hour								
6300	Ambient	202.0	174.0	18.0	-320 F	254.0	201.5	24.5
6790	Ambient	193.0	159.0	21.0	-320 F	243.5	187.5	26.0
6518	Ambient	175.5	142.5	25.0	-320 F	228.0	169.0	33.0
6394	Ambient	197.0	167.5	21.5	-320 F	247.0	191.0	27.0
	Average	191.9	160.8	21.4		243.1	187.3	27.6
Cold Worked 10%, Aged at 1325 F 2 Hours								
6300	Ambient	209.0	183.0	16.0	-320 F	260.0	208.0	21.5
6790	Ambient	197.5	170.0	20.0	-320 F	249.5	186.5	26.0
6518	Ambient	183.5	151.0	24.5	-320 F	236.0	178.0	33.0
6394	Ambient	200.0	175.5	17.5	-320 F	256.0	202.5	25.0
	Average	197.5	169.9	19.3		250.4	193.8	26.4

TABLE VIII (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

(Material Annealed at 1800 F 5 Min. - Cold Worked and Aged as Indicated)

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 10%, Aged at 1325 F 1 Hour, Furnace Cool to 1150 F, 1150 F 1 Hour								
6300	Ambient	212.0	188.0	14.0	-320 F	272.0	222.0	21.5
6790	Ambient	203.0	171.5	19.5	-320 F	263.0	202.5	24.0
6518	Ambient	190.5	158.5	23.5	-320 F	245.5	185.5	29.5
6394	Ambient	205.0	179.0	19.0	-320 F	264.0	206.0	25.5
	Average	202.6	174.3	19.0		261.1	204.0	25.1
Cold Worked 10%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6300	Ambient	215.5	192.5	14.0	-320 F	273.5	221.5	22.0
6790	Ambient	206.0	179.0	17.5	-320 F	261.5	205.0	21.5
6518	Ambient	193.5	162.0	21.5	-320 F	248.5	187.5	28.0
6394	Ambient	208.0	183.5	16.0	-320 F	269.0	212.0	20.0
	Average	205.8	179.3	17.3		263.1	206.5	22.9
Cold Worked 10%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6300	Ambient	224.5	205.5	12.5	-320 F	275.0	237.5	18.5
6790	Ambient	211.5	188.5	17.5	-320 F	263.0	217.5	23.5
6518	Ambient	202.0	171.5	20.5	-320 F	253.0	199.5	25.0
6394	Ambient	216.0	198.0	15.5	-320 F	268.5	219.0	21.5
	Average	213.5	190.9	16.5		264.9	218.4	22.1
Cold Worked 10%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6300	Ambient	219.0	198.5	13.0	-320 F	280.0	239.0	18.0
6790	Ambient	207.0	177.0	16.0	-320 F	260.0	208.0	23.0
6518	Ambient	201.0	173.0	18.0	-320 F	258.0	204.0	27.5
6394	Ambient	214.0	185.0	15.0	-320 F	276.0	226.0	20.5
	Average	210.3	183.4	15.5		268.5	219.3	22.3
Cold Worked 15%, Aged at 1250 F 2 Hours								
6300	Ambient	202.5	181.5	16.0	-320 F	264.0	222.0	19.5
6790	Ambient	197.0	169.5	17.5	-320 F	254.0	206.0	26.0
6518	Ambient	176.0	147.0	26.0	-320 F	234.0	184.5	29.5
6394	Ambient	195.0	169.5	17.0	-320 F	249.0	201.0	28.0
	Average	192.6	166.9	19.1		250.3	203.4	25.8

TABLE VIII (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

(Material Annealed at 1800 F 5 Min. - Cold Worked and Aged as Indicated)

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 15%, Aged at 1325 F 1 Hour								
6300	Ambient	210.0	189.0	13.5	-320 F	267.0	225.0	18.5
6790	Ambient	204.0	172.0	16.5	-320 F	243.0	201.5	23.0
6518	Ambient	185.5	156.0	24.5	-320 F	233.0	181.0	28.5
6394	Ambient	202.5	179.5	17.5	-320 F	254.0	206.0	23.0
	Average	200.5	174.1	18.0		249.3	203.4	23.3
Cold Worked 15%, Aged at 1325 F 2 Hours								
6300	Ambient	215.0	194.5	15.5	-320 F	272.0	229.0	19.0
6790	Ambient	203.5	174.5	18.0	-320 F	255.0	208.0	24.5
6518	Ambient	191.5	162.0	21.0	-320 F	242.5	187.5	29.0
6394	Ambient	209.0	187.5	17.5	-320 F	262.0	226.0	23.0
	Average	204.8	179.6	18.0		257.9	212.6	23.9
Cold Worked 15%, Aged at 1325 F 1 Hour, Furance Cool to 1150 F, 1150 F 1 Hour								
6300	Ambient	222.0	204.0	14.0	-320 F	274.0	232.0	19.0
6790	Ambient	208.0	181.0	16.5	-320 F	260.0	206.0	23.0
6518	Ambient	193.5	168.0	20.0	-320 F	232.5	196.0	16.5
6394	Ambient	212.0	189.5	17.0	-320 F	263.5	212.5	21.5
	Average	208.9	185.6	17.1		257.5	211.6	20.0
Cold Worked 15%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6300	Ambient	225.0	206.0	10.5	-320 F	278.0	237.5	25.5
6790	Ambient	210.0	188.5	14.0	-320 F	269.0	219.0	21.5
6518	Ambient	201.5	175.5	18.0	-320 F	254.0	210.0	25.0
6394	Ambient	214.0	194.0	13.5	-320 F	272.0	244.0	17.5
	Average	212.6	191.0	14.0		268.3	227.6	22.4
Cold Worked 15%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6300	Ambient	229.5	215.0	11.0	-320 F	289.0	250.0	18.0
6790	Ambient	216.0	200.0	15.5	-320 F	270.0	246.0	21.5
6518	Ambient	203.0	182.5	15.5	-320 F	259.0	230.0	22.5
6394	Ambient	219.0	205.5	13.5	-320 F	277.0	244.0	18.5
	Average	216.9	200.8	13.9		273.8	242.5	20.1

TABLE VIII (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

(Material Annealed at 1800 F 5 Min. - Cold Worked and Aged as Indicated)

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 15%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6300	Ambient	228.0	211.5	11.0	-320 F	286.5	250.0	16.5
6790	Ambient	210.5	184.5	16.0	-320 F	268.0	243.0	20.5
6518	Ambient	206.0	181.0	16.0	-320 F	268.0	218.0	22.5
6394	Ambient	222.0	201.5	15.0	-320 F	281.0	237.5	18.0
	Average	216.6	194.6	14.5		275.9	237.1	19.4
Cold Worked 20%, Aged at 1250 F 2 Hours								
6300	Ambient	210.0	195.0	11.5	-320 F	274.0	239.0	14.5
6790	Ambient	200.5	179.5	16.0	-320 F	258.5	224.0	22.5
6518	Ambient	182.5	159.0	21.0	-320 F	243.0	206.0	22.5
6394	Ambient	205.5	181.5	14.0	-320 F	258.0	218.0	21.5
	Average	199.6	178.8	15.6		258.4	221.8	20.3
Cold Worked 20%, Aged at 1325 F 1 Hour								
6300	Ambient	212.5	188.0	11.0	-320 F	275.0	239.0	17.5
6790	Ambient	205.0	183.5	14.0	-320 F	256.0	218.0	21.0
6518	Ambient	191.5	168.0	18.0	-320 F	245.0	200.0	25.0
6394	Ambient	209.0	190.0	16.0	-320 F	265.0	218.5	20.5
	Average	204.5	182.4	14.8		260.3	218.9	21.0
Cold Worked 20%, Aged at 1325 F 2 Hours								
6300	Ambient	221.5	207.0	12.5	-320 F	286.0	246.0	18.5
6790	Ambient	208.0	188.0	15.5	-320 F	269.0	226.0	22.5
6518	Ambient	196.0	172.0	20.0	-320 F	258.0	211.0	24.0
6394	Ambient	215.0	198.5	15.0	-320 F	277.0	237.0	16.5
	Average	210.1	191.4	15.8	-320 F	272.5	230.0	20.4
Cold Worked 20%, Aged at 1325 F 1 Hour, Furnace Cool to 1150 F, 1150 F 1 Hour								
6300	Ambient	230.0	218.0	8.0	-320 F	282.0	251.5	15.5
6790	Ambient	218.0	198.5	12.5	-320 F	269.0	232.0	19.0
6518	Ambient	204.0	183.0	17.5	-320 F	256.0	211.0	22.5
6394	Ambient	228.0	206.0	12.5	-320 F	271.0	232.0	20.0
	Average	220.0	201.4	12.6		269.5	231.6	19.3

TABLE VIII (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.040-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

(Material Annealed at 1800 F 5 Min. - Cold Worked and Aged as Indicated)

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{tu} (ksi)	% Elong. in 2 inches
Cold Worked 20%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6300	Ambient	234.0	221.0	9.5	-320 F	285.0	255.0	16.5
6790	Ambient	222.0	204.0	14.0	-320 F	271.0	238.0	18.0
6518	Ambient	210.0	187.5	16.5	-320 F	259.0	215.0	22.5
6394	Ambient	226.0	210.0	8.0	-320 F	277.5	236.0	20.0
	Average	223.0	205.6	12.0		273.1	236.0	19.3
Cold Worked 20%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6300	Ambient	239.0	228.0	8.0	-320 F	287.5	252.0	15.5
6790	Ambient	219.0	204.0	13.0	-320 F	280.0	240.0	22.0
6518	Ambient	213.0	197.5	13.5	-320 F	270.0	233.0	28.5
6394	Ambient	229.0	218.5	10.0	-320 F	290.0	252.0	15.0
	Average	225.0	212.0	11.1		281.9	244.3	20.3
Cold Worked 20%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6300	Ambient	230.0	217.0	9.0	-320 F	293.0	255.0	16.0
6790	Ambient	207.5	185.5	13.0	-320 F	269.0	223.0	20.0
6518	Ambient	205.5	184.0	16.0	-320 F	276.0	228.0	21.0
6394	Ambient	218.5	202.5	13.0	-320 F	287.0	251.0	17.5
	Average	215.4	197.3	12.8		281.3	239.3	18.6

TABLE IX

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURE

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 5%, Aged at 1250 F 2 Hours								
6518	Ambient	154.0	115.8	32.5	-320 F	206.0	145.0	30.5
6394	Ambient	171.0	138.0	23.0	-320 F	222.0	160.0	32.0
6790	Ambient	160.5	122.0	31.5	-320 F	206.5	149.0	34.0
95224	Ambient	160.0	121.5	28.5	-320 F	207.5	145.0	37.5
	Average	161.4	124.3	28.9		210.5	149.8	33.5
Cold Worked 5%, Aged at 1325 F 1 Hour								
6518	Ambient	180.0	152.0	19.0	-320 F	236.0	184.0	23.0
6394	Ambient	192.5	162.5	20.0	-320 F	250.0	193.5	22.0
6790	Ambient	178.0	146.5	23.0	-320 F	230.0	174.5	26.0
95224	Ambient	183.0	154.7	19.0	-320 F	239.0	181.0	26.5
	Average	183.4	153.9	20.3		238.8	183.3	24.4
Cold Worked 5%, Aged at 1325 F 2 Hours								
6518	Ambient	175.0	140.0	32.0	-320 F	223.0	161.0	31.0
6394	Ambient	193.0	166.0	17.0	-320 F	243.0	185.0	27.5
6790	Ambient	175.0	140.5	23.0	-320 F	227.0	162.0	28.5
95224	Ambient	176.0	143.0	23.0	-320 F	231.0	169.0	29.0
	Average	179.8	147.4	23.8		231.0	169.3	29.0
Cold Worked 5%, Aged at 1325 F 1 Hour, Furnace Cool to 1150 F, 1150 F 1 Hour								
6518	Ambient	191.5	133.0	25.5	-320 F	222.0	166.0	31.5
6394	Ambient	185.0	154.5	20.5	-320 F	241.5	183.5	23.5
6790	Ambient	175.0	136.0	25.0	-320 F	227.0	166.0	30.5
95224	Ambient	171.0	136.5	28.0	-320 F	227.5	167.0	30.0
	Average	185.6	140.0	24.8		229.4	170.6	28.9
Cold Worked 5%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6518	Ambient	185.0	159.0	21.0	-320 F	244.5	194.5	24.0
6394	Ambient	202.0	182.0	13.5	-320 F	262.0	218.0	16.5
6790	Ambient	192.5	172.0	13.5	-320 F	251.0	206.5	18.5
95224	Ambient	184.0	161.0	20.0	-320 F	249.5	203.5	20.5
	Average	190.9	168.5	17.0		251.8	205.6	19.9

TABLE IX (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 5%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6518	Ambient	188.0	162.0	19.0	-320 F	241.0	189.0	25.0
6394	Ambient	203.0	185.0	12.0	-320 F	263.5	214.5	16.5
6790	Ambient	188.0	165.0	18.0	-320 F	251.0	198.0	18.5
95224	Ambient	190.0	166.0	17.0	-320 F	248.0	200.5	21.5
	Average	192.3	169.5	16.5		250.9	200.5	20.4
Cold Worked 5%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6518	Ambient	195.0	173.5	16.0	-320 F	253.0	202.5	21.0
6394	Ambient	208.0	186.5	12.0	-320 F	269.5	222.0	16.5
6790	Ambient	194.5	171.0	16.0	-320 F	251.0	203.5	18.5
95224	Ambient	199.0	181.0	18.0	-320 F	261.0	212.0	19.0
	Average	199.1	178.0	15.5		258.6	210.0	18.8
Cold Worked 10%, Aged at 1250 F 2 Hours								
6518	Ambient	161.0	129.0	25.5	-320 F	212.0	157.0	34.5
6394	Ambient	178.5	152.5	23.0	-320 F	230.0	185.0	26.5
6790	Ambient	169.5	141.5	24.0	-320 F	215.5	162.0	32.0
95224	Ambient	163.0	134.5	27.5	-320 F	218.0	163.0	30.0
	Average	168.0	139.4	25.0		218.9	166.8	30.8
Cold Worked 10%, Aged at 1325 F 1 Hour								
6518	Ambient	187.5	164.0	17.5	-320 F	242.0	198.5	20.0
6394	Ambient	198.0	176.5	17.0	-320 F	251.0	215.5	17.0
6790	Ambient	184.5	159.5	16.5	-320 F	237.0	201.0	27.0
95224	Ambient	190.0	170.0	17.5	-320 F	244.5	194.5	21.0
	Average	190.0	167.5	17.1		243.6	202.4	21.3
Cold Worked 10%, Aged at 1325 F 2 Hours								
6518	Ambient	177.0	148.0	25.0	-320 F	228.0	174.5	25.0
6394	Ambient	194.0	171.0	17.5	-320 F	248.0	192.5	21.0
6790	Ambient	181.0	151.0	22.0	-320 F	235.0	176.5	29.0
95224	Ambient	181.0	154.0	20.5	-320 F	203.0	156.0	25.0
	Average	183.3	156.0	21.3		228.5	174.9	25.0

TABLE IX (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURE

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 10%, Aged at 1325 F 1 Hour, Furnace Cool to 1150 F, 1150 F 1 Hour								
6518	Ambient	159.5	146.5	22.5	-320 F	230.0	178.5	24.0
6394	Ambient	191.0	167.0	18.0	-320 F	248.0	198.0	21.5
6790	Ambient	181.0	151.0	23.5	-320 F	235.0	176.0	30.5
95224	Ambient	179.5	154.0	24.5	-320 F	236.0	185.0	26.0
	Average	177.8	154.6	22.1		237.3	184.4	25.5
Cold Worked 10%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6518	Ambient	191.5	170.5	19.0	-320 F	250.0	200.0	18.5
6394	Ambient	210.0	196.0	12.5	-320 F	265.0	226.5	13.0
6790	Ambient	198.5	177.0	13.5	-320 F	255.0	206.0	19.5
95224	Ambient	197.0	180.0	14.5	-320 F	257.0	206.0	22.0
	Average	199.3	180.9	14.9		256.8	209.6	18.3
Cold Worked 10%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6518	Ambient	191.0	170.0	17.5	-320 F	247.0	199.0	19.0
6394	Ambient	206.5	191.0	12.0	-320 F	267.5	225.0	15.0
6790	Ambient	196.0	176.5	15.0	-320 F	252.5	202.0	21.5
95224	Ambient	197.0	181.0	16.0	-320 F	225.5	184.0	18.5
	Average	197.6	179.6	15.1		248.1	202.5	18.5
Cold Worked 10%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6518	Ambient	199.0	180.0	17.5	-320 F	257.5	211.0	20.5
6394	Ambient	204.5	193.5	13.0	-320 F	272.5	231.0	15.0
6790	Ambient	199.0	177.0	16.5	-320 F	254.0	204.5	18.5
95224	Ambient	208.0	196.0	13.5	-320 F	265.0	230.0	18.0
	Average	202.6	186.5	15.1		262.3	219.1	18.0
Cold Worked 15%, Aged at 1250 F 2 Hours								
6518	Ambient	178.0	155.5	20.5	-320 F	243.0	202.5	24.5
6394	Ambient	186.0	162.5	19.5	-320 F	240.0	195.0	23.0
6790	Ambient	177.0	153.0	23.0	-320 F	229.5	183.5	27.5
95224	Ambient	172.0	146.5	25.0	-320 F	199.0	161.5	27.5
	Average	178.3	154.4	22.0		227.9	185.6	25.6

TABLE IX (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 15%, Aged at 1325 F 1 Hour								
6518	Ambient	193.0	173.0	15.5	-320 F	247.0	202.0	21.5
6394	Ambient	205.0	185.0	15.0	-320 F	263.0	225.5	13.5
6790	Ambient	191.5	166.5	20.0	-320 F	219.0	178.5	19.0
95224	Ambient	195.0	174.0	16.0	-320 F	250.5	204.0	23.0
	Average	196.1	174.6	16.6		249.9	202.5	19.3
Cold Worked 15%, Aged at 1325 F 2 Hours								
6518	Ambient	165.0	155.0	21.0	-320 F	240.0	191.5	24.0
6394	Ambient	200.0	179.0	16.0	-320 F	254.0	210.5	18.5
6790	Ambient	188.0	163.0	18.0	-320 F	242.5	194.5	22.5
95224	Ambient	185.0	158.5	20.0	-320 F	242.0	225.5	23.5
	Average	184.5	163.9	18.8		244.6	205.5	22.1
Cold Worked 15%, Aged at 1325 F 1 Hour, Furance Cool to 1150 F, 1150 F 1 Hour								
6518	Ambient	200.0	152.0	21.5	-320 F	236.5	190.0	24.5
6394	Ambient	202.0	187.5	11.0	-320 F	276.0	215.0	18.5
6790	Ambient	187.5	160.0	20.0	-320 F	244.0	196.5	22.5
95224	Ambient	191.0	171.5	16.5	-320 F	238.5	194.5	22.0
	Average	194.4	167.8	17.3		248.5	199.0	21.9
Cold Worked 15%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6518	Ambient	199.0	180.5	17.0	-320 F	256.0	262.5	21.0
6394	Ambient	216.5	209.0	8.0	-320 F	275.0	250.5	12.5
6790	Ambient	200.0	183.0	17.0	-320 F	259.0	218.0	14.0
95224	Ambient	206.0	193.0	10.0	-320 F	257.0	223.0	15.0
	Average	205.4	191.4	13.0		261.8	238.5	15.6
Cold Worked 15%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6518	Ambient	197.5	181.0	14.0	-320 F	256.5	214.5	14.0
6394	Ambient	216.0	206.0	8.5	-320 F	274.5	237.0	17.0
6790	Ambient	200.0	185.0	14.5	-320 F	259.0	214.0	17.5
95224	Ambient	202.0	188.0	12.5	-320 F	262.5	220.0	16.0
	Average	203.9	190.0	12.4		263.1	221.4	16.1

TABLE IX (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 15%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6518	Ambient	202.0	184.0	15.0	-320 F	264.0	222.5	12.5
6394	Ambient	219.5	208.0	9.5	-320 F	288.5	240.5	15.5
6790	Ambient	204.0	186.0	12.5	-320 F	261.5	216.0	16.5
95224	Ambient	213.0	201.5	12.5	-320 F	272.0	231.0	20.5
	Average	209.6	194.9	12.4		271.5	227.5	16.3
Cold Worked 20%, Aged at 1250 F 2 Hours								
6518	Ambient	186.0	172.0	16.0	-320 F	234.0	193.0	23.0
6394	Ambient	194.5	178.0	16.0	-320 F	248.0	211.0	24.0
6790	Ambient	180.0	157.0	20.5	-320 F	234.0	192.5	22.5
95224	Ambient	184.0	166.5	14.0	-320 F	230.0	197.0	25.5
	Average	186.1	168.4	16.6		236.5	198.4	23.8
Cold Worked 20%, Aged at 1325 F 1 Hour								
6518	Ambient	200.0	152.5	12.0	-320 F	251.5	207.0	20.0
6394	Ambient	213.5	199.0	11.0	-320 F	270.5	233.5	15.5
6790	Ambient	196.0	178.5	11.5	-320 F	267.0	222.0	18.5
95224	Ambient	200.5	186.0	13.5	-320 F	259.5	218.5	21.0
	Average	202.5	179.0	12.0		262.1	220.3	18.8
Cold Worked 20%, Aged at 1325 F 2 Hours								
6518	Ambient	190.0	169.0	19.0	-320 F	250.0	211.0	17.0
6394	Ambient	208.0	192.5	11.5	-320 F	265.0	228.5	16.0
6790	Ambient	198.0	178.0	14.0	-320 F	266.0	227.0	13.5
95224	Ambient	199.0	180.5	14.0	-320 F	256.0	213.0	20.5
	Average	198.8	180.0	14.6		259.3	219.9	16.8
Cold Worked 20%, Aged at 1325 F 1 Hour, Furnace Cool to 1150 F, 1150 F 1 Hour								
6518	Ambient	191.5	170.5	16.5	-320 F	248.0	212.5	19.5
6394	Ambient	209.0	196.0	11.0	-320 F	266.5	238.0	14.0
6790	Ambient	193.0	172.0	16.5	-320 F	249.5	210.5	21.0
95224	Ambient	198.0	181.0	15.5	-320 F	250.5	214.0	20.5
	Average	197.9	179.9	14.9		253.6	218.8	18.8

TABLE IX (Cont.)

EFFECT OF COLD WORK AND VARIATIONS IN AGING CYCLES ON THE TENSILE PROPERTIES OF 0.209-INCH INCONEL 718 ALLOY AT AMBIENT (75 F) AND CRYOGENIC (-320 F) TEMPERATURES

Heat No.	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches	Test Temp.	F_{tu} (ksi)	F_{ty} (ksi)	% Elong. in 2 inches
Cold Worked 20%, Aged at 1325 F 2 Hours, Furnace Cool to 1150 F, 1150 F 2 Hours								
6518	Ambient	206.0	194.0	10.5	-320 F	262.0	223.5	19.0
6394	Ambient	223.5	220.0	6.5	-320 F	287.0	263.0	7.5
6790	Ambient	209.0	197.5	10.5	-320 F	261.0	225.0	15.0
95224	Ambient	209.0	200.0	7.5	-320 F	267.0	238.5	16.0
	Average	211.9	202.9	8.8		269.3	237.5	14.4
Cold Worked 20%, Aged at 1325 F 4 Hours, Furnace Cool to 1150 F, 1150 F 4 Hours								
6518	Ambient	204.0	190.0	11.5	-320 F	264.0	230.0	14.0
6394	Ambient	220.5	214.0	6.5	-320 F	282.0	252.0	12.5
6790	Ambient	209.5	198.0	9.0	-320 F	220.5	208.5	9.5
95224	Ambient	210.0	200.0	12.5	-320 F	270.0	231.5	17.0
	Average	211.0	200.5	9.9		259.1	230.5	13.3
Cold Worked 20%, Aged at 1325 F 8 Hours, Furnace Cool to 1150 F, 1150 F 8 Hours								
6518	Ambient	192.5	179.0	14.0	-320 F	270.0	232.5	13.5
6394	Ambient	225.0	217.5	8.0	-320 F	290.0	257.5	9.5
6790	Ambient	209.0	192.0	12.0	-320 F	265.0	223.5	18.0
95224	Ambient	214.0	207.0	10.0	-320 F	275.0	241.0	16.5
	Average	210.1	198.9	11.0		275.0	238.6	14.4

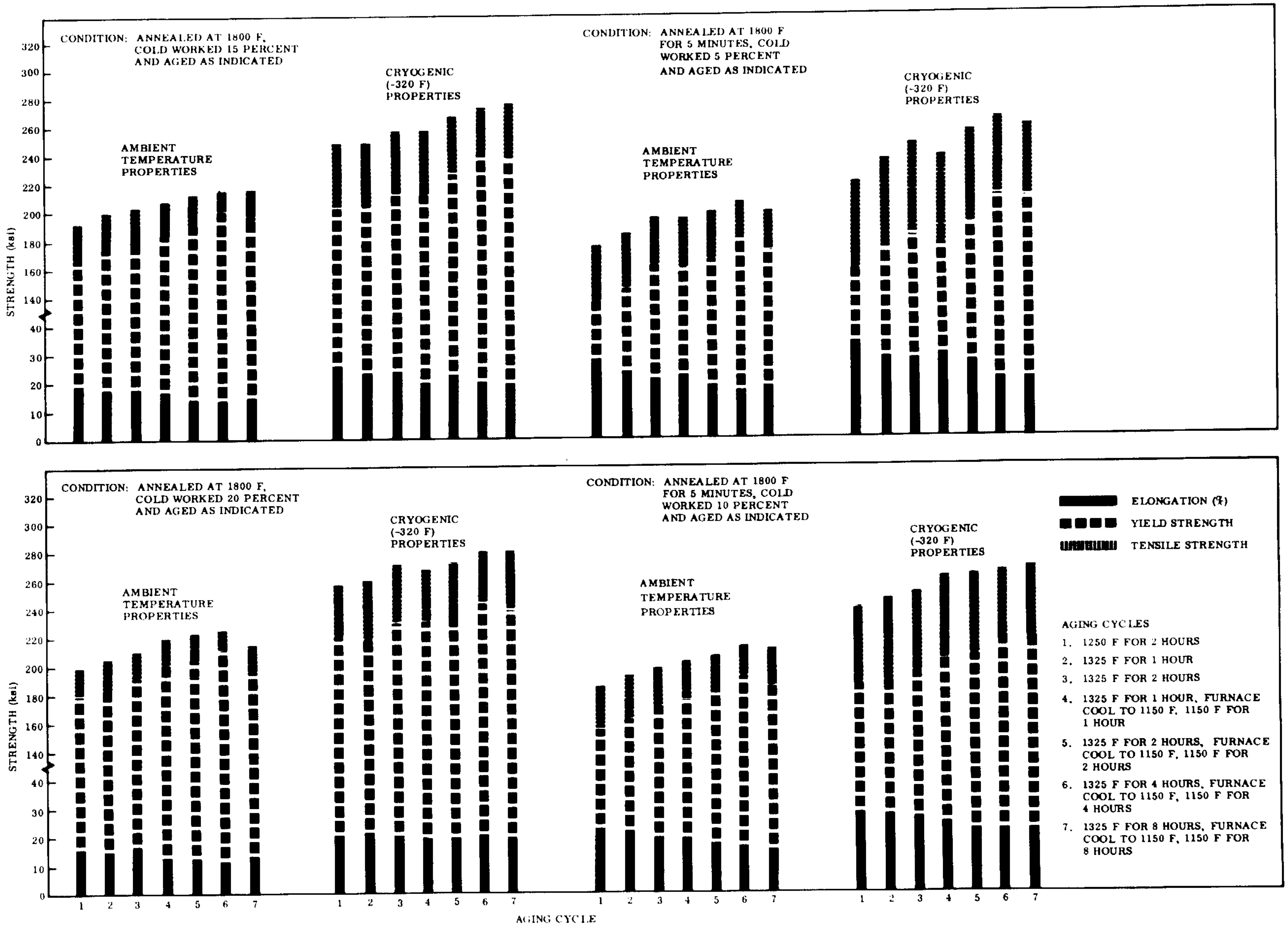


FIGURE 11. TENSILE STRENGTH VERSUS COLD WORKED AND AGED; 0.040-Inch Inconel 718 Alloy

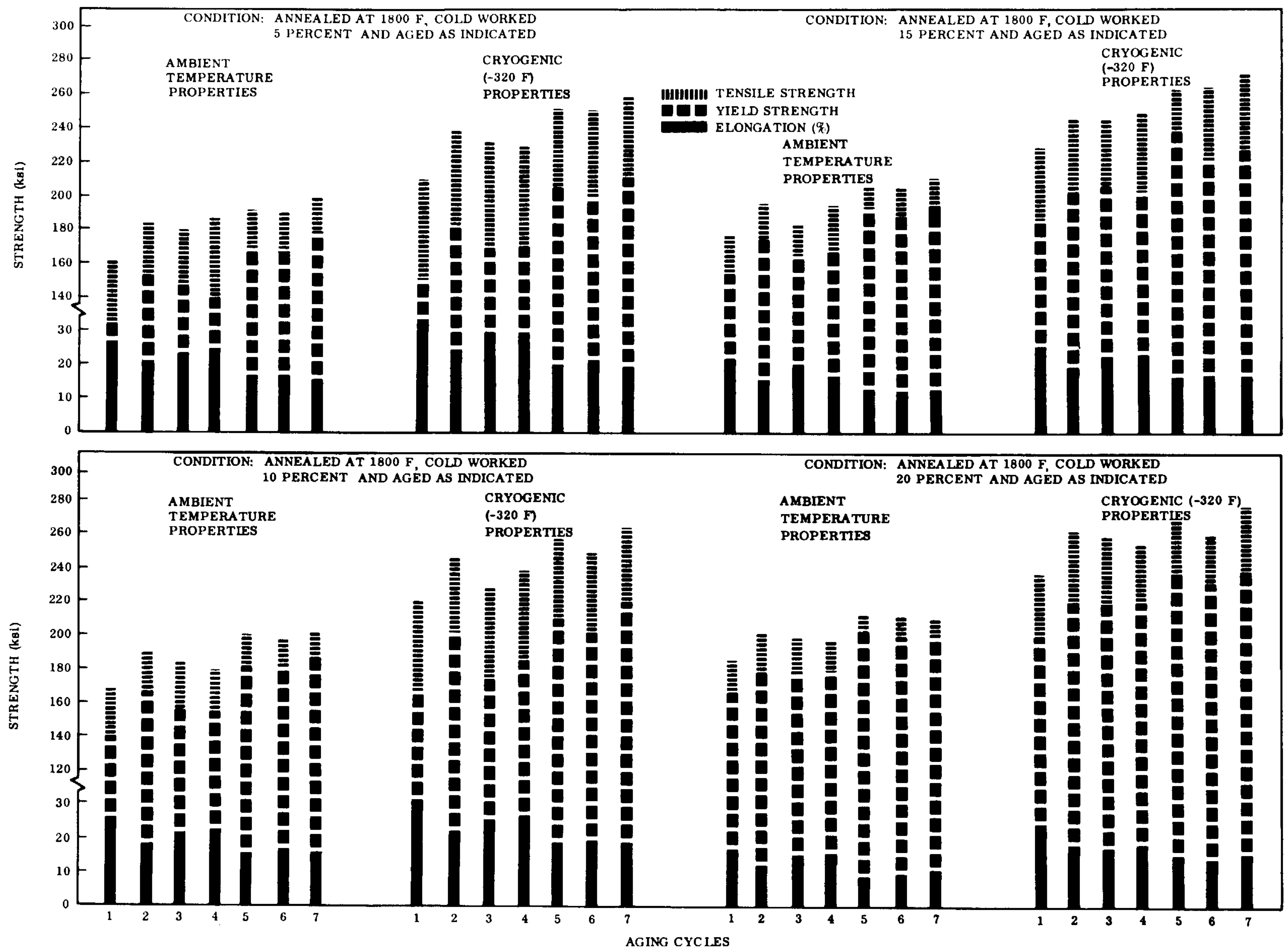


FIGURE 12. TENSILE STRENGTH VERSUS COLD WORKED AND AGED; 0.209-Inch Inconel 718 Alloy

2.4 VARESTRAINT TESTS

The Varestraint specimen configuration used in this investigation was flat, 1.75 inches wide by 9.0 inches long by nominal thickness. Guide block radii for the 0.040-inch and 0.209-inch specimens were one and four inches, respectively. The nominal value of the applied augmented-tangential strain in the outer fibers of the test specimen was 2.0 for the 0.040-inch material and 2.6 for the 0.209-inch material. In most instances, duplicate and sometimes triplicate tests were conducted on different combinations of annealing and aging conditions. The welding parameters for the bead-on-plate TIG welding for all conditions was held constant.

Baseline weld cracking susceptibility data on age-hardened specimens was obtained using the following standard annealing and aging cycles:

Cycle Number	Annealing Temperature (F)	Aging Cycle
A	1750	1325 F 8 hr - furnace cool 100 degrees F/hr to 1150 F - 1150 F 8 hr
B	1800	1325 F 4 hr - furnace cool to 1150 F - 1150 F 4 hr
C	1850	1325 F 8 hr - furnace cool to 1150 F - 1150 F 8 hr
D	1900	1325 F 8 hr - furnace cool to 1150 F - 1150 F 8 hr
E	1950	1400 F 10 hr - furnace cool to 1200 F - 1200 F 10 hr

The effect of variations in abbreviated aging cycles on the crack susceptibility of the Inconel 718 alloy was obtained by use of the following aging cycles:

Cycle Number	Aging Cycle
F	1150 F 1 hour
G	1250 F 1 hour
H	1325 F 1 hour
I	1350 F 1 hour
J	1450 F 1 hour
K	1325 F 0.5 hr - furnace cool to 1150 F - 1150 F 0.5 hr

There are several parameters which give an indication of the cracking sensitivity of a particular alloy when using the Varestraint test. These include:

- Cracking threshold
- Maximum crack length

- Number of cracks
- Total combined length either in weld or in the heat-affected zone.

For this evaluation, the total crack length produced in the heat-affected zone is the quantitative parameter used to evaluate the cracking sensitivity of the Inconel 718 alloy.

2.5 VARESTRAINT TEST RESULTS

2.5.1 Standard Thermal Treatment

Figures 13 and 14 and Tables X and XI summarize the results of the Varestraint test. In all figures, the total crack length in the heat-affected zone is shown as a function of a thermal treatment. The welding parameters as well as the nominal augmented strain are held constant. Thus, direct comparison of the hot-cracking sensitivity of the Inconel 718 alloy with variations in chemical composition and thermal treatments may be made.

Figure 15 and Table XII show the effect of unequal thickness and variation in augmented strain on miscellaneous samples supplied by the Firth Sterling and Armco Steel companies.

Evaluation of test results indicate that compositional variations of the titanium-aluminum ratio cannot be consistently attributed to the differences in heat-affected zone cracking sensitivity. Considerable variation in cracking sensitivity was noted between heats. In addition, there is no apparent pattern in cracking sensitivity from heat to heat. What may be the trend for one thickness does not necessarily hold for another thickness. It does appear, however, that the cracking sensitivity increases as the material gage becomes thicker. The pattern that is also very evident, is that all heats and all thicknesses become significantly more sensitive to heat-affected zone hot cracking as the annealing temperature is increased above 1750 F. For example, the total crack length in the heat-affected zone of the 0.040-inch specimens annealed at 1750 F and double aged, averaged just over 0.050 inch. Specimens annealed at 1950 F and double aged showed a total crack length in excess of 0.100 inch. The same trend is evident with the thicker 0.209-inch material, i.e., the specimens annealed at 1750 F exhibited an average crack length of 0.0644 inch, while specimens annealed at the 1950 F temperature resulted in a substantial increase in heat-affected zone cracking to 0.1438 inch.

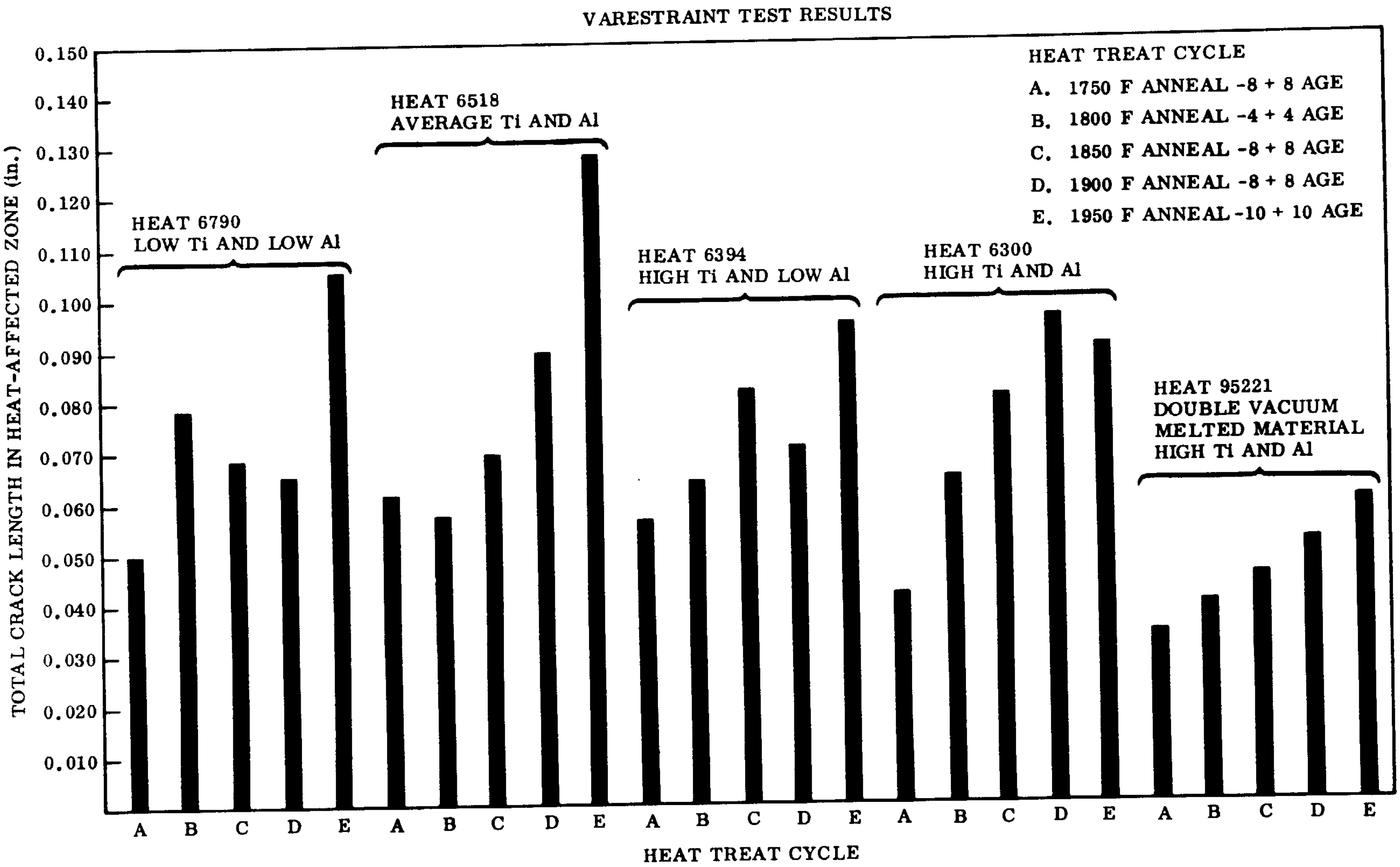


FIGURE 13. VARESTRAINT TESTS ON 0.040-INCH MATERIAL

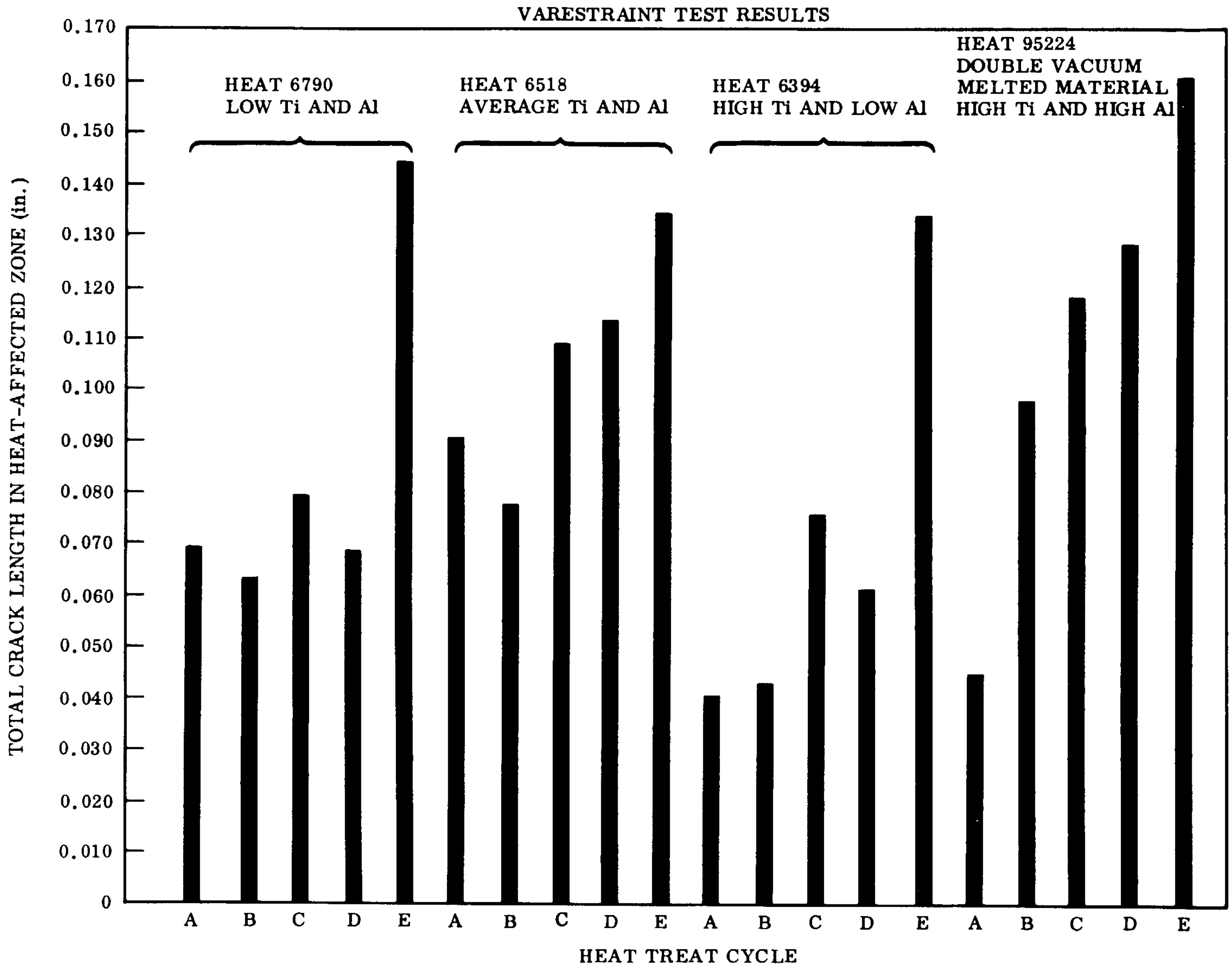


FIGURE 14. VARESTRAINT TESTS ON 0.209-INCH MATERIAL

TABLE X

VARESTRAINT TEST RESULTS ON 0.040 INCH 718 MATERIAL (Standard Thermal Cycle)

Heat(1) Treat Cycle	Specimen Number	Total Heat-Affected Zone Crack Length (in.)					Total Heat-Affected Zone Crack Length Average for the Five Heats
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium and Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 6300 High Titanium High Aluminum	Heat No. 95221 Double Vacuum Melted Heat Supplied by Eastern	
A	1	0.0536	0.0564	0.0516	0.0396	0.0472	
	2	0.0480	0.0688	0.0580	0.0420	0.0392	
	3	0.0490	0.0596	0.0596	0.0428	0.0192	
Average		0.0500	0.0616	0.0564	0.0414	0.0335	0.0486
B	1	0.0772	0.0608	0.0640	0.0620	0.0356	
	2	0.0768	0.0580	0.0696	0.0688	0.0344	
	3	0.0818	0.0536	0.0584	0.0628	0.0476	
Average		0.0786	0.0574	0.0640	0.0645	0.0392	0.0607
C	1	0.0672	0.0696	0.0808	0.0816	0.0496	
	2	0.0716	0.0696	0.0828	0.0792	0.0436	
	3	0.0672	0.0684	--	0.0816	0.0416	
Average		0.0686	0.0692	0.0818	0.0808	0.0449	0.0690
D	1	0.0684	0.0832	0.0692	0.1040	0.0428	
	2	0.0608	0.0804	0.0744	0.0920	0.0556	
	3	0.0680	0.1052	0.0688	0.0930	0.0564	
Average		0.0657	0.0896	0.0708	0.0960	0.0516	0.0747
E	1	0.1080	0.1296	0.0924	0.0896	0.0468	
	2	0.1032	0.1044	0.0960	0.0908	0.0620	
	3	0.1056	0.1516	0.0968	0.0924	0.0070	
Average		0.1056	0.1285	0.0950	0.0909	0.0596	0.0959

Nominal Value of Applied Augmented Strain --- 2.0 Percent

Heat Treat Cycle (A) 1750 F air cool, 1325 F 8 hours, furnace cool 100 degrees F/hour to 1150 F, hold at 1150 F so that total aging time is 18 hours

Heat Treat Cycle (B) 1800 F air cool, 1325 F 4 hours, furnace cool to 1150 F, hold at 1150 F for 4 hours

Heat Treat Cycle (C) 1850 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours

Heat Treat Cycle (D) 1900 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours

Heat Treat Cycle (E) 1950 F air cool, 1400 F 10 hours, furnace cool to 1200 F, hold at 1200 F so that total aging time is 20 hours

TABLE XI

VARESTRAINT TEST RESULTS ON 0.209 INCH THICK MATERIAL (Standard Thermal Cycles)

Heat Treat Cycle	Specimen Number	Total Heat-Affected Zone Crack Length (in.)				Average Crack Length in Heat-Affected Zone for the Four Heats
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Low Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 95224 Double Vacuum Melted Alloy High Titanium and Low Aluminum	
A	1	0.0884	0.0884	0.0428	0.0568	
	2	0.0332	0.1000	0.0256	0.0612	
	3	0.0876	0.0868	0.0536	0.0488	
Average		0.0697	0.0917	0.0408	0.0556	0.0644
B	1	0.0444	0.0700	0.0436	0.1120	
	2	0.0772	0.0904	0.0312	0.0756	
	3	0.0692	0.0732	0.0552	0.1088	
Average		0.0636	0.0778	0.0433	0.0988	0.0708
C	1	0.0844	0.1028	0.0656	0.1268	
	2	0.0904	0.1224	0.0884	0.0976	
	3	0.0632	0.1028	0.0756	0.1324	
Average		0.0793	0.1093	0.0765	0.1189	0.0960
D	1	0.0480	0.0848	0.0820	0.1712	
	2	0.0780	0.1456	0.0504	0.1116	
	3	0.0804	0.1140	0.0536	0.1060	
Average		0.0688	0.1144	0.0620	0.1296	0.0937
E	1	0.1856	0.1076	0.1316	0.1308	
	2	0.1292	0.1816	0.1288	0.1916	
	3	0.1188	0.1160	0.1428	0.1616	
Average		0.1445	0.1350	0.1344	0.1613	0.1438

Nominal Value of Applied Augmented Strain --- 2.6 Percent

Heat Treat Cycle A	1750 F air cool, 1325 F 8 hours, furnace cool 100 degrees F/hour to 1150 F, hold at 1150 F for 8 hours
Heat Treat Cycle B	1800 F air cool, 1325 F 4 hours, furnace cool to 1150 F, hold at 1150 F for 4 hours
Heat Treat Cycle C	1850 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours
Heat Treat Cycle D	1900 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours
Heat Treat Cycle E	1950 F air cool, 1400 F 10 hours, furnace cool to 1200 F, hold at 1200 F for 10 hours

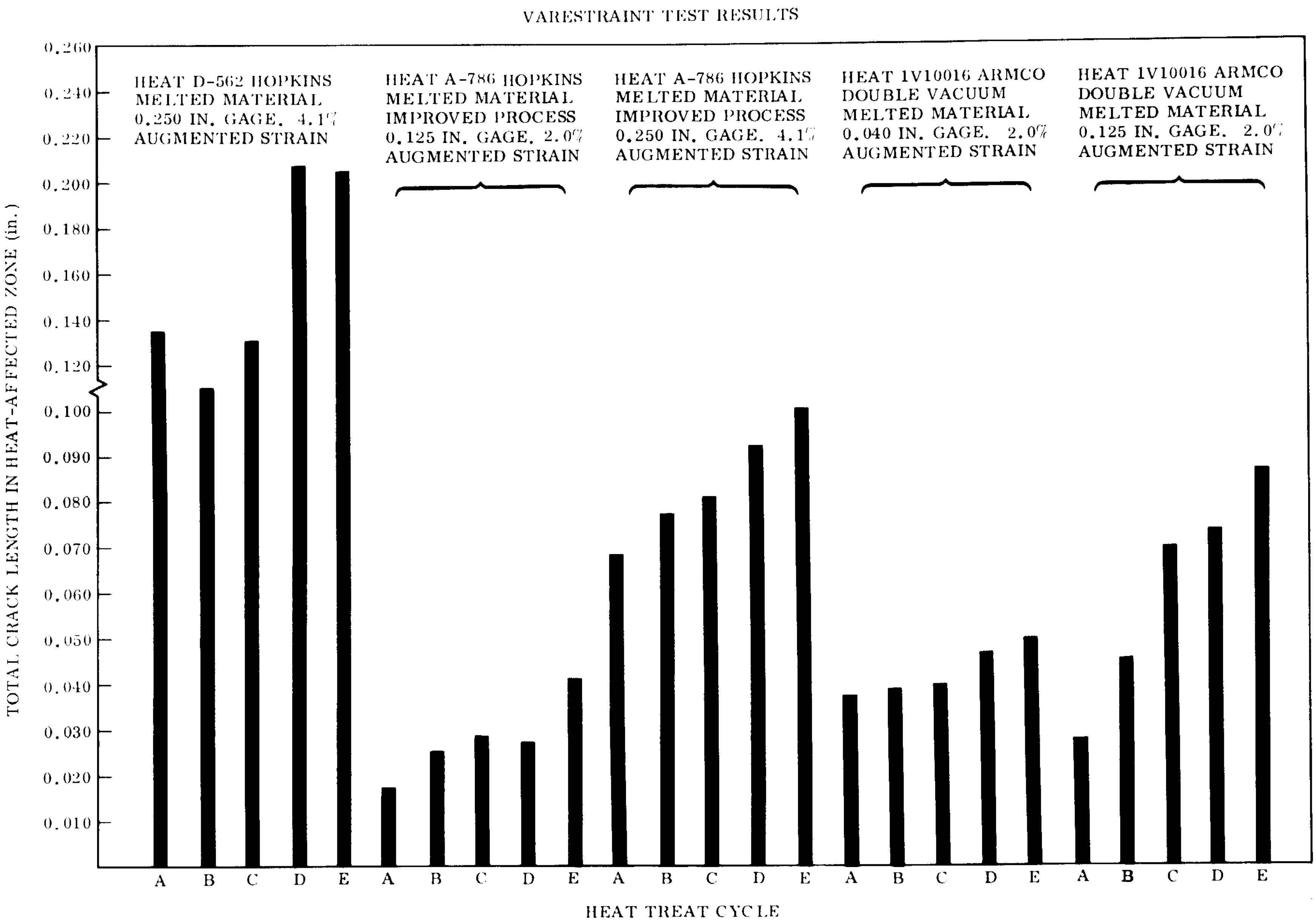


FIGURE 15. VARESTRAINT TESTS ON FIRTH STERLING AND ARMCO MATERIAL

TABLE XII

VARESTRAINT TEST RESULTS ON MATERIAL SUPPLIED BY FIRTH STERLING AND ARMCO
(Standard Thermal Cycles)

Heat Treat Cycle	Specimen Number	Total Heat-Affected Zone Crack Length (in.)				
		Hopkins Processed Material Heat D-562 0.250 in.	Hopkins Processed Material Heat A-786 0.128 in.	Hopkins Processed Material Heat A-786 0.250 in.	Armco Double Vacuum Melted 0.125 inch Material Heat 1V10016	Armco Double Vacuum Melted 040 inch Material Heat 1V10016
A	1	0.1376	0.0180	0.0488	0.0312	0.0380
	2	0.1484	0.0176	0.0880	0.0240	0.0370
	3	0.1216				
Average		0.1359	0.0178	0.0684	0.0296	0.0375
B	1	0.0980	0.0344	0.0976	0.0360	0.0386
	2	0.1264	0.0172	0.0576	0.0540	0.0384
	3	0.1060				
Average		0.1101	0.0258	0.0776	0.0450	0.0385
C	1	0.1280	0.0132	0.0940	0.0772	0.0396
	2	0.1300	0.0288	0.0682	0.0612	0.0392
	3	0.1360				
Average		0.1313	0.0210	0.0811	0.0697	0.0394
D	1	0.1856	0.0356	0.0896	0.0776	0.0448
	2	0.2308	0.0192	0.0960	0.0696	0.0480
	3	0.1948				
Average		0.2037	0.0274	0.0928	0.0736	0.0464
E	1	0.1960	0.0476	0.1300	0.0836	0.0496
	2	0.1904	0.0348	0.0872	0.0896	0.0492
	3	0.2232				
Average		0.2032	0.0412	0.1086	0.0866	0.0494

Nominal Augmented Strain Applied --- 0.040 inch material -- 2.0 Percent
0.125 inch material -- 2.0 Percent
0.250 inch material -- 4.1 Percent

Heat Treat Cycle A	1750 F air cool, 1325 F 8 hours, furnace cool 100 degrees F/hour to 1150 F for 8 hours
Heat Treat Cycle B	1800 F air cool, 1325 F 4 hours, furnace cool to 1150 F, hold for 4 hours
Heat Treat Cycle C	1850 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold for 8 hours
Heat Treat Cycle D	1900 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold for 8 hours
Heat Treat Cycle E	1950 F air cool, 1400 F 10 hours, furnace cool to 1200 F, hold for 10 hours

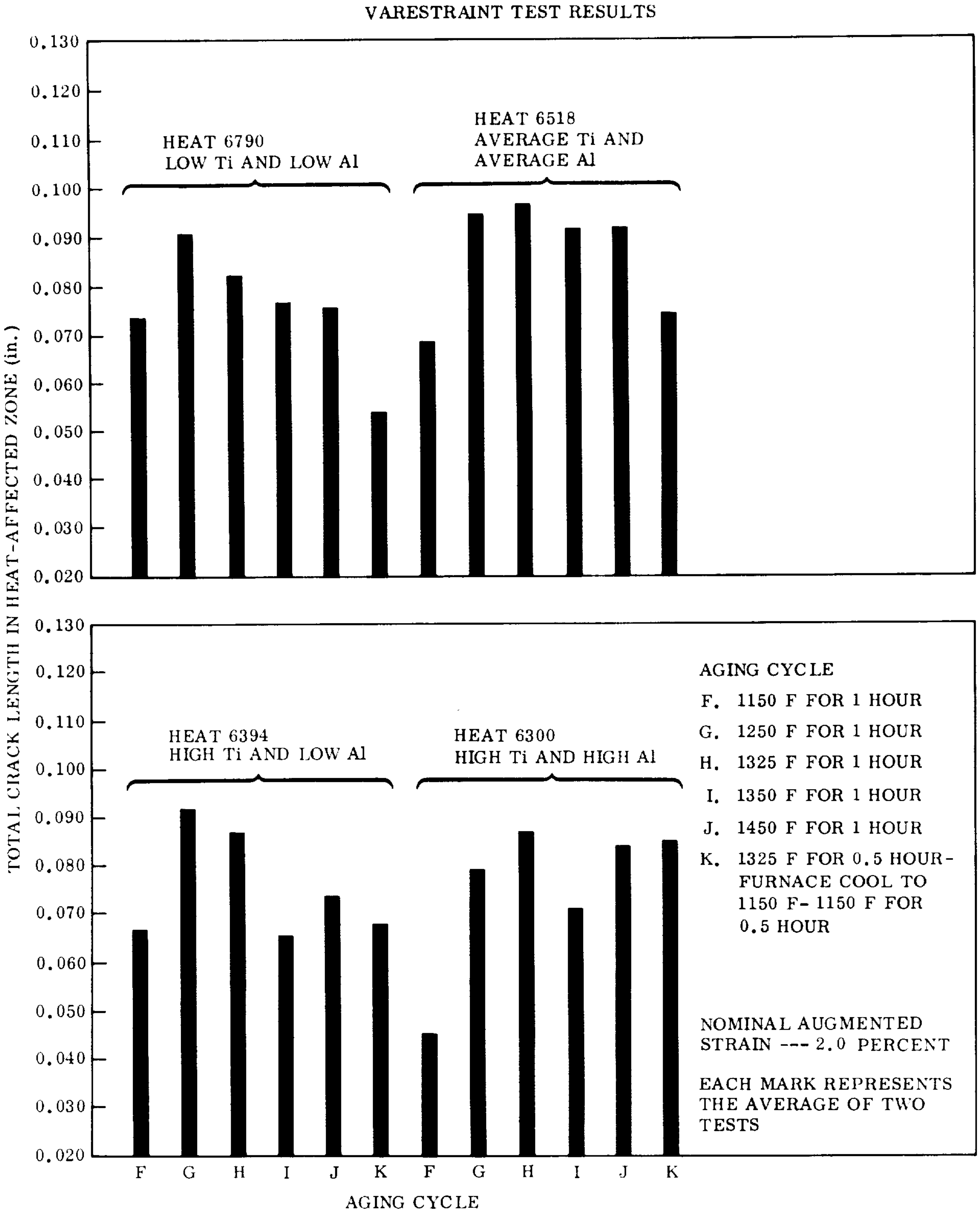


FIGURE 16. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS; 0.040-Inch Material at 1750F

Double vacuum melted material supplied by Armco as well as the Hopkins-melted material supplied by Firth Sterling again show the same trend, i.e., cracking sensitivity increases as the annealing temperature is increased above 1750 F.

Varestraint tests on double vacuum melted 0.040-inch material supplied by Eastern and Armco show some reduction in cracking sensitivity in comparison to the 0.040-inch Inconel 718 alloy air melted and single vacuum melted material supplied by Huntington. However, this reduced cracking sensitivity of the double vacuum melted material is not manifested in the thicker 0.209-inch material, particularly on material annealed at the 1950 F temperature. The difference in cracking sensitivity appears to be related to structural differences which are discussed in Section 2.8.

Figure 15 compares the cracking sensitivity of the sample pieces supplied by Armco and Firth Sterling. The total heat-affected zone crack length measured directly from the as-welded surface is plotted for different thermal treatments.

It is evident that there is considerable difference in cracking sensitivity on the two thicknesses of the double vacuum melted heat supplied by Armco. Additionally, the two Hopkins-melted heats of the 0.250-inch material differ considerably. Heat D-562 is more crack sensitive than Heat A-786. Microstructural differences are discussed in Section 2.8. In addition, information supplied by Firth Sterling shows that the more crack sensitive heat is older material that had been in their warehouse for some time and, consequently, was not representative of current technology. Heat A-786 is a product of their currently improved solidification and quality controlled processing. It is apparent that by improvements in their solidification efforts and controlled processing, the cracking sensitivity of the Hopkins-melted material is comparable to material from other producers evaluated in this study.

2.6 VARIATIONS IN ANNEALING AND ABBREVIATED AGING CYCLES

Figures 16 through 22 and Tables XIII through XVIII summarize the results of Varestraint tests obtained on material processed through variations in annealing and abbreviated aging cycles. The nominal augmented strain as well as the welding parameters were held constant. Thus, direct comparison of the hot cracking tendency of the Inconel 718 alloy with variations in thermal treatments may be made.

Evaluation of test results indicates that differences in heat-affected zone cracking susceptibility cannot be consistently attributed to the compositional variations such as the titanium-aluminum ratio. In addition, there is considerable variation in cracking

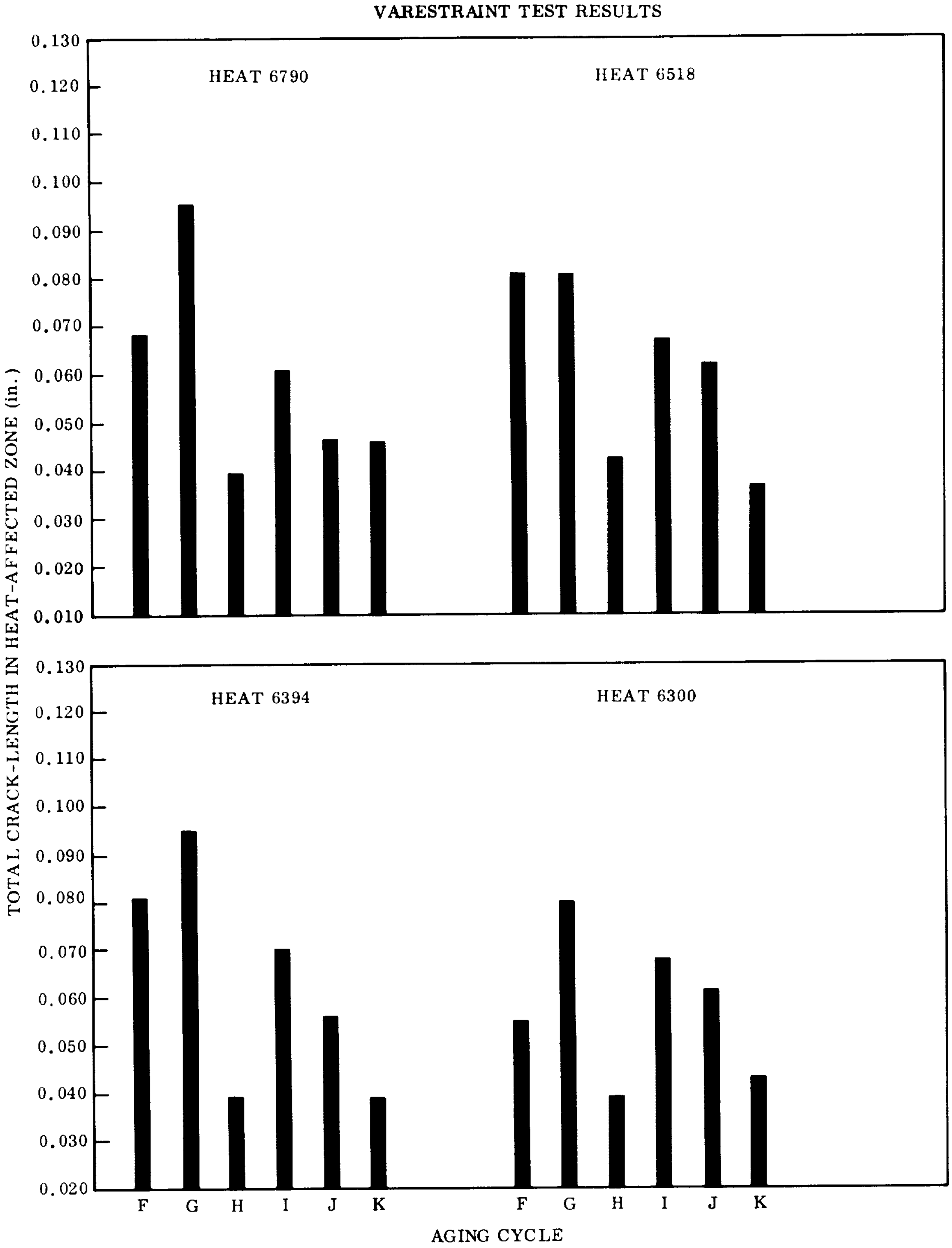


FIGURE 17. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS; 0.040-Inch Material at 1850 F

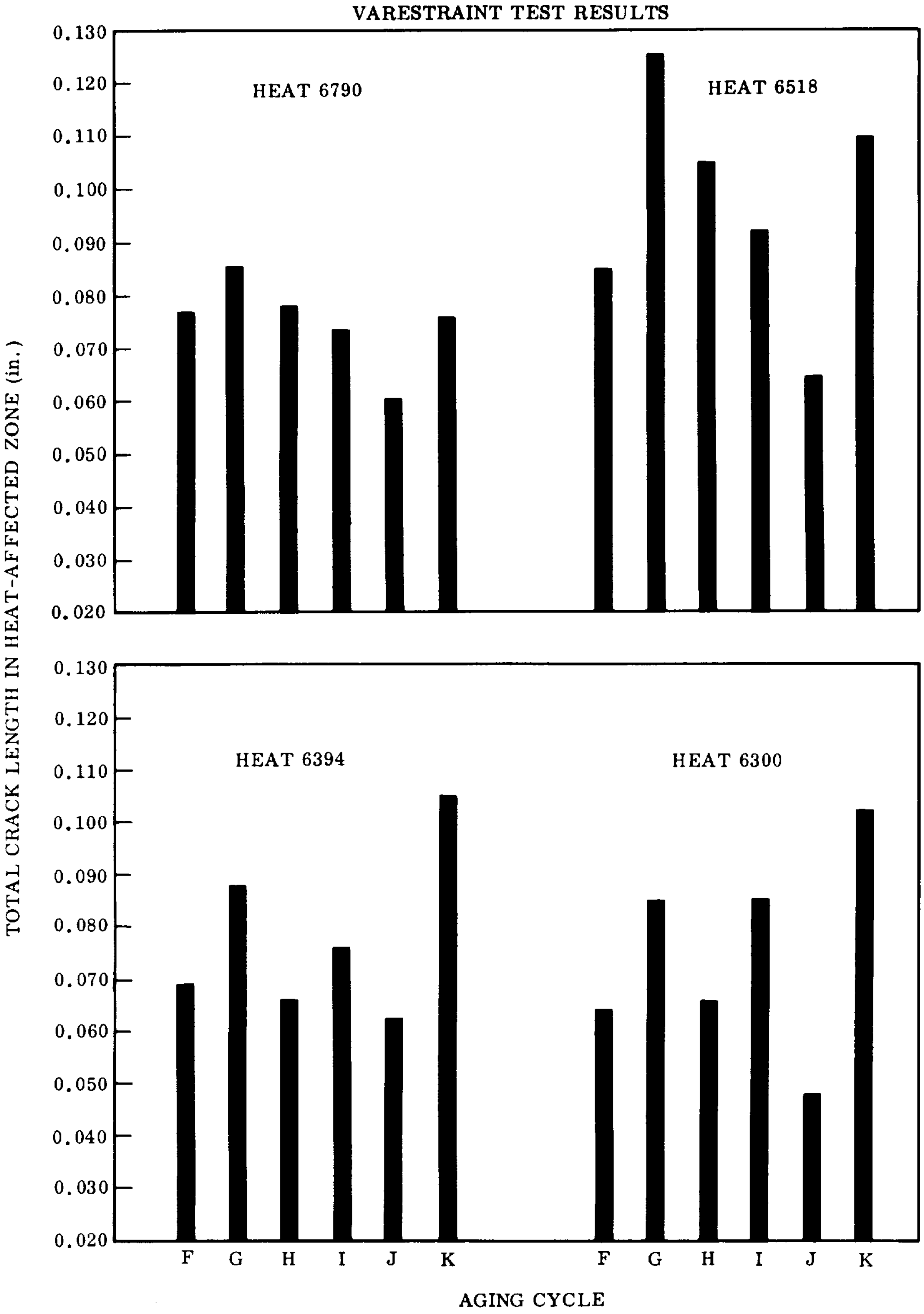


FIGURE 18. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS; 0.040-Inch Material at 1950 F

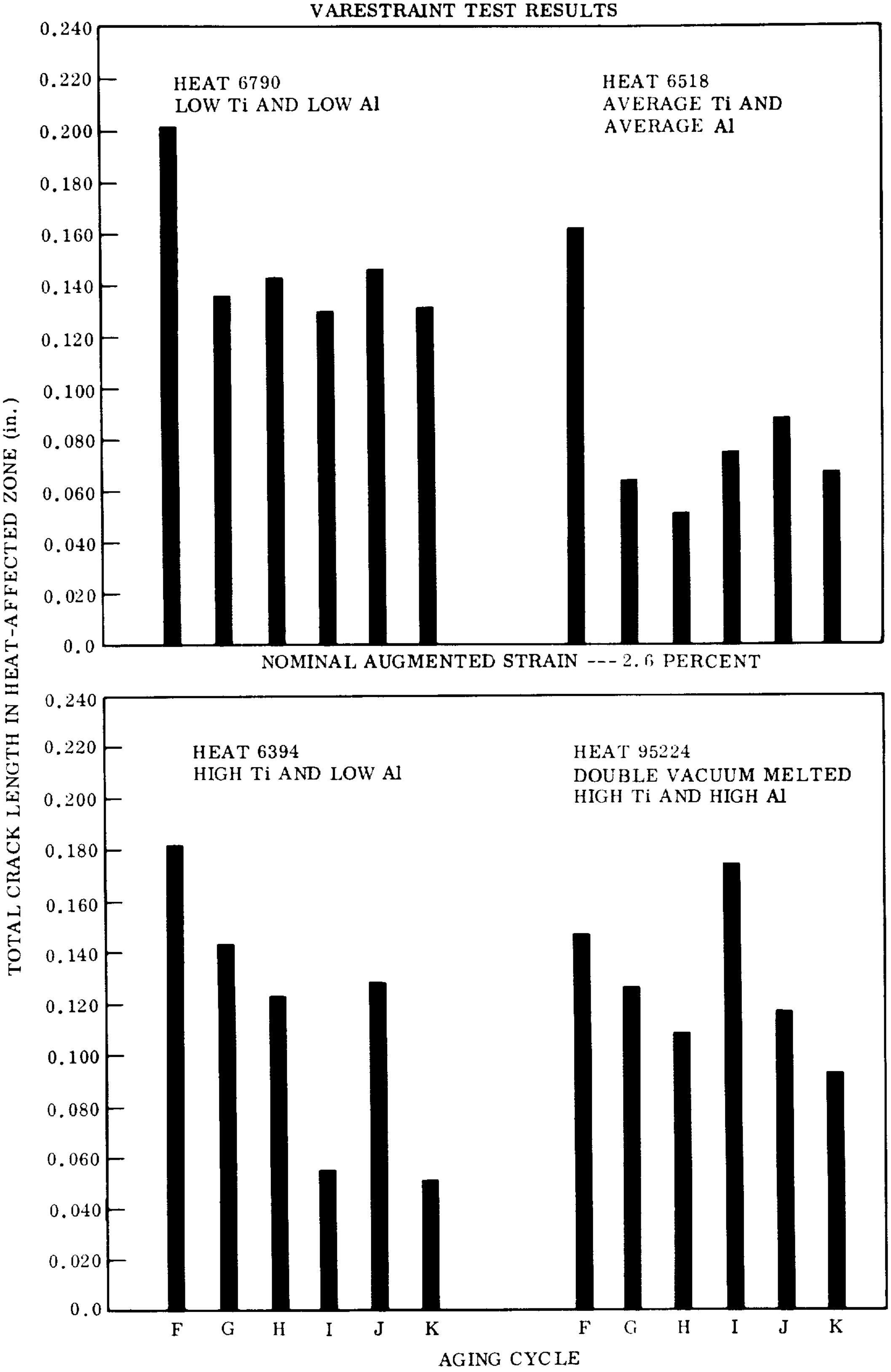


FIGURE 19. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS; 0.209-Inch Material at 1750 F

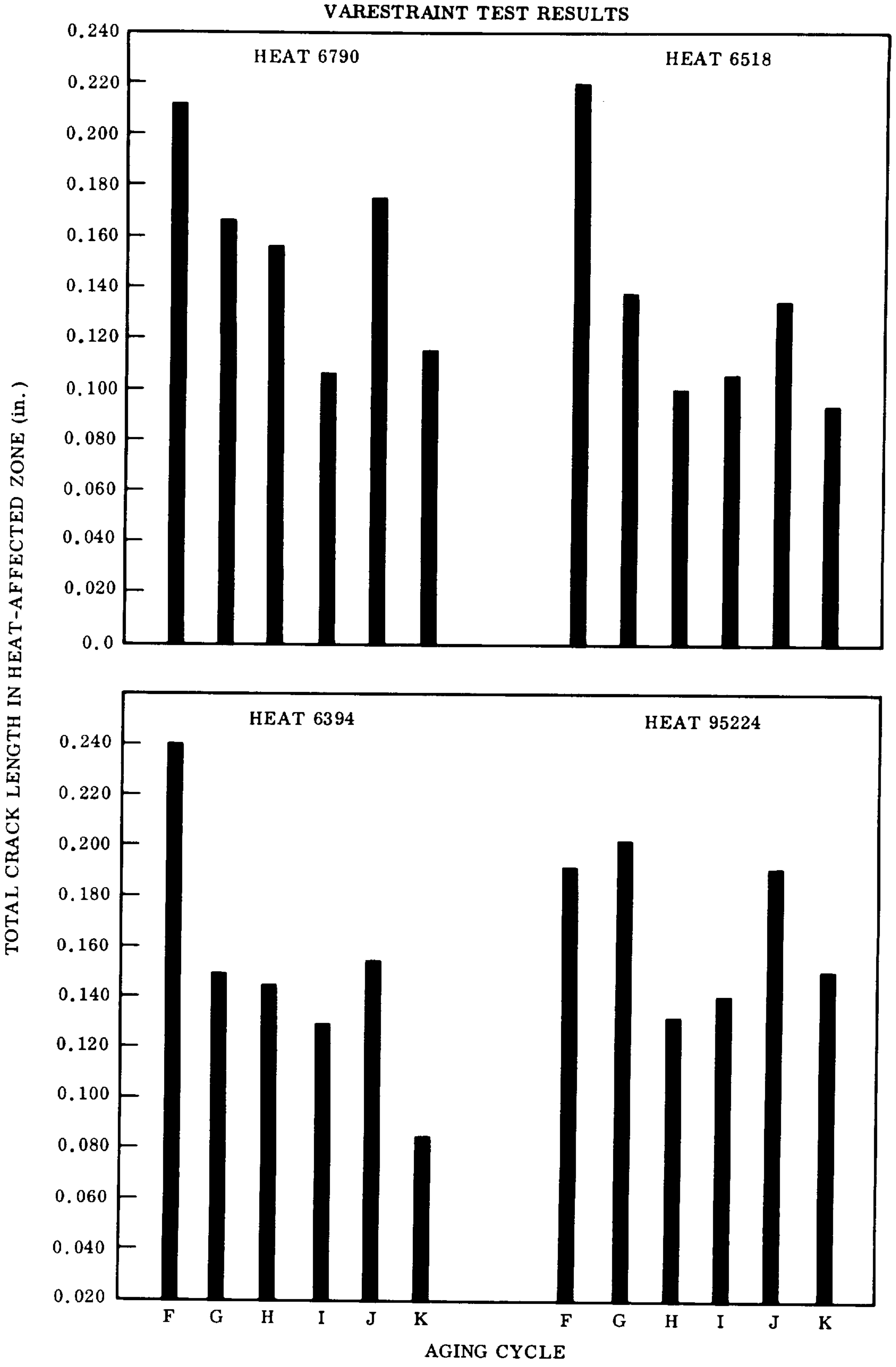


FIGURE 20. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS; 0.209-Inch Material at 1850 F

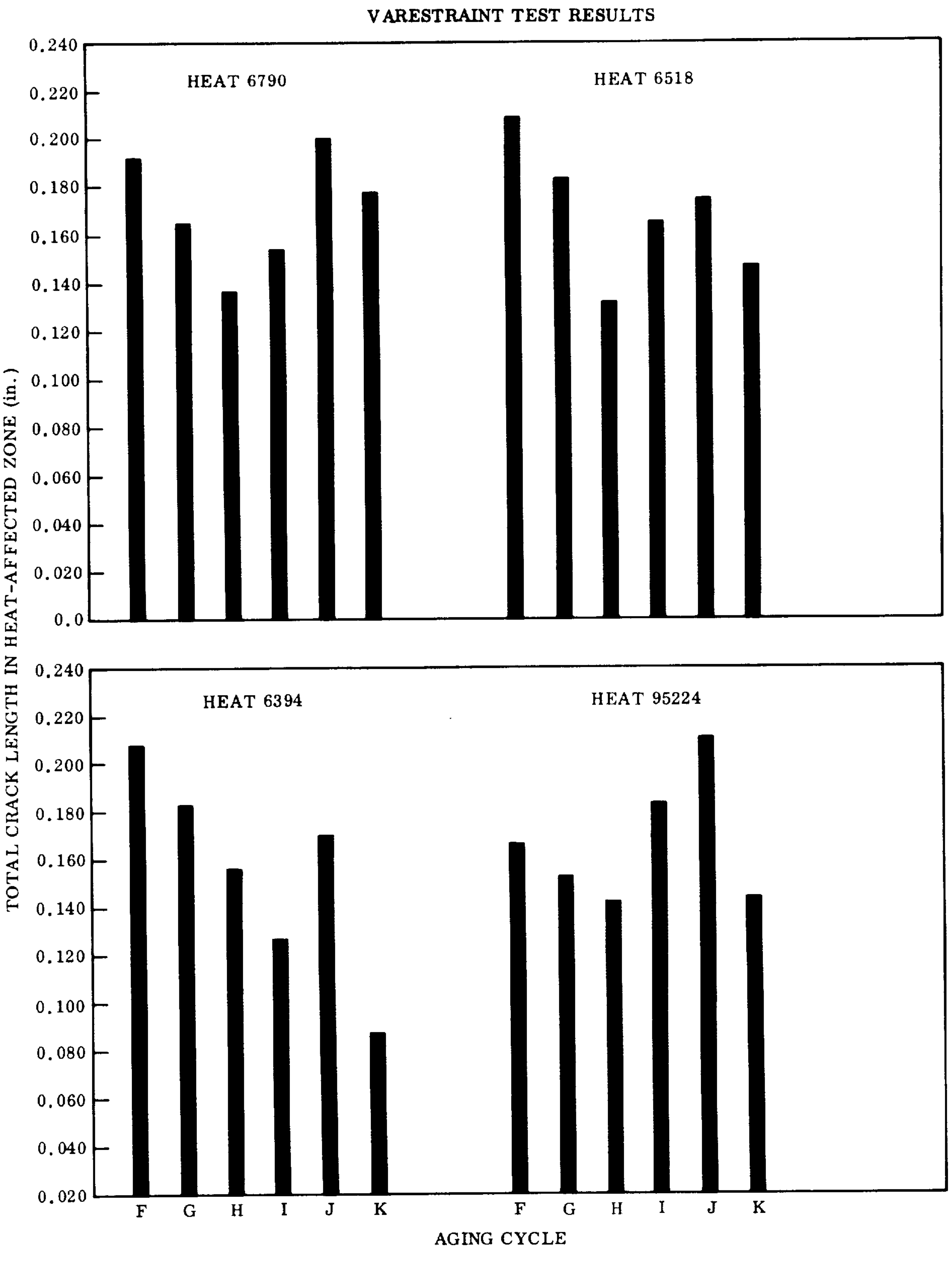


FIGURE 21. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS; 0.209-Inch Material at 1950 F

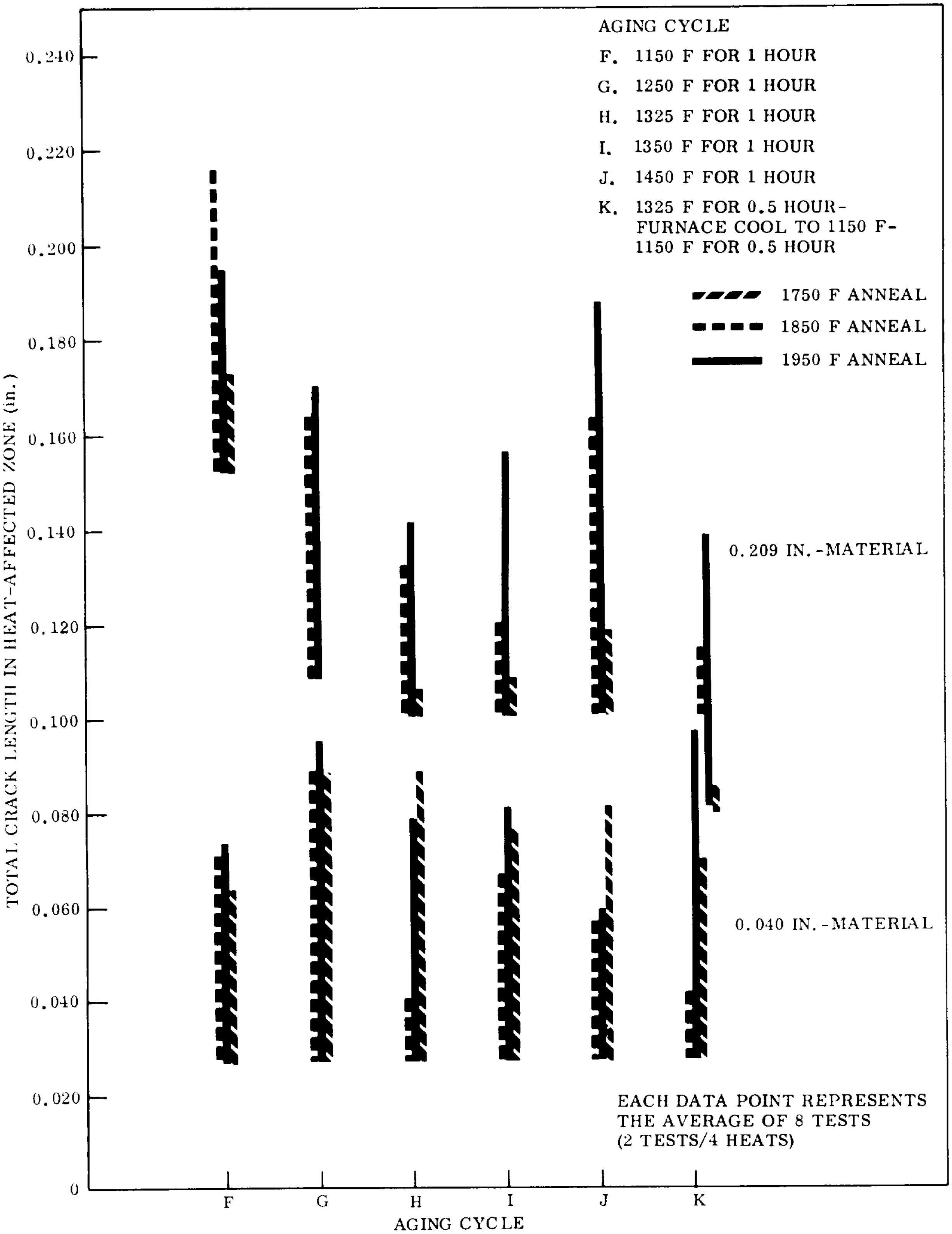


FIGURE 22. EFFECT OF ABBREVIATED AGING CYCLE ON VARESTRAINT TEST RESULTS: average of all Heats, 0.040- and 0.209-Inch Material

TABLE XIII

VARESTRAINT TEST RESULTS
Effect of Abbreviated Aging Cycles on the Cracking Susceptibility of the 0.040 inch thick 718 Material Annealed at 1750 F

Heat Treat Cycle(1)	Specimen Number	Total Heat-Affected Zone Crack Length (in.)(2)				Total Heat-Affected Zone Crack Length Average for Four Heats (in.)
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Average Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 6300 High Titanium High Aluminum	
F	1	0.0712	0.0640	0.0788	0.0520	
	2	0.0760	0.0736	0.0552	0.0396	
Average		0.0736	0.0688	0.0670	0.0458	0.0638
G	1	0.0872	0.1004	0.0950	0.0797	
	2	0.0934	0.0892	0.0895	0.0793	
Average		0.0903	0.0948	0.0922	0.0795	0.0892
H	1	0.0828	0.9360	0.0812	0.0824	
	2	0.0800	0.1004	0.0932	0.0918	
Average		0.0814	0.0970	0.0872	0.0871	0.0882
I	1	0.0920	0.0840	0.0632	0.0744	
	2	0.0616	0.0988	0.0680	0.0684	
Average		0.0768	0.0914	0.0656	0.0714	0.0763
J	1	0.0704	0.0816	0.0760	0.0764	
	2	0.0804	0.1028	0.0712	0.0920	
Average		0.0754	0.0917	0.0736	0.0842	0.0812
K	1	0.0556	0.0764	0.0620	0.0908	
	2	0.0528	0.0728	0.0740	0.0808	
Average		0.0542	0.0746	0.0680	0.0858	0.0706

1. | | |
|---|---|
| Heat Treat Cycle F | Aged 1150 F 1 hour |
| Heat Treat Cycle G | Aged 1250 F 1 hour |
| Heat Treat Cycle H | Aged 1325 F 1 hour |
| Heat Treat Cycle I | Aged 1350 F 1 hour |
| Heat Treat Cycle J | Aged 1450 F 1 hour |
| Heat Treat Cycle K | Aged 1325 F 0.5 hour, furnace cool to 1150 F, 1150 F 0.5 hour. |

2. Nominal Augmented Strain --- 2.0 Percent

TABLE XIV

VARESTRAINT TEST RESULTS
Effect of Abbreviated Aging Cycles on the Cracking Susceptibility of the 0.040 inch 718 Material Annealed at 1850 F

Heat Treat Cycle(1)	Specimen Number	Total Heat-Affected Zone Crack Length (in.)(2)				Total Heat-Affected Zone Crack Length Average for Four Heats (in.)
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Average Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 6300 High Titanium High Aluminum	
F	1	0.0700	0.1008	0.0704	0.0528	
	2	0.0680	0.0616	0.0920	0.0600	
Average		0.0690	0.0812	0.0812	0.0560	0.0718
G	1	0.0948	0.0755	0.0988	0.0776	
	2	0.0973	0.0865	0.0912	0.0840	
Average		0.0960	0.0810	0.0950	0.0808	0.0882
H	1	0.0400	0.0464	0.0404	0.0384	
	2	0.0408	0.0400	0.0380	0.0400	
Average		0.0404	0.0432	0.0392	0.0392	0.0405
I	1	0.0676	0.0696	0.0640	0.0596	
	2	0.0548	0.0660	0.0764	0.0764	
Average		0.0612	0.0678	0.0702	0.0680	0.0668
J	1	0.0552	0.0604	0.0488	0.0468	
	2	0.0392	0.0652	0.0640	0.0764	
Average		0.0472	0.0628	0.0564	0.0616	0.0570
K	1	0.0492	0.0340	0.0468	0.0472	
	2	0.0444	0.0408	0.0324	0.0392	
Average		0.0468	0.0374	0.0396	0.0432	0.0417

1. Heat Treat Cycle F Aged 1150 F 1 hour
   Heat Treat Cycle G Aged 1250 F 1 hour
   Heat Treat Cycle H Aged 1325 F 1 hour
   Heat Treat Cycle I Aged 1350 F 1 hour
   Heat Treat Cycle J Aged 1450 F 1 hour
   Heat Treat Cycle K Aged 1325 F 0.5 hour, furnace cool to 1150 F, 1150 F 0.5 hour

2. Nominal Augmented Strain --- 2.0 Percent

TABLE XV

VARESTRAINT TEST RESULTS
Effect of Abbreviated Aging Cycles on the Cracking Susceptibility of the 0.040 inch thick 718 Material Annealed at 1950 F

Heat Treat Cycle(1)	Specimen Number	Total Heat-Affected Zone Crack Length (in.)(2)				Total Heat-Affected Zone Crack Length Average for Four Heats (in.)
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Average Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 6300 High Titanium High Aluminum	
F	1	0.0864	0.0828	0.0576	0.0616	
	2	0.0680	0.0880	0.0800	0.0668	
Average		0.0772	0.0854	0.0688	0.0642	0.0736
G	1	0.0840	0.1444	0.0884	0.0832	
	2	0.0868	0.1064	0.0860	0.0848	
Average		0.0854	0.1254	0.0872	0.0840	0.0955
H	1	0.0632	0.1008	0.0692	0.0688	
	2	0.0932	0.1096	0.0640	0.0644	
Average		0.0785	0.1052	0.0660	0.0660	0.0788
I	1	0.0632	0.0904	0.0820	0.0808	
	2	0.0844	0.0944	0.0688	0.0884	
Average		0.0738	0.0924	0.0754	0.0846	0.0815
J	1	0.0616	0.0644	0.0480	0.0436	
	2	0.0596	0.0660	0.0776	0.0520	
Average		0.0606	0.0652	0.0628	0.0478	0.0591
K	1	0.076	0.1008	0.1372	0.1144	
	2	---	0.1180	0.0724	0.0888	
Average		0.076	0.1094	0.1048	0.1016	0.0979

1. Heat Treat Cycle F Aged 1150 F 1 hour
   Heat Treat Cycle G Aged 1250 F 1 hour
   Heat Treat Cycle H Aged 1325 F 1 hour
   Heat Treat Cycle I Aged 1350 F 1 hour
   Heat Treat Cycle J Aged 1450 F 1 hour
   Heat Treat Cycle K Aged 1325 F 0.5 hour, furnace cool to 1150 F, 1150 F 0.5 hour.

2. Nominal Augmented Strain --- 2.0 Percent

TABLE XVI

VARESTRAINT TEST RESULTS
Effect of Abbreviated Aging Cycles on the Cracking Susceptibility of the 0.209 inch thick 718 Material Annealed at 1750 F

Heat Treat Cycle[1]	Specimen Number	Total Heat-Affected Zone Crack Length (in.)[2]				Total Heat-Affected Zone Crack Length Average for Four Heats (in.)
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Average Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 95224 Double Vacuum Melted Heat	
F	1	0.2192	0.1844	0.1732	0.1052	0.1731
	2	0.1852	0.1380	0.1916	0.1880	
Average		0.2022	0.1612	0.1824	0.1466	
G	1	0.1652	0.0744	0.1328	0.1196	0.1174
	2	0.1080	0.0528	0.1548	0.1316	
Average		0.1366	0.0636	0.1438	0.1256	
H	1	0.1528	0.0600	0.1340	0.0940	0.1066
	2	0.1328	0.0440	0.1116	0.1236	
Average		0.1428	0.0520	0.1228	0.1088	
I	1	0.1144	0.0732	0.0552	0.1808	0.1085
	2	0.1460	0.0776	0.0548	0.1460	
Average		0.1302	0.0754	0.0550	0.1734	
J	1	0.1376	0.0929	0.0928	0.1296	0.1193
	2	0.1540	0.0820	0.1624	0.1040	
Average		0.1458	0.0870	0.1276	0.1168	
K	1	0.1012	0.0464	0.0616	0.0788	0.0856
	2	0.1620	0.0888	0.0396	0.1068	
Average		0.1316	0.0676	0.0506	0.0928	

1. Heat Treat Cycle F — Aged 1150 F 1 hour
Heat Treat Cycle G — Aged 1250 F 1 hour
Heat Treat Cycle H — Aged 1325 F 1 hour
Heat Treat Cycle I — Aged 1350 F 1 hour
Heat Treat Cycle J — Aged 1450 F 1 hour
Heat Treat Cycle K — Aged 1325 F 0.5 hour, furnace cool to 1150 F, 1150 F 0.5 hour.

2. Nominal Augmented Strain --- 2.6 Percent

TABLE XVII

VARESTRAINT TEST RESULTS
Effect of Abbreviated Aging Cycles on the Cracking Susceptibility of the 0.209 inch thick 718 Material Annealed at 1850 F

Heat Treat Cycle(1)	Specimen Number	Total Heat-Affected Zone Crack Length (in.)(2)				Total Heat-Affected Zone Crack Length Average for Four Heats (in.)
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Average Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 95224 Double Vacuum Melted Heat	
F	1	0.1716	0.2100	0.2360	0.1804	
	2	0.2508	0.2296	0.2436	0.2040	
Average		0.2112	0.2198	0.2398	0.1922	0.2157
G	1	0.1339	0.1388	0.1404	0.1944	
	2	0.1990	0.1367	0.1584	0.2120	
Average		0.1663	0.1377	0.1494	0.2032	0.1641
H	1	0.1140	0.0960	0.1196	0.1348	
	2	0.1980	0.0988	0.1684	0.1296	
Average		0.1562	0.0974	0.1440	0.1322	0.1324
I	1	0.1088	0.0912	0.1468	0.1200	
	2	0.1032	0.1192	0.1108	0.1612	
Average		0.1060	0.1052	0.1288	0.1406	0.1201
J	1	0.1588	0.1644	0.1412	0.1648	
	2	0.1892	0.1048	0.1672	0.2180	
Average		0.1740	0.1346	0.1542	0.1914	0.1635
K	1	0.0992	0.1144	0.0932	0.1544	
	2	0.1300	0.0748	0.0776	0.1480	
Average		0.1146	0.0946	0.0854	0.1512	0.1144

1. Heat Treat Cycle F Aged 1150 F 1 hour
   Heat Treat Cycle G Aged 1250 F 1 hour
   Heat Treat Cycle H Aged 1325 F 1 hour
   Heat Treat Cycle I Aged 1350 F 1 hour
   Heat Treat Cycle J Aged 1450 F 1 hour
   Heat Treat Cycle K Aged 1325 F 0.5 hour, furance cool to 1150 F. 1150 F 0.5 hour.

2. Nominal Augmented Strain --- 2.6 Percent

TABLE XVIII

VARESTRAINT TEST RESULTS
Effect of Abbreviated Aging Cycles on the Cracking Susceptibility of the 0.209 inch thick 718 Material Annealed at 1950 F

Heat Treat Cycle(1)	Specimen Number	Total Heat-Affected Zone Crack Length (in.)(2)				Total Heat-Affected Zone Crack Length Average for Four Heats (in.)
		Heat No. 6790 Low Titanium Low Aluminum	Heat No. 6518 Average Titanium Average Aluminum	Heat No. 6394 High Titanium Low Aluminum	Heat No. 95224 Double Vacuum Melted Heat	
F	1	0.2200	0.2304	0.2296	0.1808	
	2	0.1644	0.1860	0.1876	0.1452	
Average		0.1922	0.2082	0.2086	0.1630	0.1955
G	1	0.1664	0.1704	0.2008	0.1564	
	2	0.1636	0.1924	0.1664	0.1484	
Average		0.1650	0.1814	0.1836	0.1524	0.1706
H	1	0.1468	0.1184	0.1748	0.1428	
	2	0.1268	0.1456	0.1376	0.1420	
Average		0.1368	0.1320	0.1562	0.1424	0.1418
I	1	0.1476	0.1576	0.1600	0.1460	
	2	0.1608	0.1724	0.0952	0.2172	
Average		0.1542	0.1650	0.1276	0.1816	0.1571
J	1	0.2136	0.1308	0.1624	0.2168	
	2	0.1864	0.2176	0.1772	0.2048	
Average		0.2000	0.1742	0.1698	0.2108	0.1887
K	1	0.1964	0.1260	0.0964	0.1384	
	2	0.1596	0.1692	0.0756	0.1496	
Average		0.1780	0.1476	0.0860	0.1440	0.1389

1. Heat Treat Cycle F Aged 1150 F 1 hour
Heat Treat Cycle G Aged 1250 F 1 hour
Heat Treat Cycle H Aged 1325 F 1 hour
Heat Treat Cycle I Aged 1350 F 1 hour
Heat Treat Cycle J Aged 1450 F 1 hour
Heat Treat Cycle K Aged 1325 F 0.5 hour, furnace cool to 1150 F, 1150 F 0.5 hour.

2. Nominal Augmented Strain --- 2.6 Percent

sensitivity relative to variations in abbreviated aging treatments. No real trend is noticeable that would indicate that a particular heat or an abbreviated aging cycle is slightly more crack sensitive than another. The apparent superiority of a particular heat over another heat as shown in Figure 18 (Heat No. 6394 versus Heat No. 6300 - abbreviated aging treatment D) is reversed by the use of a different abbreviated aging treatment K.

The heat-affected zone cracking tendency of abbreviated aged specimens is increased as the annealing temperature is raised to 1950 F. Figure 22 which summarizes the data of all heats and abbreviated thermal treatments, shows the apparent increase in cracking tendency of the Inconel 718 alloy after annealing at 1950 F. This increase in heat-affected zone cracking tendency is more pronounced for the thicker, 0.209-inch material.

The least heat-affected zone cracking obtained by an abbreviated aging treatment on the 0.040-inch material was observed on material annealed at 1850 F and subsequently aged at 1325 F for one hour. Average heat-affected zone cracking for the four heats evaluated amounted to 0.0405 inch.

Material annealed at 1950 F and subsequently double aged at 1325 F for 0.5 hour then furnace cooled to 1150 F where it remained for 0.5 hour resulted in the most heat-affected zone cracking (0.0979 in.) in the 0.040-inch material.

For the 0.209-inch material evaluated, the least heat-affected zone cracking occurred with the use of a 1750 F anneal followed by the short abbreviated aging cycle consisting of: 1325 F for 0.5 hour - furnace cool to 1150 F - 1150 for 0.5 hour.

The particular abbreviated aging treatment that resulted in the most heat-affected zone cracking of the 0.209-inch material was observed on material annealed at 1850 F and subsequently aged at 1150 F for one hour.

2.7 OPTIMUM THERMAL TREATMENT

The summary of Varestraint tests contained in Tables X through XVIII and shown in Figures 13 through 22 indicated that no single thermal treatment yielded the least amount of heat-affected zone cracking for the two thicknesses involved in this evaluation. The thermal treatment resulting in the least amount of heat-affected zone cracking for the 0.040-inch Inconel 718 material did not result in the least amount of cracking in the 0.209-inch Inconel 718 material. Consequently, it was decided that the thermal treatment which resulted in the least combined (0.040 inch and 0.209 inch) heat-affected zone cracking would be chosen as the optimum heat treating process.

The thermal treatment which resulted in the best combination of weldability and high-strength properties is the Pratt & Whitney thermal treatment (AMS 5596). The next best thermal cycle is Solar's, which consists of an 1800 F anneal, followed by an abbreviated double aging cycle of 8.5 hours duration. The combined total cracking in the heat-affected zone of both 0.040- and 0.209-inch specimens after the Pratt & Whitney thermal cycle amounted to 0.1170 inch, and 0.1369 inch for specimens processed through Solar's thermal cycle. The abbreviated thermal cycle which produced the least amount of heat-affected zone cracking on both the 0.040- and 0.209-inch specimens consisted of:

- 1850 anneal
- Aged at 1325 F 0.5 hour - furnace cool to 1150 F - 1150 F 0.5 hour

Total combined heat-affected zone cracking for this thermal cycle amounted to 0.1531 inch.

The Pratt & Whitney thermal cycle as outlined in Appendix B was selected as the optimum thermal treatment for bellows and gimbal structures because it apparently provides the best combination of weldability and strength properties. This thermal treatment was, therefore, used for the Phase II study.

2.8 METALLOGRAPHIC STUDIES

2.8.1 As-Received Material

The structure of the Inconel 718 alloy in the as-received condition of the various heats evaluated in this program is shown in Figures 23 through 26. The microstructure of the Inconel 718 material in this condition consists of equiaxed grains showing extensive twinning which is characteristic of the cold-worked austenitic matrix. The primary carbides, (Cb, Ti)C, can be observed as randomly dispersed particles. Also observable are networks of apparently spherical particles which seem to transcend the present equiaxed structure, but delineate grain boundaries in a previously deformed structure. The grain size is fairly uniform from heat to heat, with the grain size ranging from ASTM 4.5 to 7.0.

Heat-Affected Zone Cracking of Aged Varestraint Tested Specimens

Figure 27 shows the typical cracking pattern in the 0.040-inch Varestraint test specimens. The macrograph shown in Figure 27 is representative of the cracking pattern of the thicker, 0.209-inch Inconel 718 material. The area designated as A

Material: 0.040-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 7
Magnification: 200X

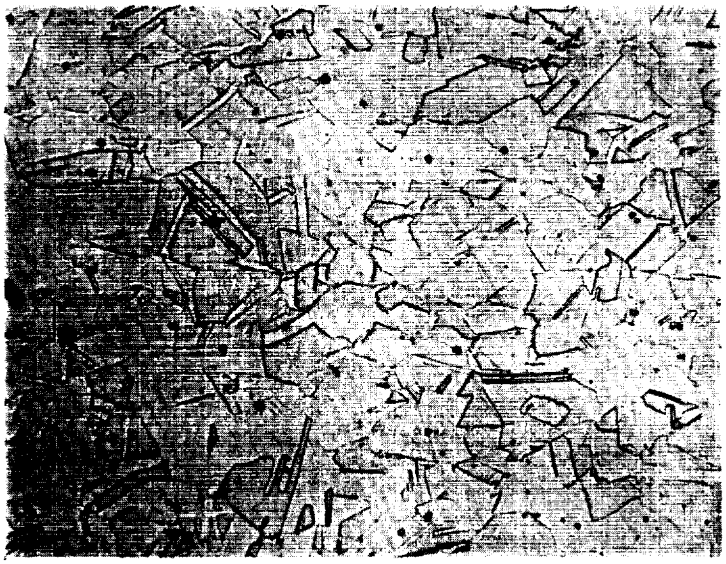
Material: 0.209-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 6
Magnification: 200X

FIGURE 23. MICROSTRUCTURE OF AS-RECEIVED MATERIAL; Heat 6790

Material: 0.040-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 6
Magnification: 200X

Material: 0.209-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 6
Magnification: 200X

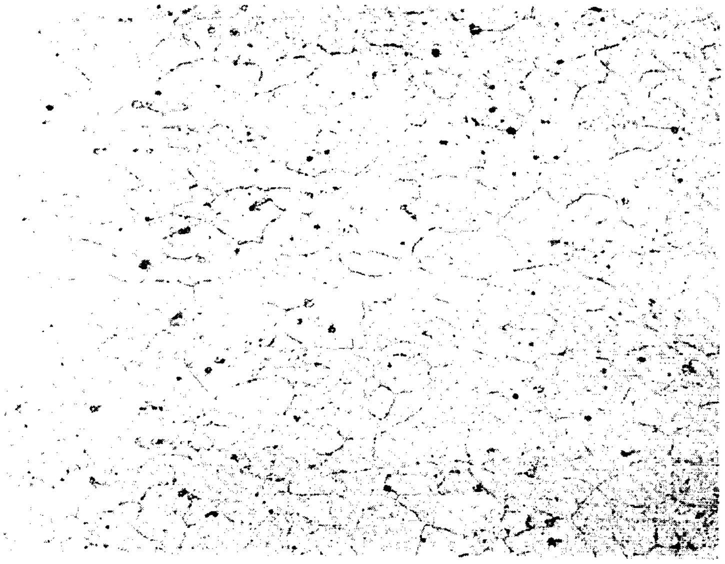
FIGURE 24. MICROSTRUCTURE OF AS-RECEIVED MATERIAL; Heat 6394



Material: 0.040-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 6
Magnification: 200X

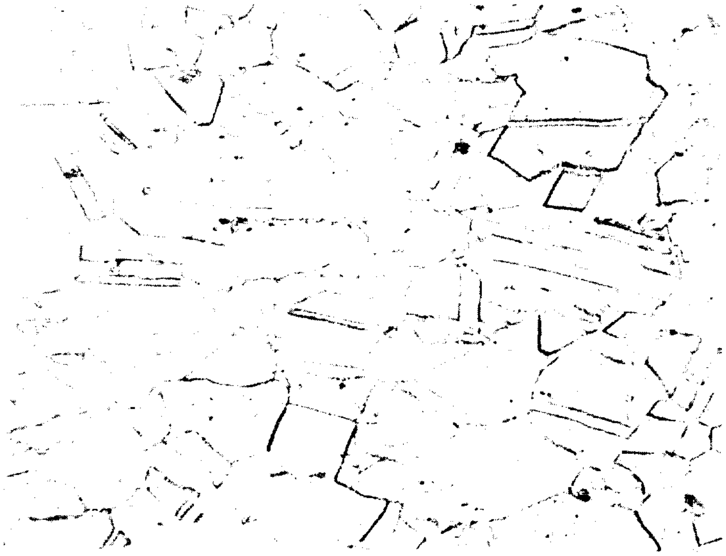
Material: 0.209-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 5
Magnification: 200X

FIGURE 25. MICROSTRUCTURE OF AS-RECEIVED MATERIAL; Heat 6518



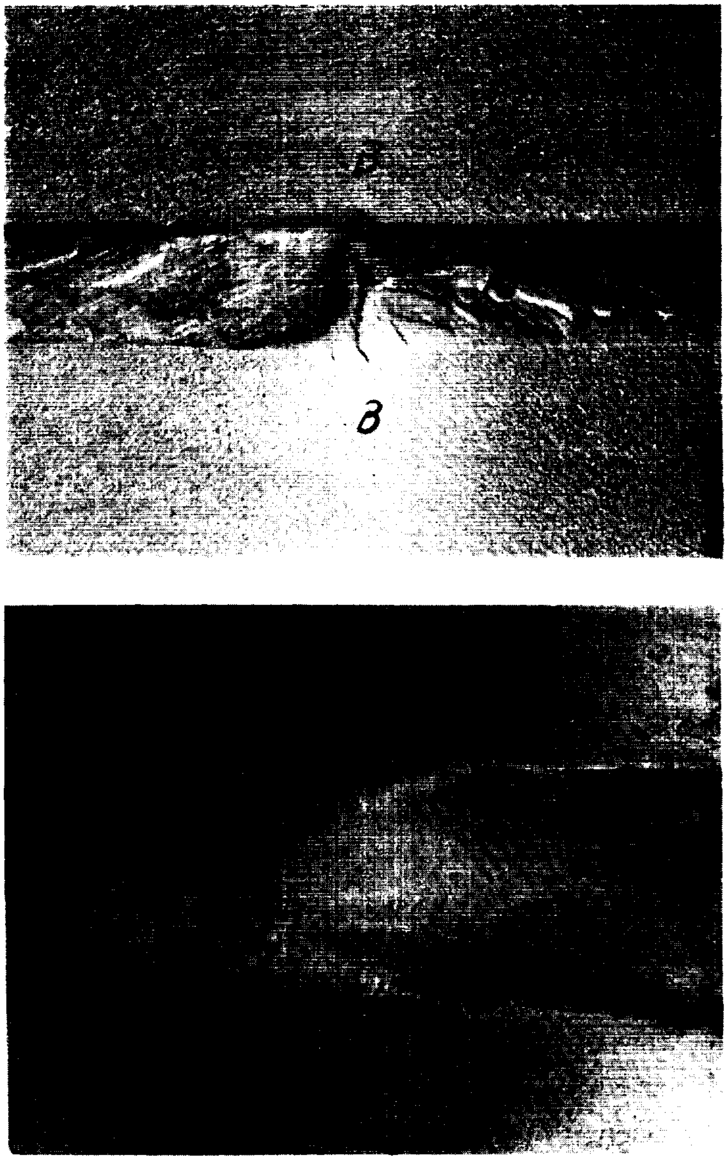
Material: 0.040-inch Inconel 718 alloy
Etchant: Kallings
ASTM Grain Size: 7
Magnification: 200X

Material: 0.040-inch Inconel 718 alloy
Double Vacuum Melted
Etchant: Kallings
ASTM Grain Size: 4.5
Magnification: 200X



Material: 0.209-inch Inconel 718 alloy
Double Vacuum Melted
Etchant: Kallings
ASTM Grain Size: 5
Magnification: 200X

FIGURE 26. MICROSTRUCTURE OF AS-RECEIVED MATERIAL; Heats 95221 and 95224



Macrograph showing typical cracking pattern in the 0.040-inch Inconel 718 Varestraint specimens.

Magnification: Approx. 10X

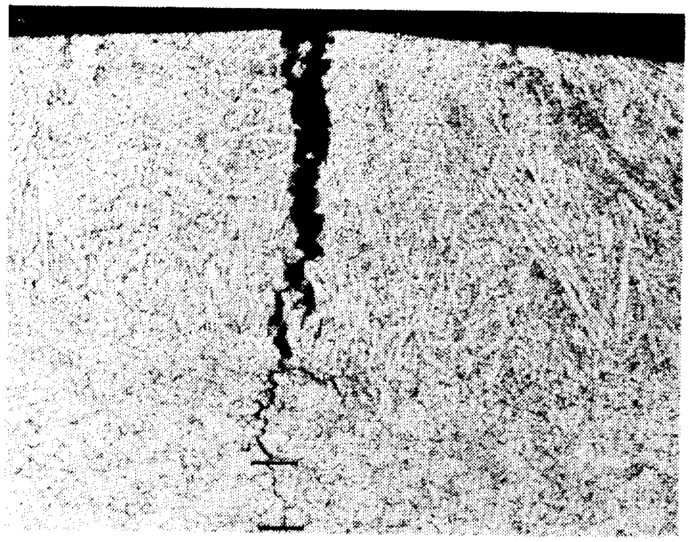
Macrograph showing typical cracking pattern in the thicker (0.209-inch) Inconel 718 material.

Magnification: Approx. 4X

FIGURE 27. TYPICAL CRACKING PATTERNS OF 0.040- AND 0.209-INCH VARESTRAINT SPECIMENS

shows the extent of cracking in the weld metal. Area B indicates where heat-affected zone cracking occurred.

Figures 28 through 54 show a series of photomicrographs of Varestraint specimens which represent the thermal treatments used in this study. Cracking in the weld metal interface is shown at the magnification of 100X. A more highly magnified view of the cracked area in the heat-affected zone is shown in the adjacent micrograph. The microstructure of the base metal as affected by the thermal treatment is shown in the next photomicrograph.



A. WELD/PARENT-METAL INTERFACE

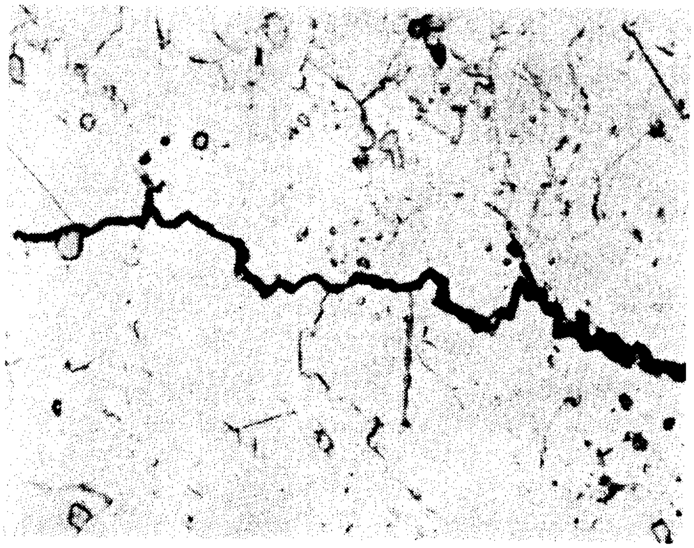
Material: 0.040-inch Inconel 718 alloy

Heat No.: 6394

Annealed: 1750 F

Etchant: Kallings

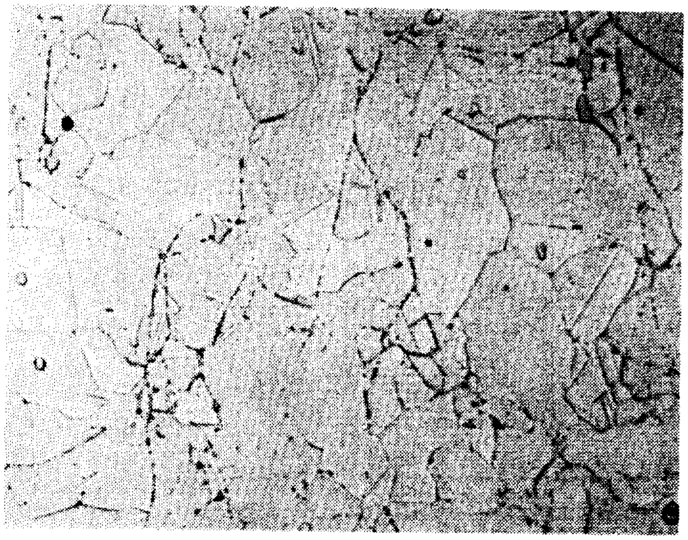
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note presence of intergranular crack.

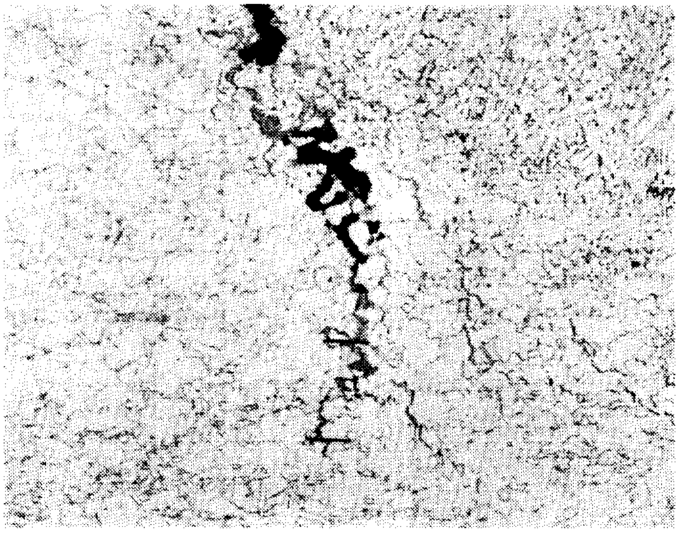
Magnification: 700X



C. PARENT METAL

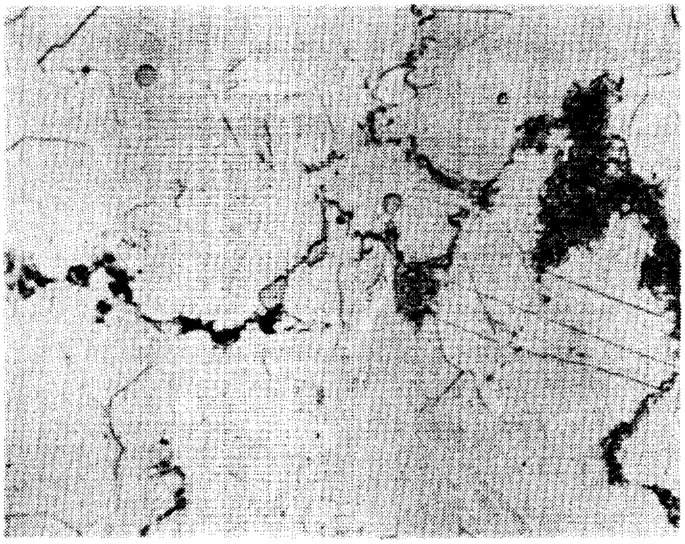
Magnification: 700X

FIGURE 28. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT A AT 1750 F WITH 0.040-INCH MATERIAL



A. WELD/PARENT-METAL INTERFACE

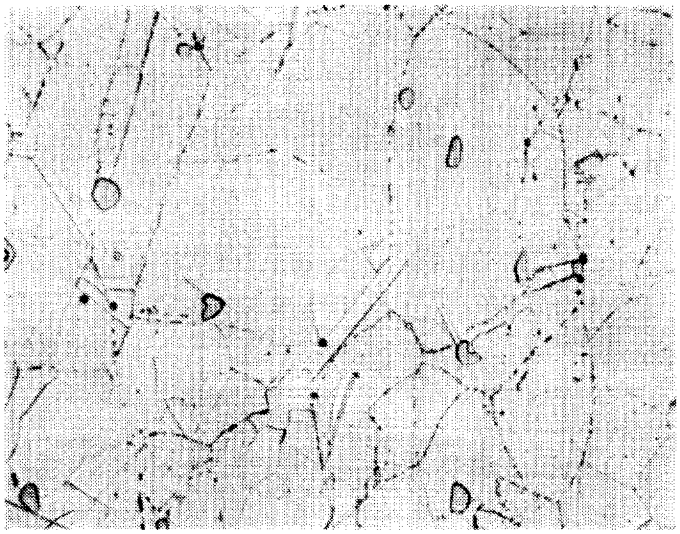
Material: 0.040-inch Inconel 718 alloy
Heat No.: 6394
Annealed: 1750 F
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note presence of a formerly liquid phase along grain boundaries.

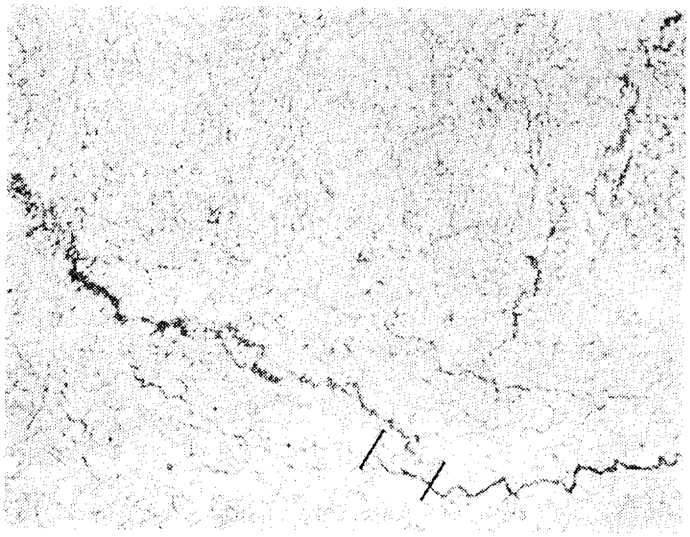
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 29. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT F AT 1750 F



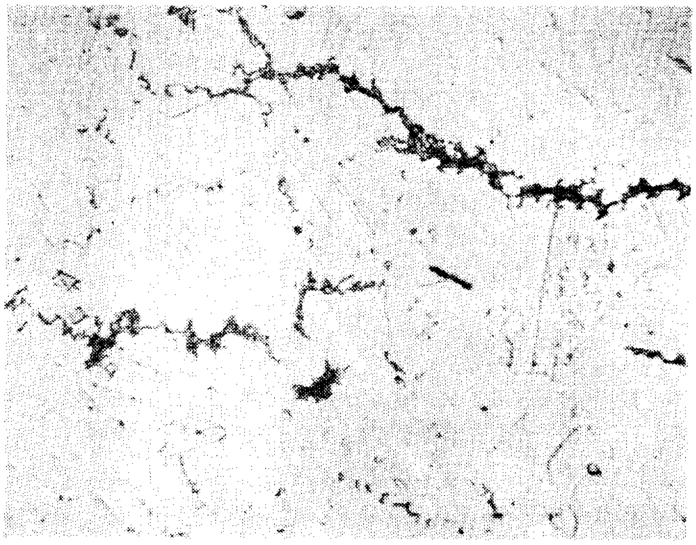
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6394

Annealed: 1750 F

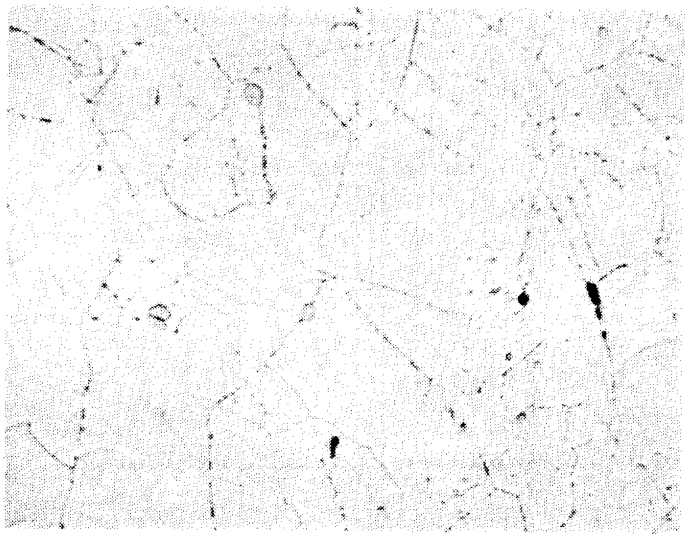
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note intergranular cracking.

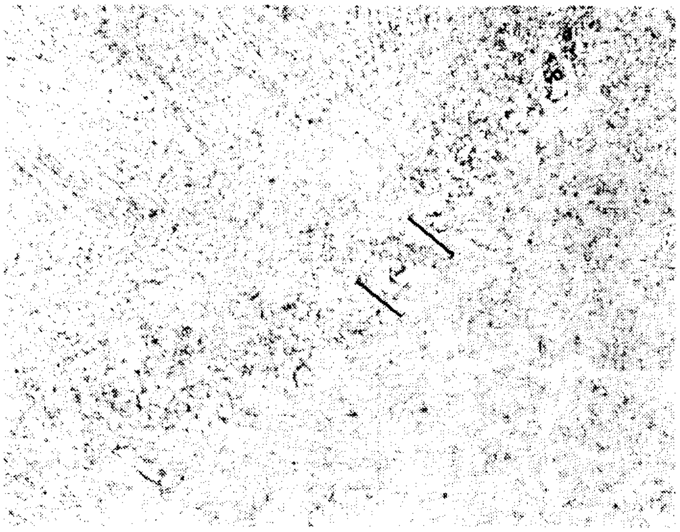
Magnification: 700X



C. PARENT METAL

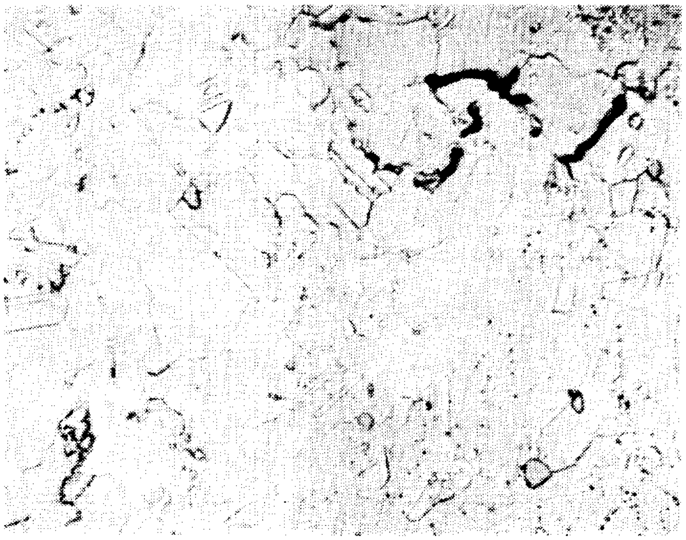
Magnification: 700X

FIGURE 30. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT G AT 1750 F



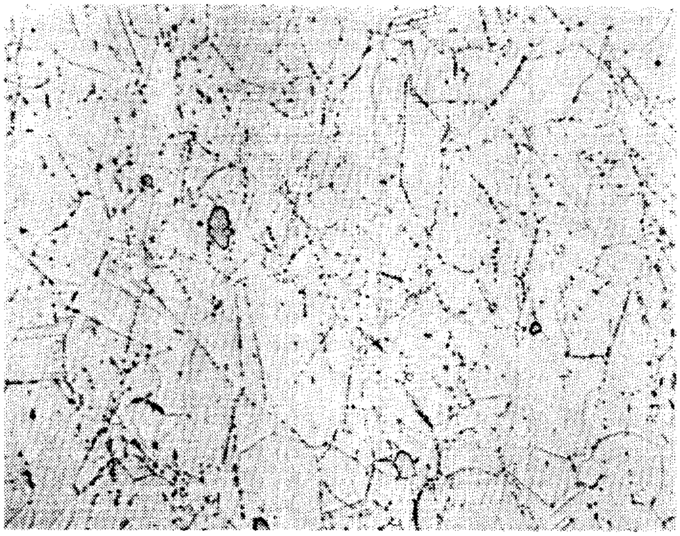
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy
Heat No.: 6300
Annealed: 1800 F
Magnification: 100X



B. HEAT-AFFECTED ZONE

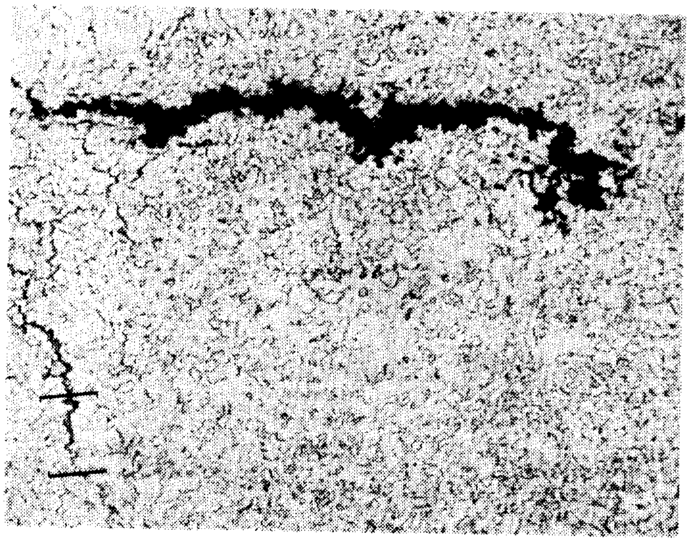
Note intergranular cracking.
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 31. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT B AT 1800 F ON 0.040-INCH MATERIAL; Heat 6300



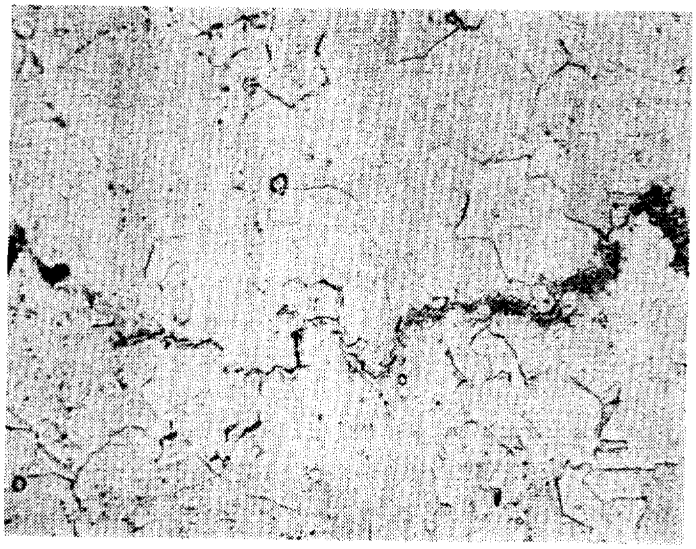
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6300

Annealed: 1850 F

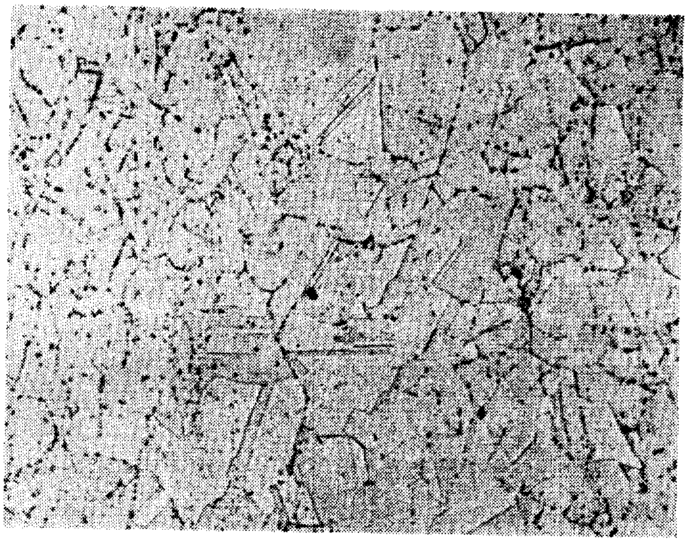
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note presence of a formerly liquid phase along grain boundaries.

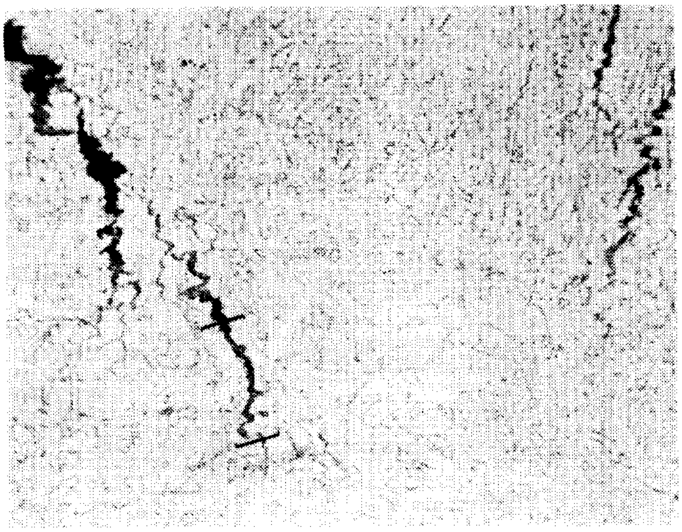
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 32. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT C AT 1850 F ON 0.040-INCH MATERIAL



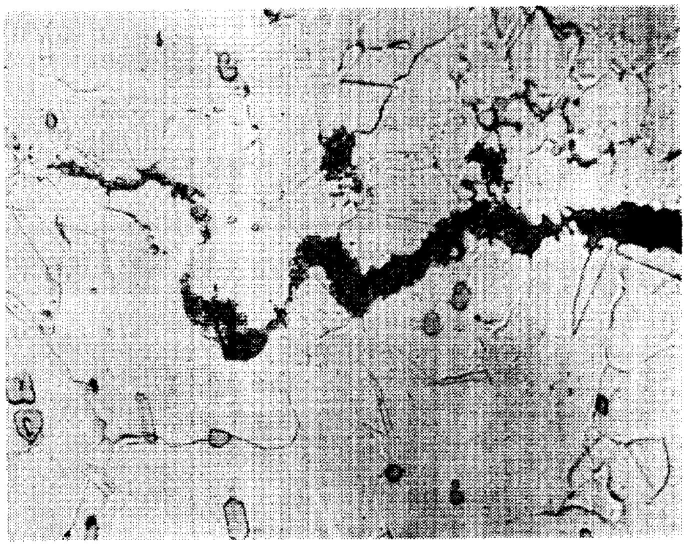
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6394

Annealed: 1850 F

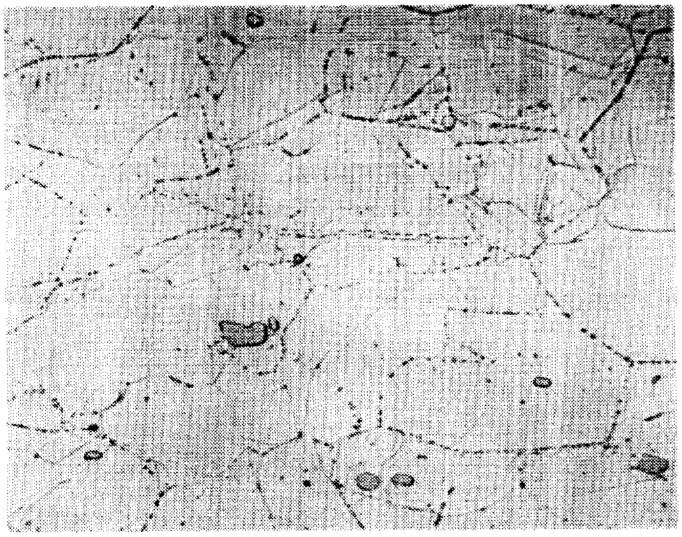
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note cracking and a formerly liquid phase along the grain boundaries.

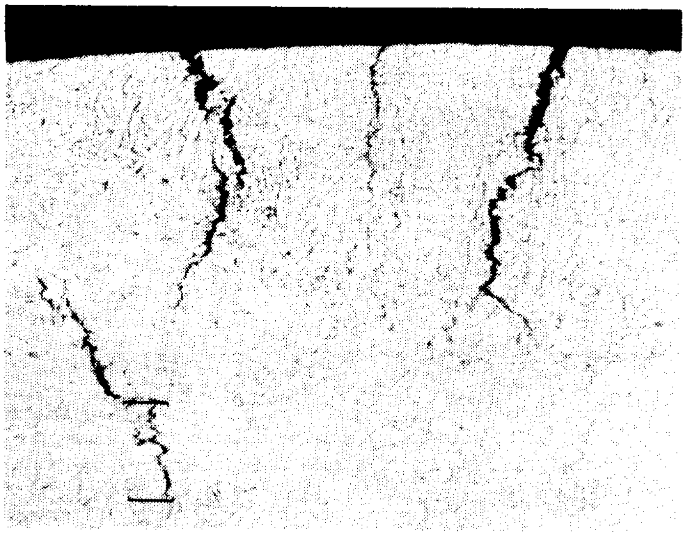
Magnification: 700X



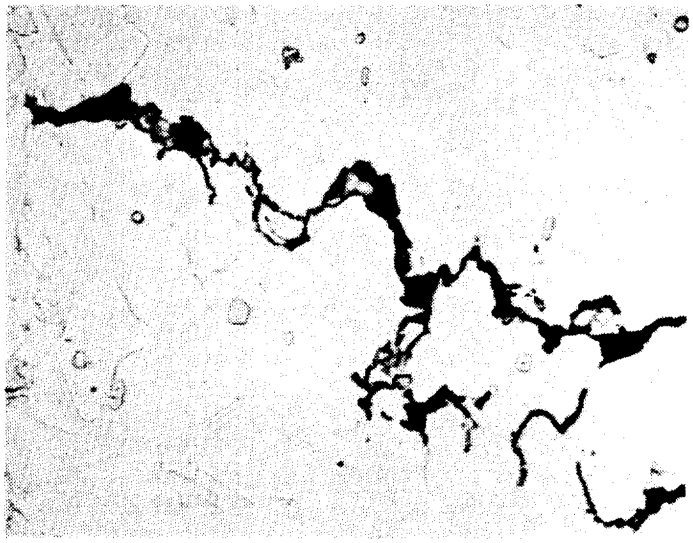
C. PARENT METAL

Magnification: 700X

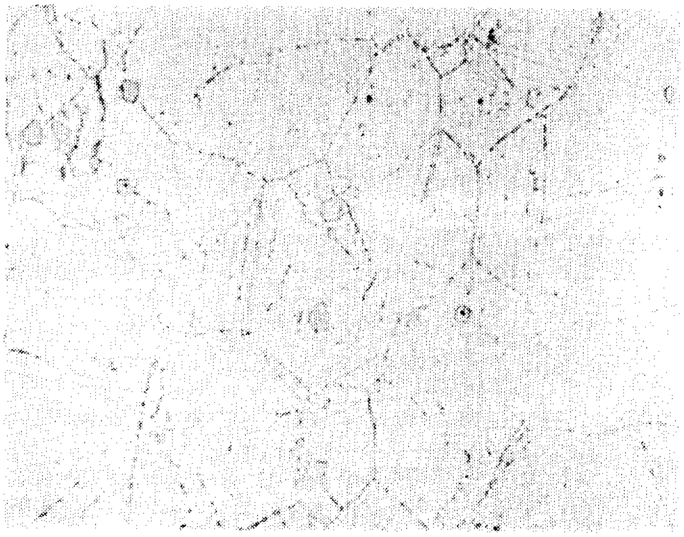
FIGURE 33. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT F AT 1850 F



A. WELD/PARENT-METAL INTERFACE
Material: 0.040-inch Inconel 718 alloy
Heat No.: 6394
Annealed: 1850 F
Magnification: 100X

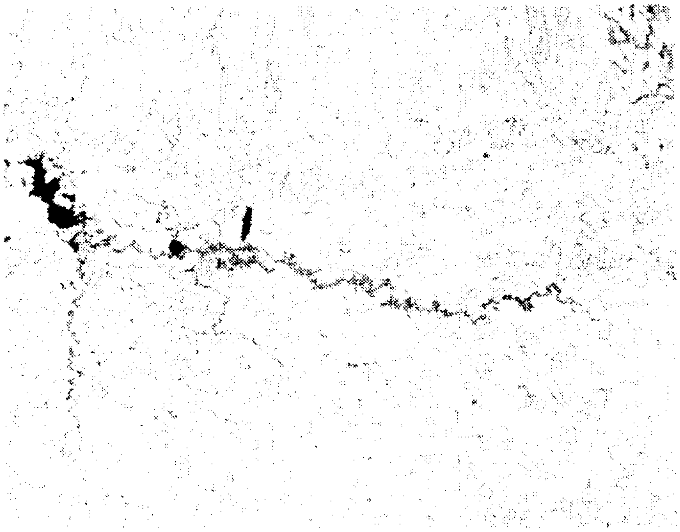


B. HEAT-AFFECTED ZONE
Note intergranular cracking.
Magnification: 700X



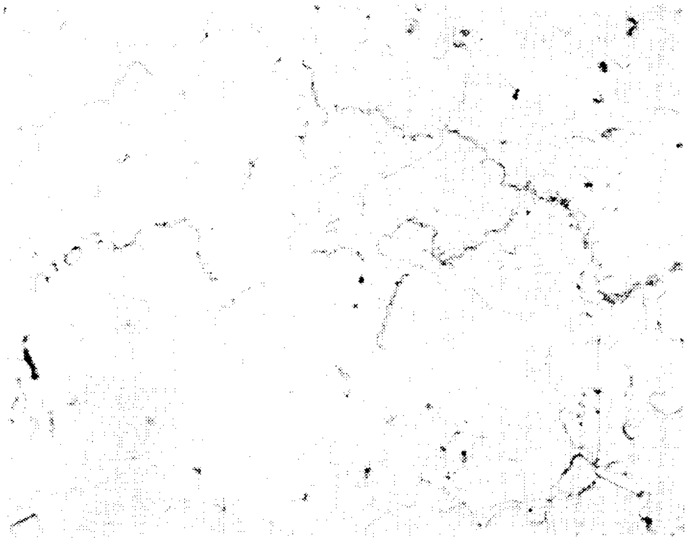
C. PARENT METAL
Magnification: 700X

FIGURE 34. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT G AT 1850 F



A. WELD/PARENT-METAL INTERFACE

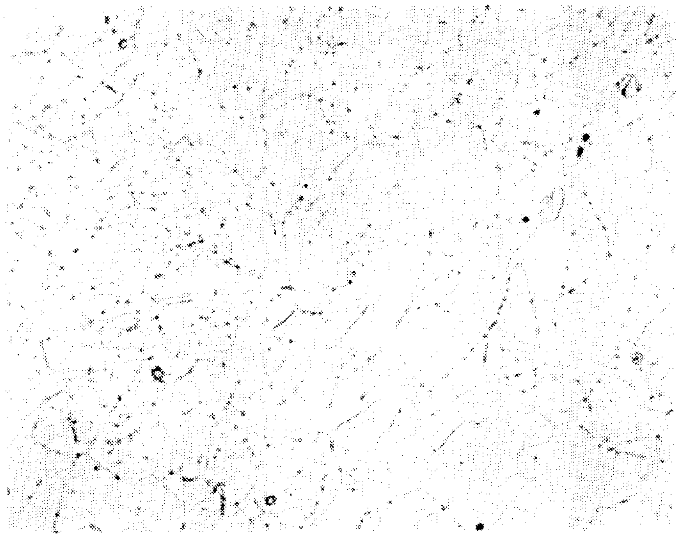
Material: 0.040-inch Inconel 718 alloy
Heat No.: 6300
Annealed: 1900 F
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note presence of a formerly liquid phase along grain boundaries.

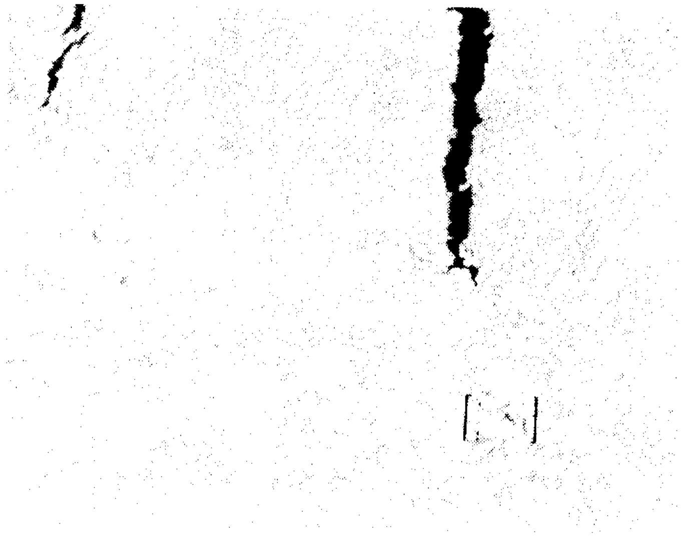
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 35. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT D AT 1900 F ON 0.040-INCH MATERIAL



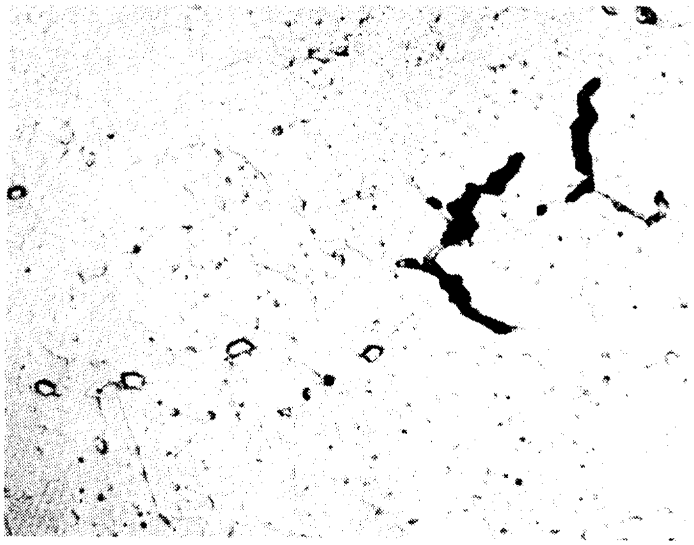
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6300

Annealed: 1950 F

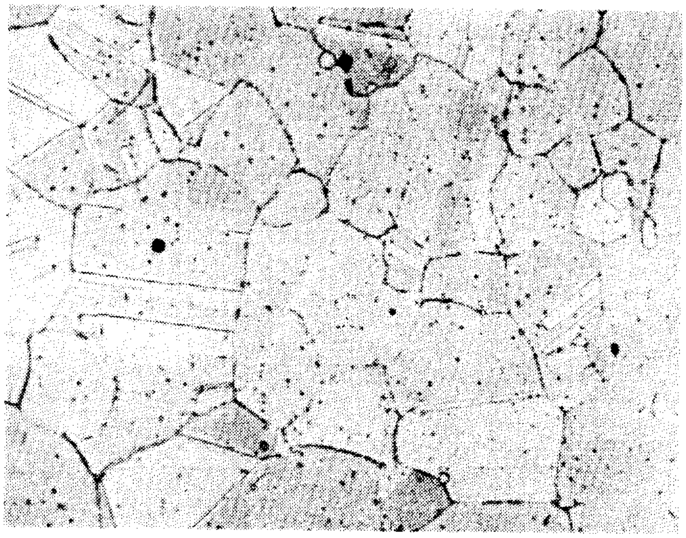
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note intergranular cracking some distance from the fusion zone.

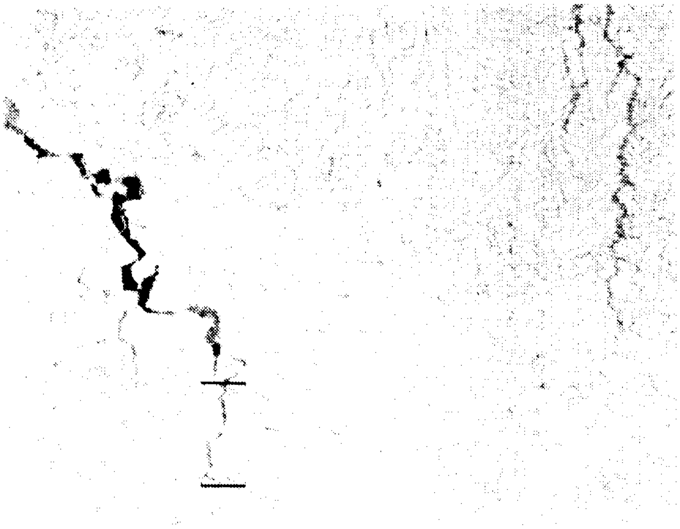
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 36. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT E



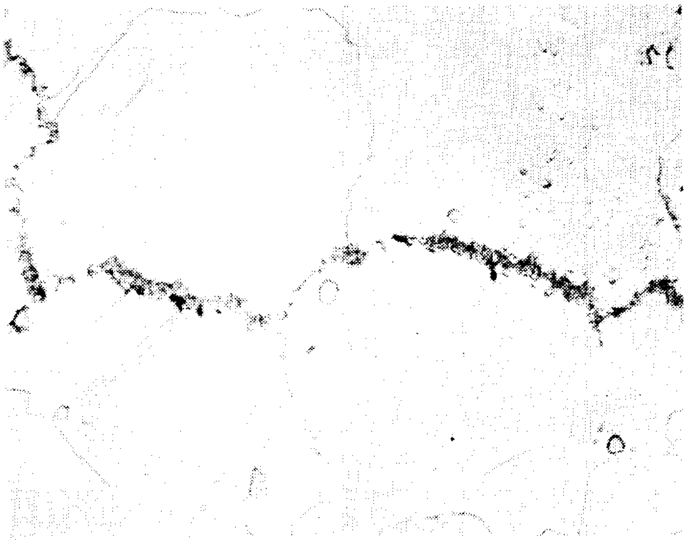
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6394

Annealed: 1950 F

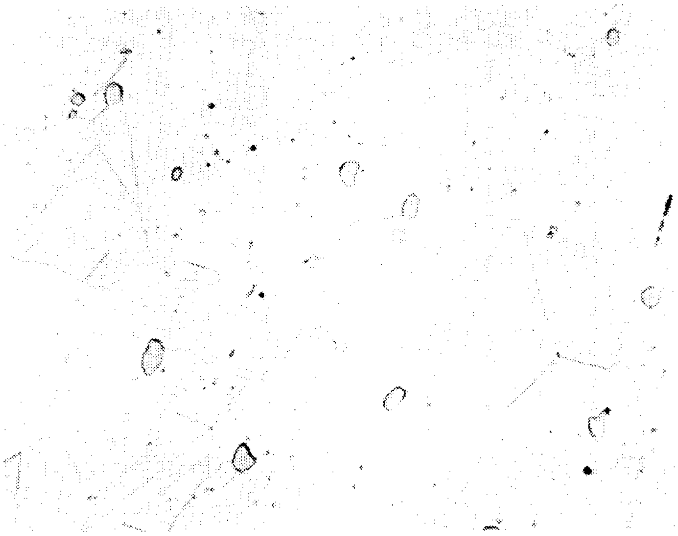
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note eutectic melted phase along grain boundaries.

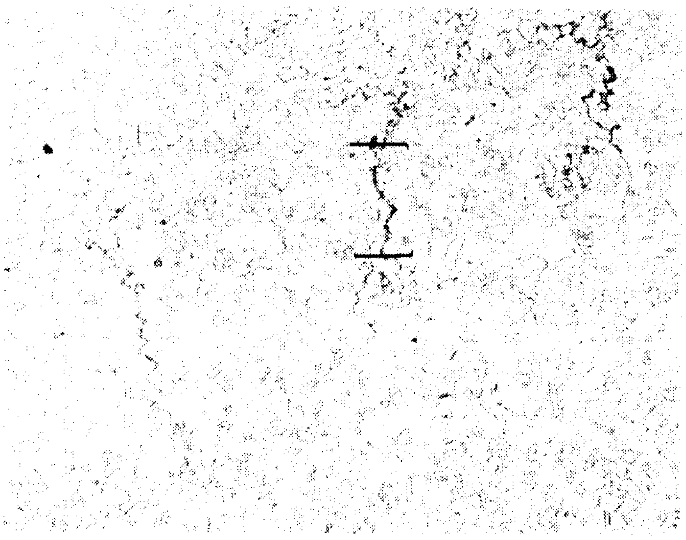
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 37. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMEN SHOWING EFFECT OF THERMAL TREATMENT F AT 1950 F ON 0.040-INCH MATERIAL



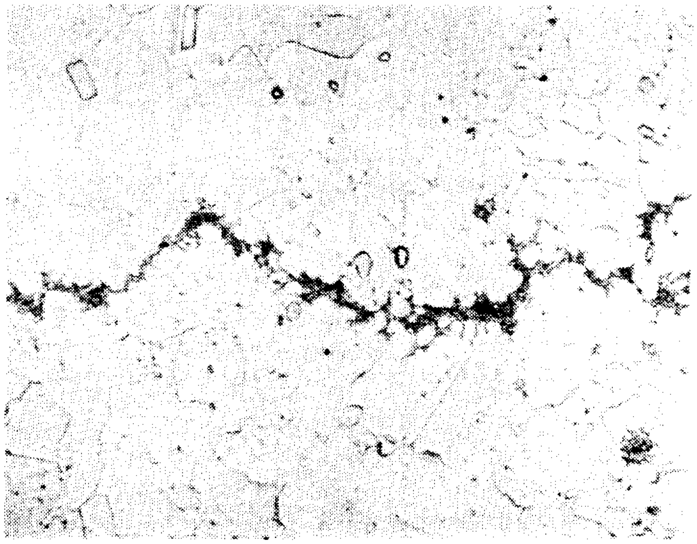
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6300

Annealed: 1950 F

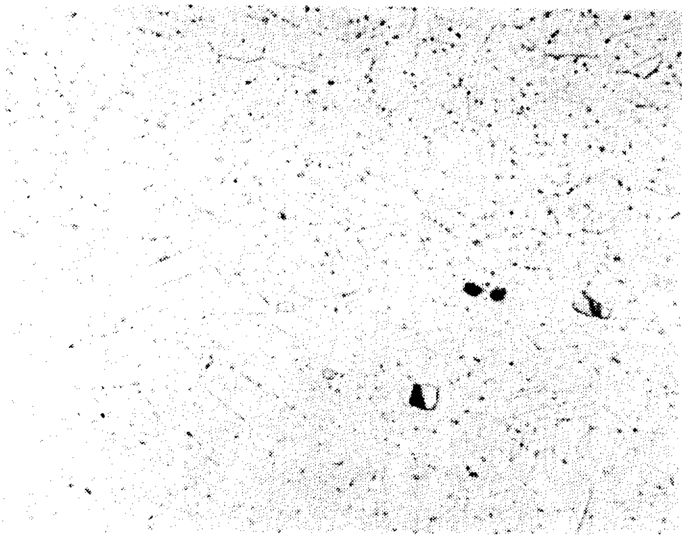
Magnification: 100X



B. HEAT-AFFECTED ZONE

Intergranular cracking and the presence of a formerly liquid phase are seen along grain boundaries.

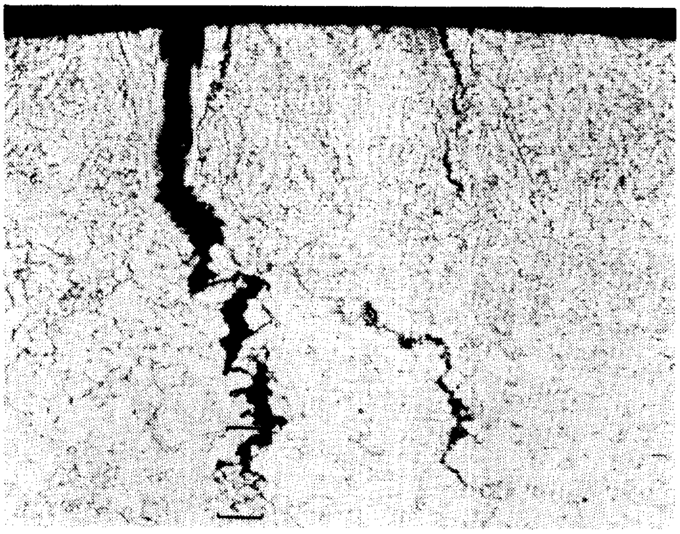
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 38. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT G AT 1950 F



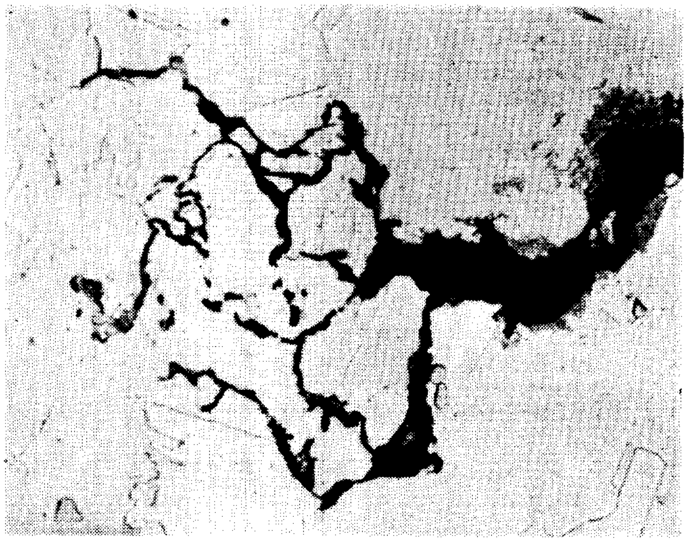
A. WELD/PARENT-METAL INTERFACE

Material: 0.040-inch Inconel 718 alloy

Heat No.: 6394

Annealed: 1950 F

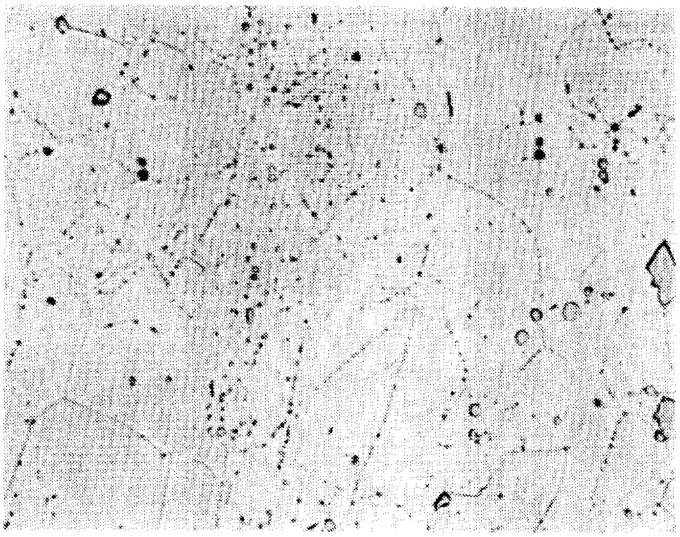
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note severe intergranular cracking and a low-temperature eutectic phase.

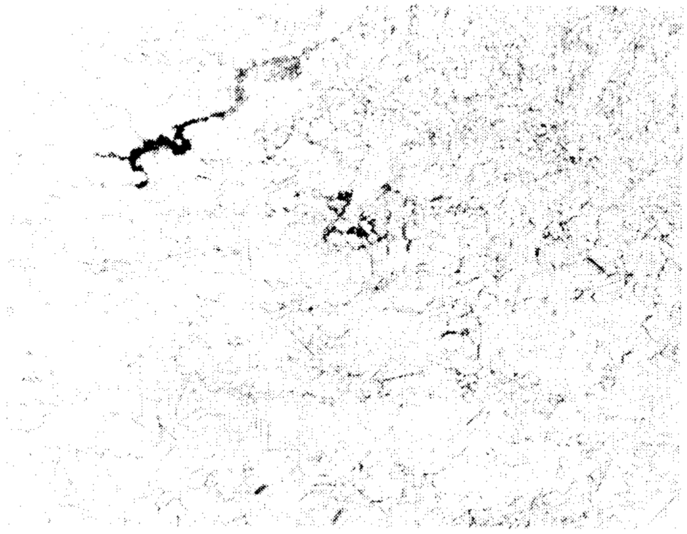
Magnification: 700X



C. PARENT METAL

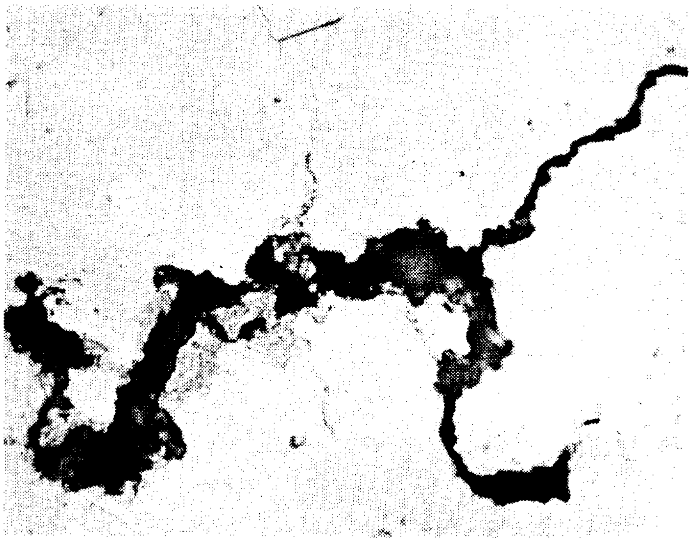
Magnification: 700X

FIGURE 39. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT I AT 1950 F ON 0.040-INCH MATERIAL



A. WELD/PARENT-METAL INTERFACE

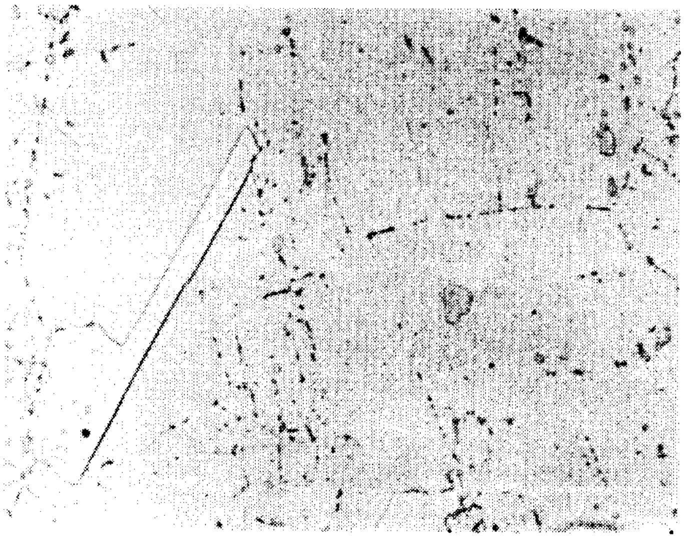
Material: 0.209-inch Inconel 718 alloy
Heat No.: 6518
Annealed: 1750 F
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note severe intergranular cracking and a formerly liquid phase.

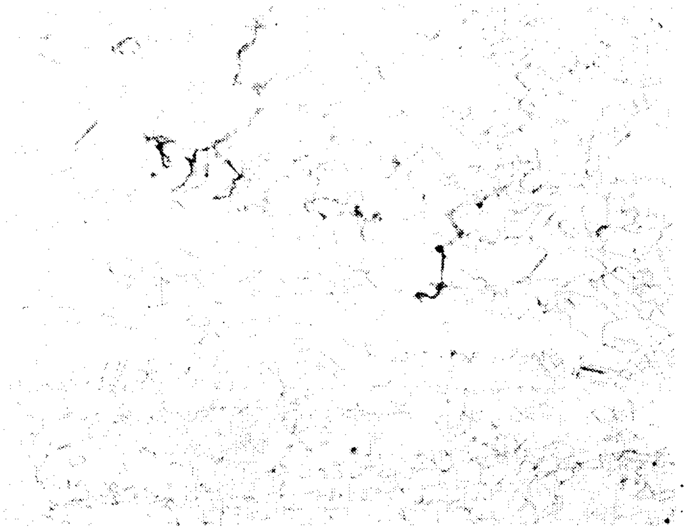
Magnification: 700X



C. PARENT METAL

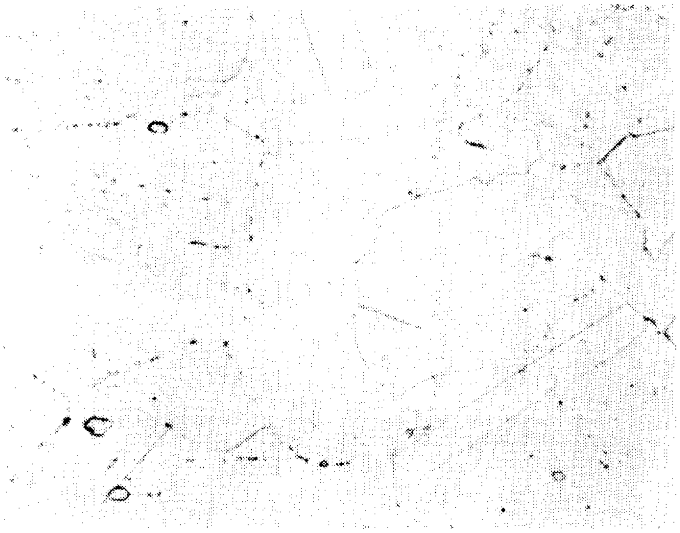
Magnification: 700X

FIGURE 40. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMEN SHOWING EFFECT OF THERMAL TREATMENT A AT 1750 F ON 0.209-INCH MATERIAL



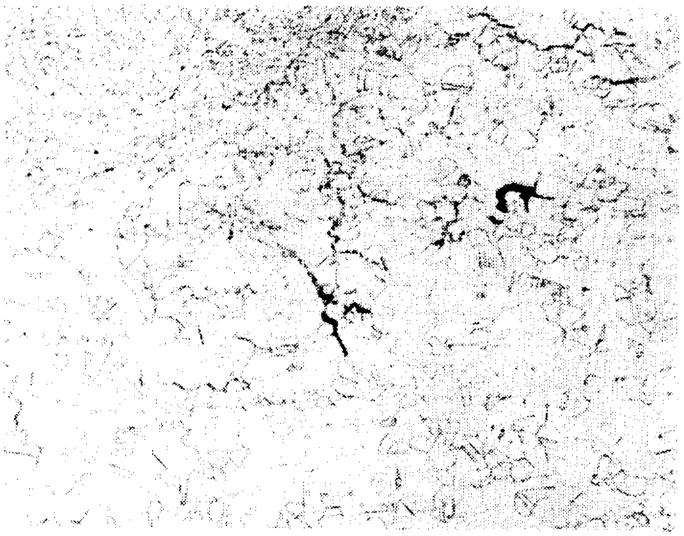
A. WELD/PARENT-METAL INTERFACE
Material: 0.209-inch Inconel 718 alloy
Heat No.: 6518
Annealed: 1800 F
Magnification: **100X**

B. HEAT-AFFECTED ZONE
Note presence of intergranular cracking.
Magnification: 700X



C. PARENT METAL
Magnification: 700X

FIGURE 41. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT B AT 1800 F ON 0.209-INCH MATERIAL; Heat 6518



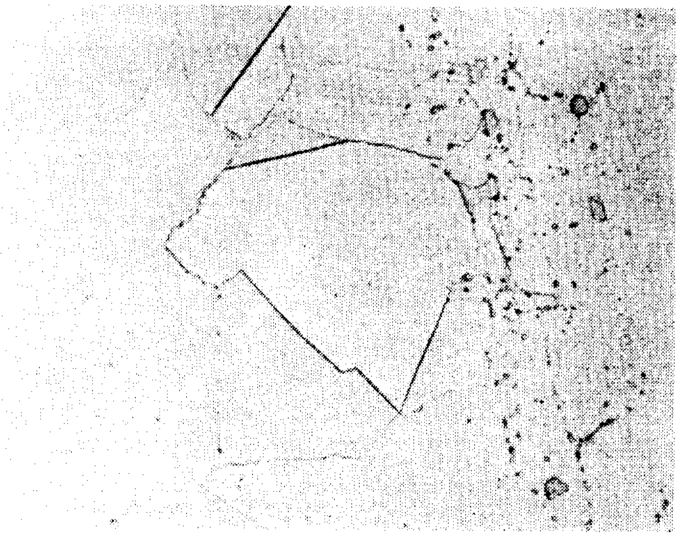
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy
Heat No.: 6518
Annealed: 1750 F
Magnification: 100X

B. HEAT-AFFECTED ZONE

Note presence of a formerly liquid phase and cracks along grain boundaries.

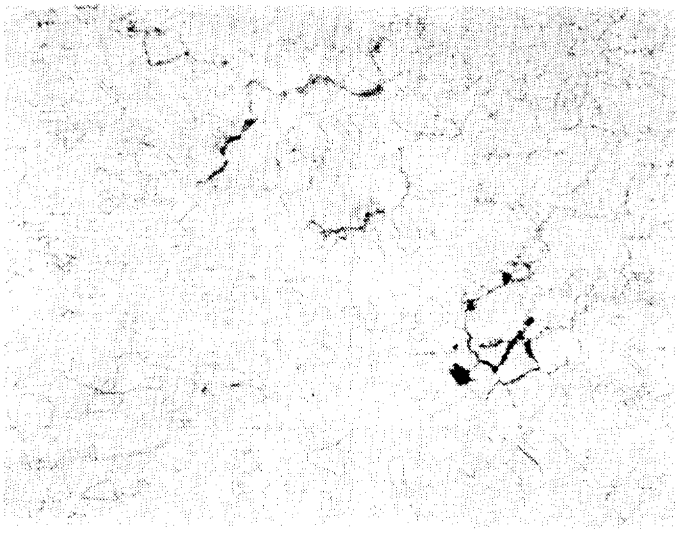
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 42. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT C AT 1850 F ON 0.209-INCH MATERIAL



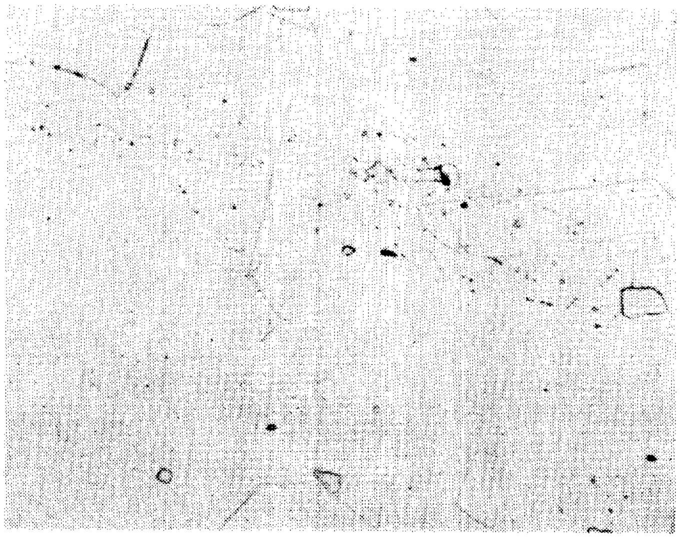
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy
Heat No.: 6518
Annealed: 1900 F
Magnification: 100X

B. HEAT-AFFECTED ZONE

Note presence of small amount of the formerly liquid phase and cracks along grain boundaries.

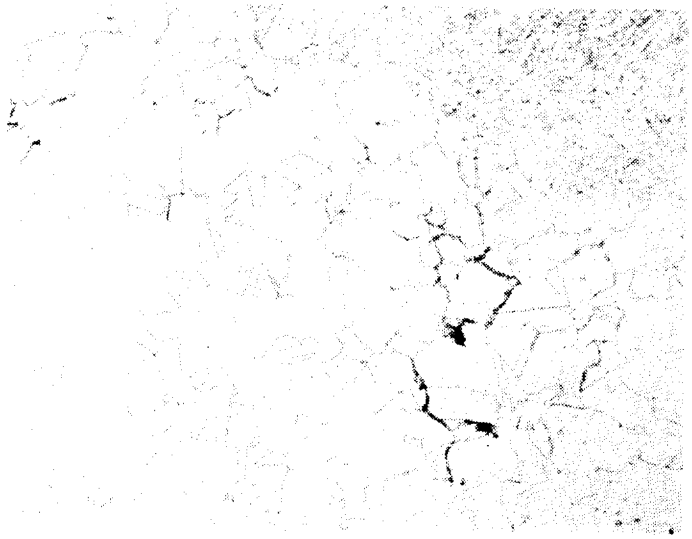
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 43. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT D AT 1900 F ON 0.209-INCH MATERIAL



A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy

Heat No.: 6518

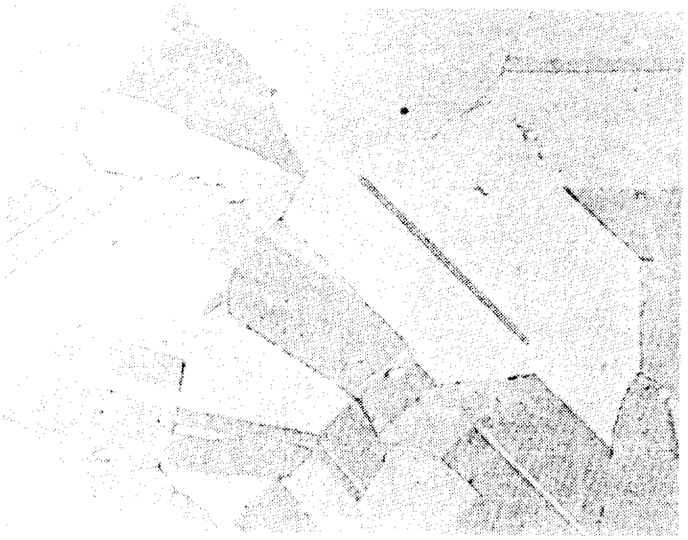
Annealed: 1950 F

Magnification: 100X

B. HEAT-AFFECTED ZONE

Note presence of intergranular cracking.

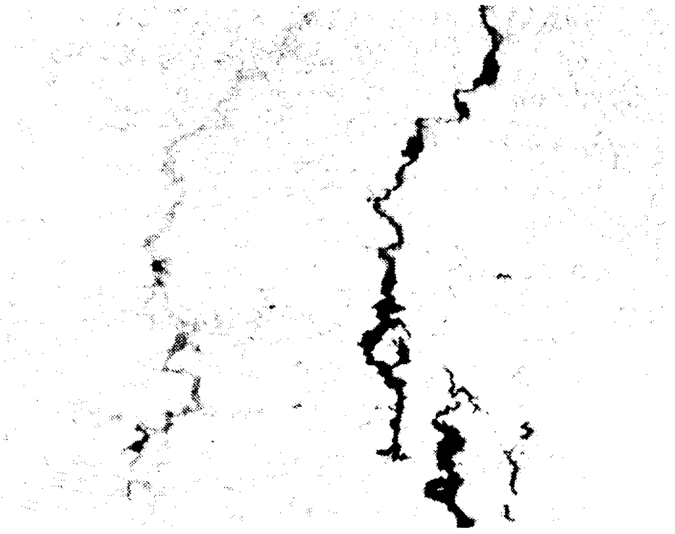
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 44. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT D AT 1950 F ON 0.209-INCH MATERIAL



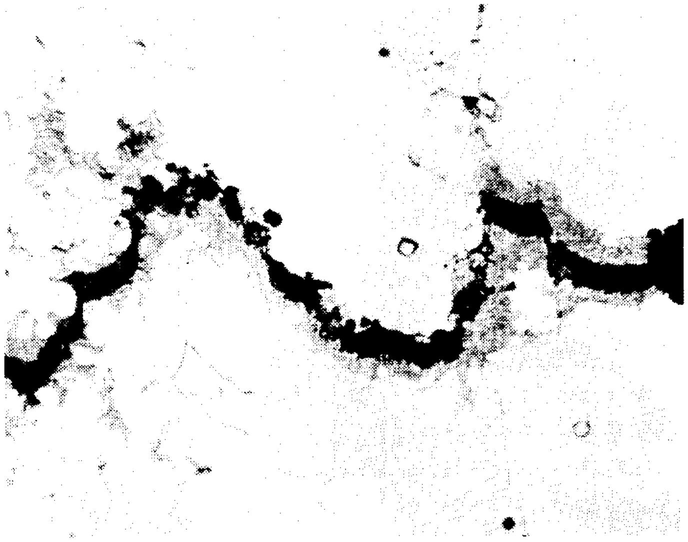
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy

Heat No.: 6518

Annealed: 1750 F

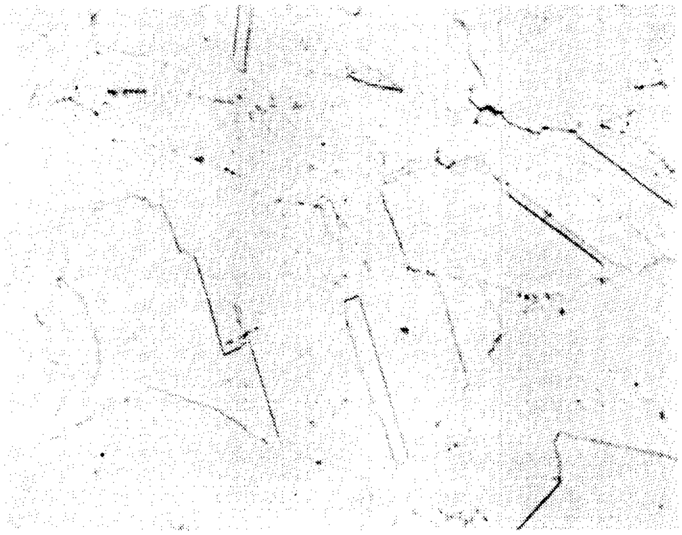
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note presence of a formerly liquid phase and severe cracking along grain boundaries.

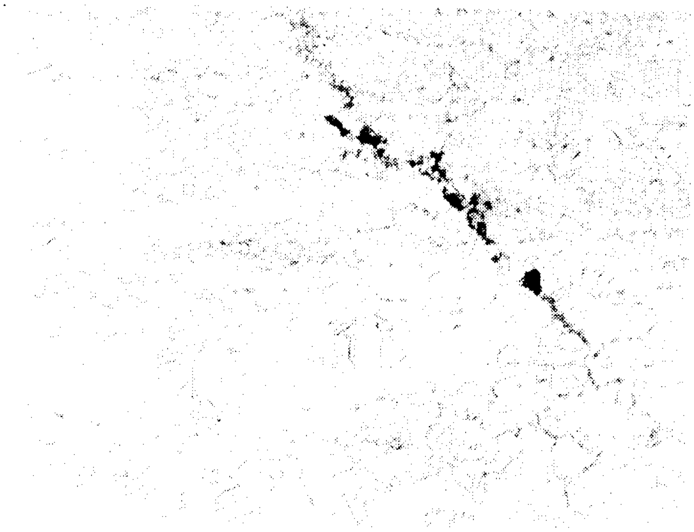
Magnification: 700X



C. PARENT METAL

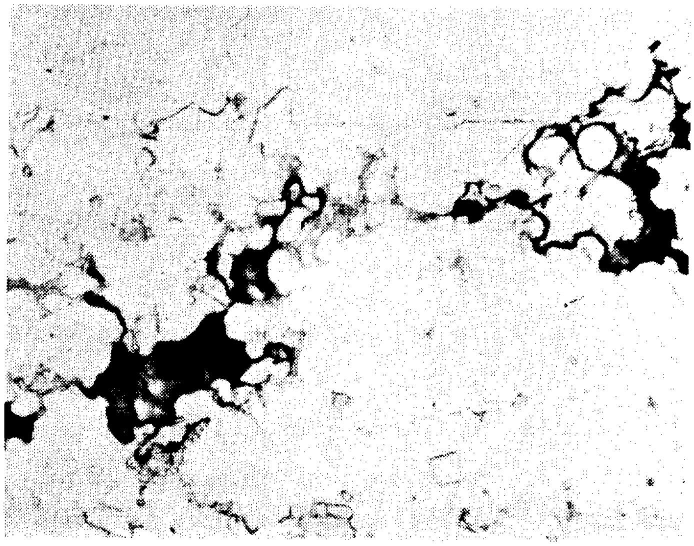
Magnification: 700X

FIGURE 45. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT I AT 1750 F ON 0.209-INCH MATERIAL



A. WELD/PARENT-METAL INTERFACE

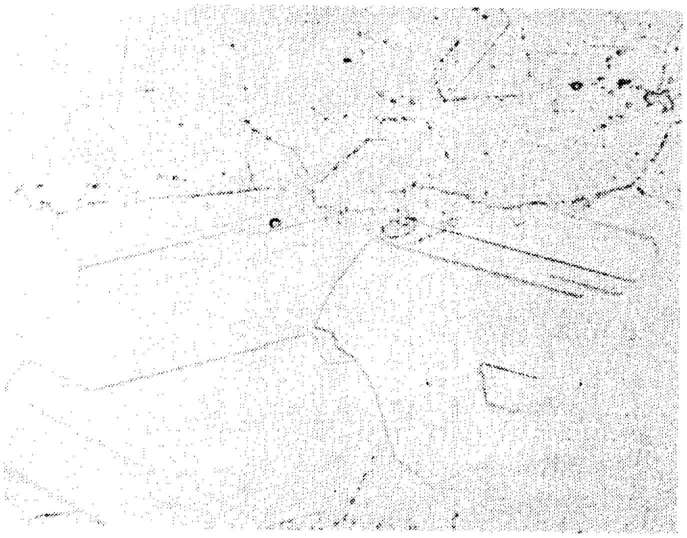
Material: 0.209-inch Inconel 718 alloy
Heat No.: 6518
Annealed: 1750 F
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note intergranular cracks and small amount of eutectic melted phase along grain boundaries.

Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 46. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT F AT 1750 F ON 0.209-INCH MATERIAL

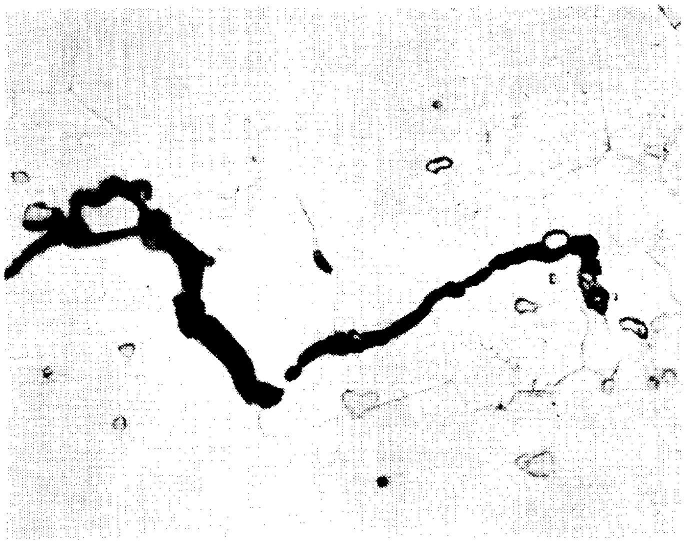
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy

Heat No.: 6518

Annealed: 1850 F

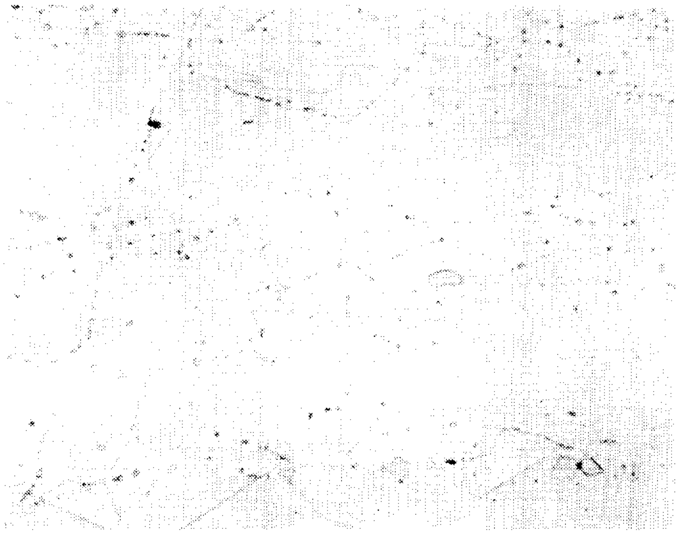
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note intergranular cracks.

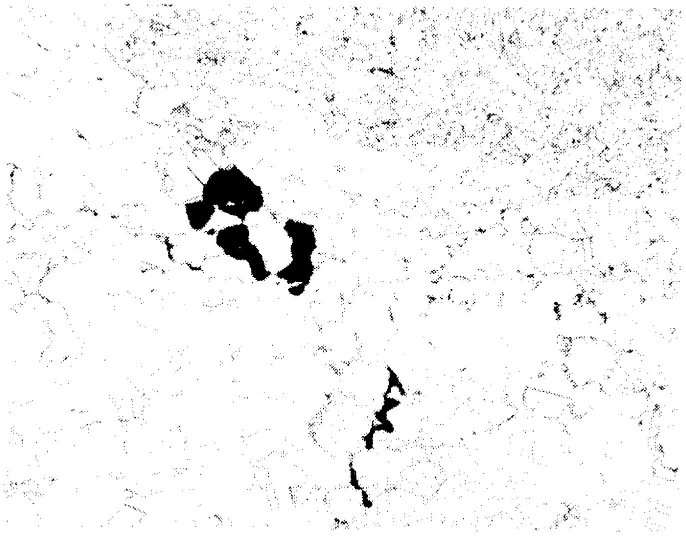
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 47. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT I AT 1850 F ON 0.209-INCH MATERIAL



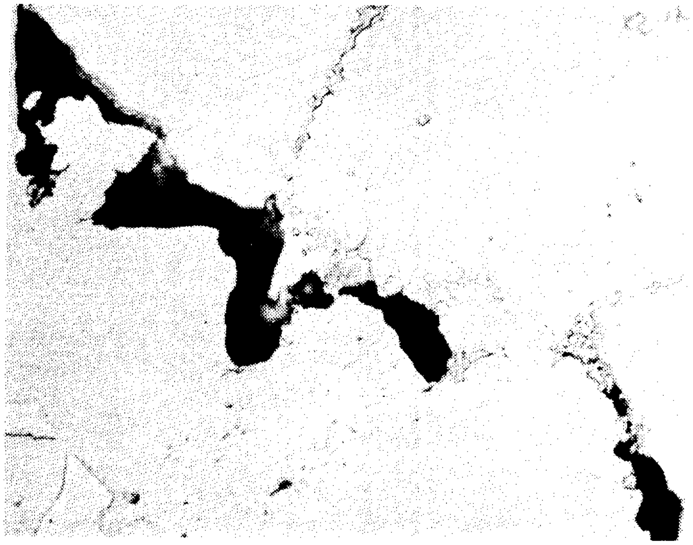
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy

Heat No.: 6518

Annealed: 1850 F

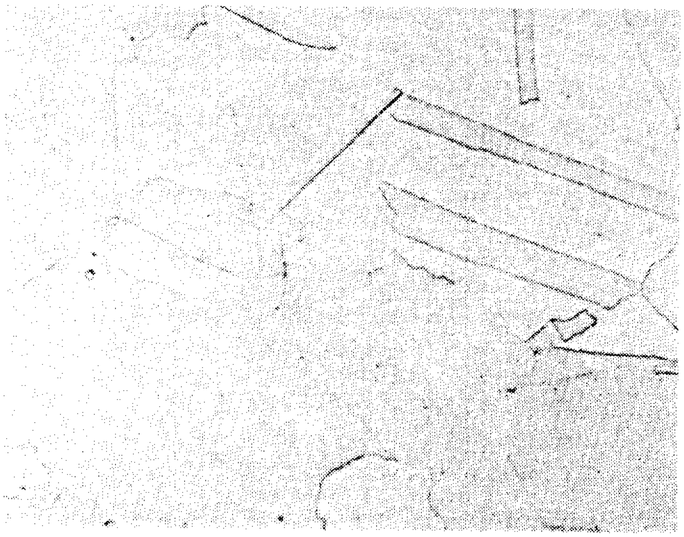
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note small amount of a formerly liquid phase and cracking along grain boundaries

Magnification: 700X

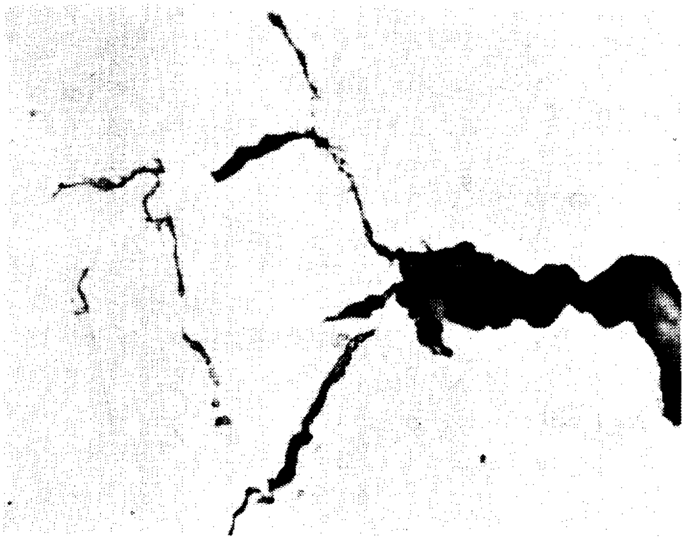


C. PARENT METAL

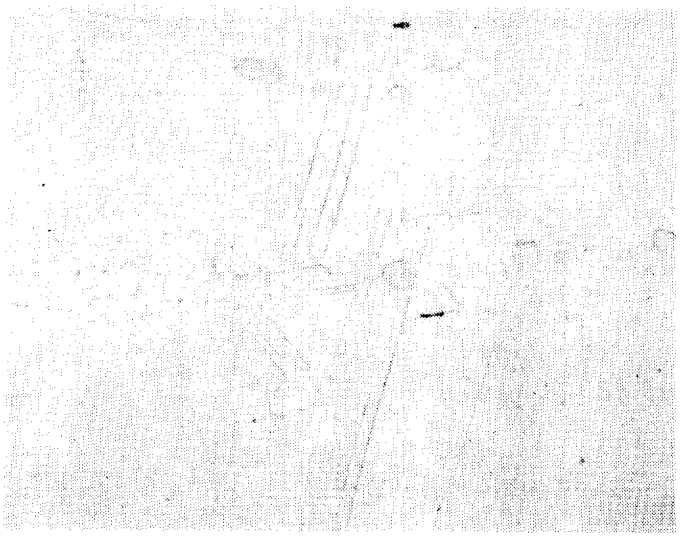
Magnification: 700X

FIGURE 48. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT F AT 1850 F ON 0.209-INCH MATERIAL

A. WELD/PARENT-METAL INTERFACE
Material: 0.209-inch Inconel 718 alloy
Heat No.: 6790
Annealed: 1950 F
Magnification: 100X

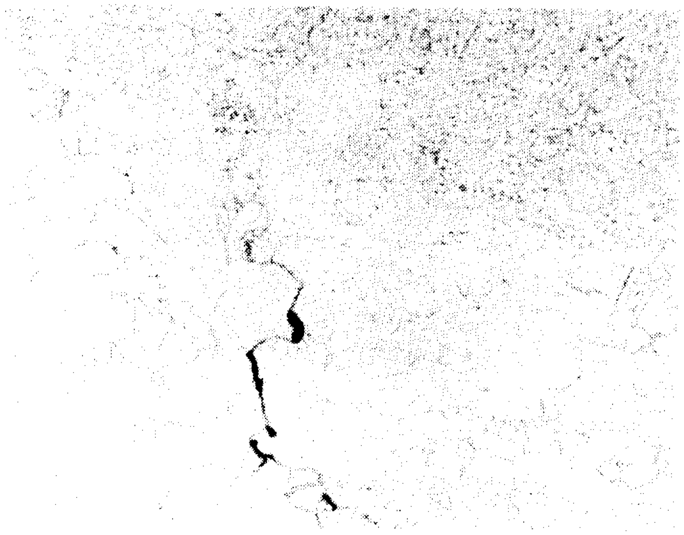


B. HEAT-AFFECTED ZONE
Note intergranular cracking.
Magnification: 700X



C. PARENT METAL
Magnification: 700X

FIGURE 49. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT I AT 1950 F ON 0.209-INCH MATERIAL



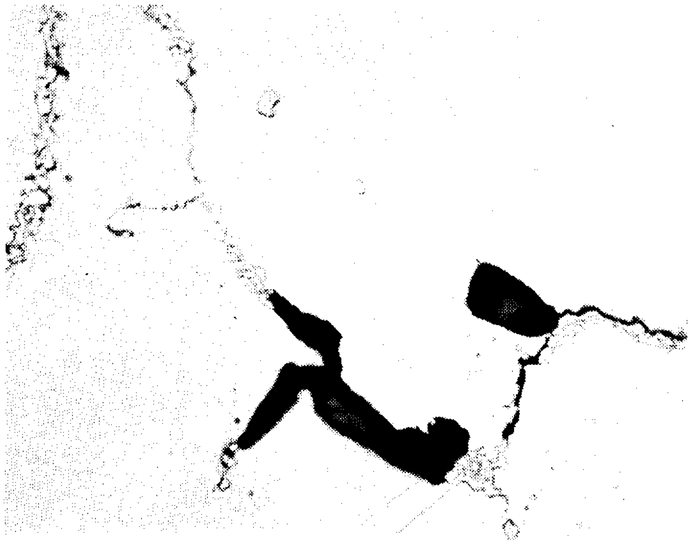
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy

Heat No.: 6518

Annealed: 1950 F

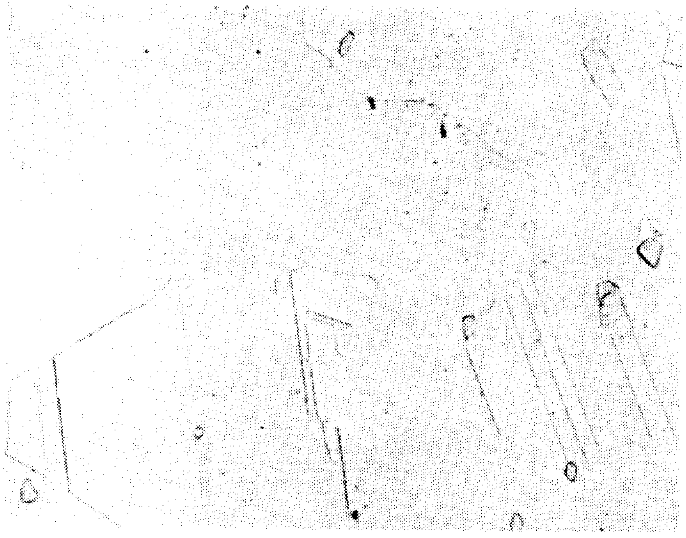
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note presence of some low-melting eutectic phase and cracks along grain boundaries.

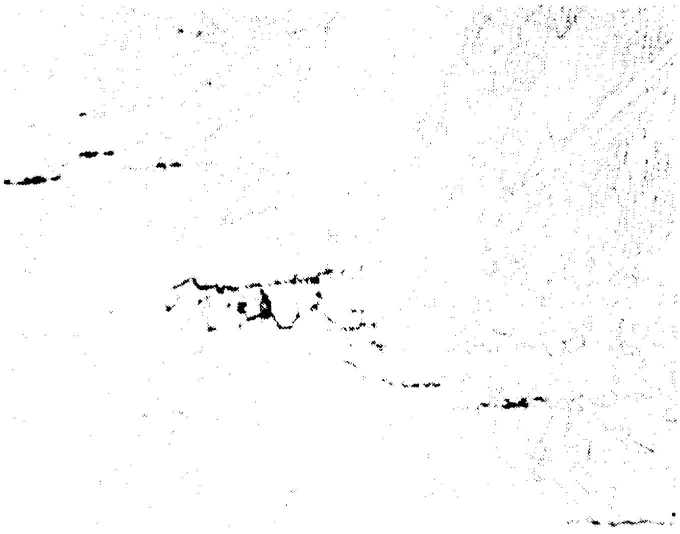
Magnification: 700X



C. PARENT METAL

Magnification: 700X

FIGURE 50. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT F AT 1900 F ON 0.209-INCH MATERIAL



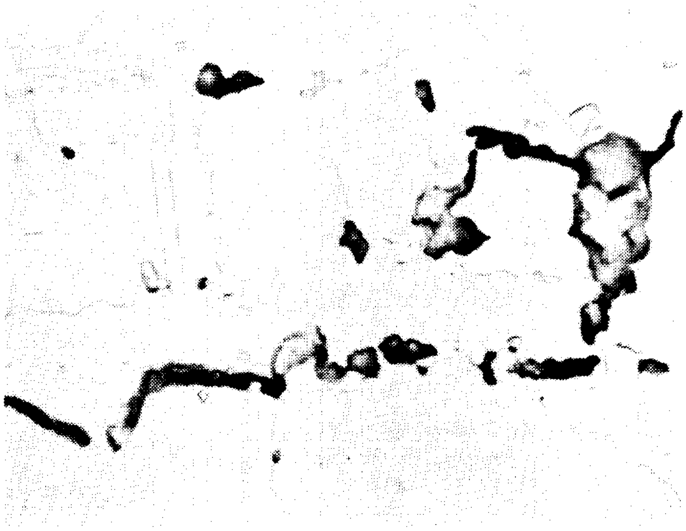
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy. Double vacuum melted-Eastern supplied.

Heat No.: 95224

Annealed: 1900 F

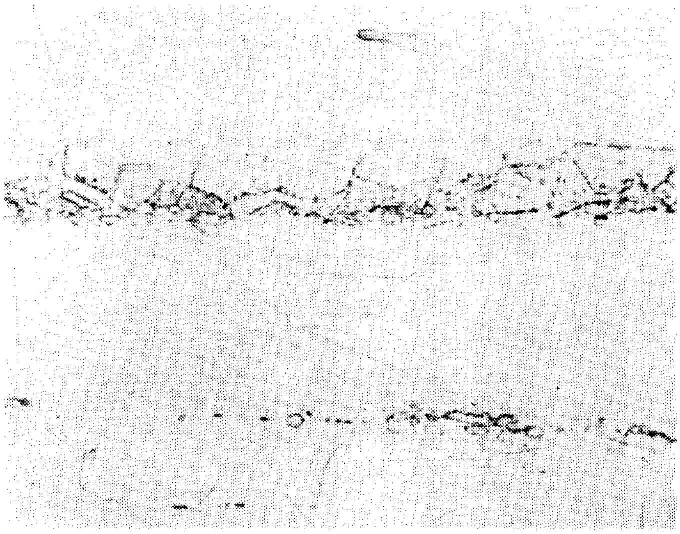
Magnification: 100X



B. HEAT-AFFECTED ZONE

Note cracking following Cb Ti(C,N) particles interdispersed with Laves phase.

Magnification: 700X

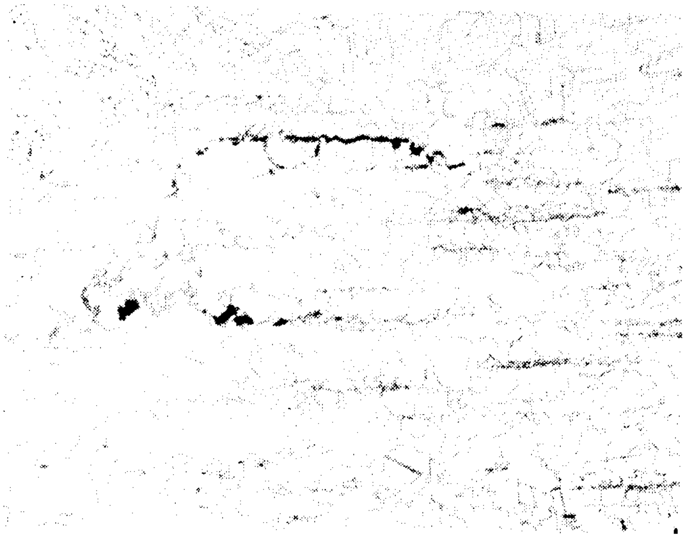


C. PARENT METAL

Note Cb Ti(C,N) stringer formation

Magnification: 700X

FIGURE 51. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT D AT 1900 F ON 0.209-INCH MATERIAL



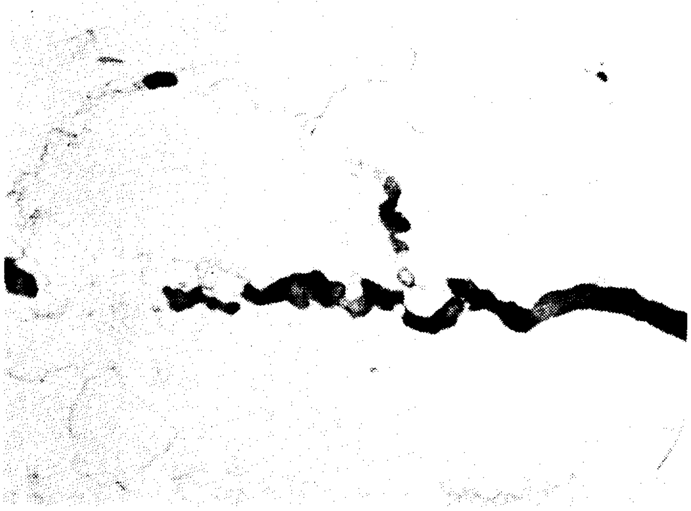
A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy. Double vacuum melted-Eastern supplied.

Heat No.: 95224

Annealed: 1800 F

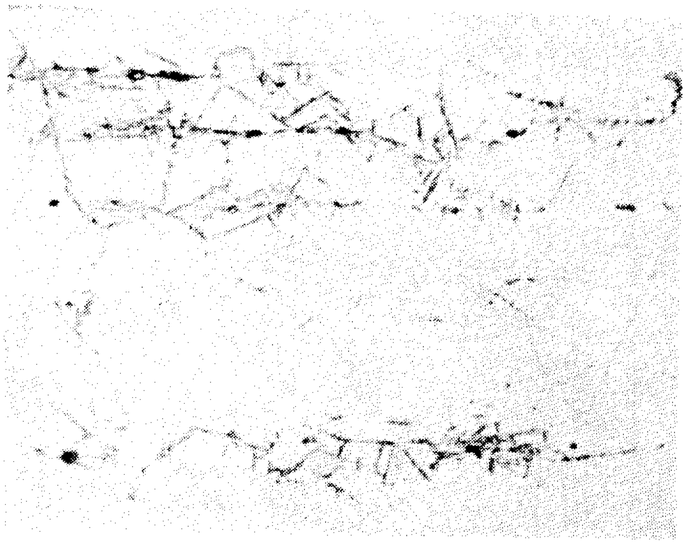
Magnification: 100X



B. HEAT-AFFECTED ZONE

Cracking follows Cb Ti(C,N) Laves phase stringering.

Magnification: 700X



C. PARENT METAL

Note Cb Ti(C,N) stringer formation

Magnification: 700X

FIGURE 52. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT B AT 1800 F ON 0.209-INCH MATERIAL; HEAT 95224

A. WELD/PARENT-METAL INTERFACE

Material: 0.209-inch Inconel 718 alloy. Double vacuum melted-Eastern supplied.

Heat No.: 95224

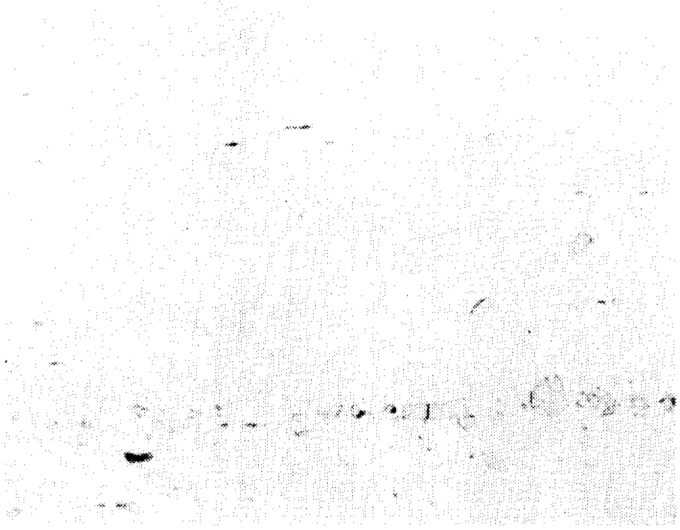
Annealed: 1950 F

Magnification: 100X

B. HEAT-AFFECTED ZONE

Cracking follows Laves phase and Cb Ti(C,N) stringering.

Magnification: 700X

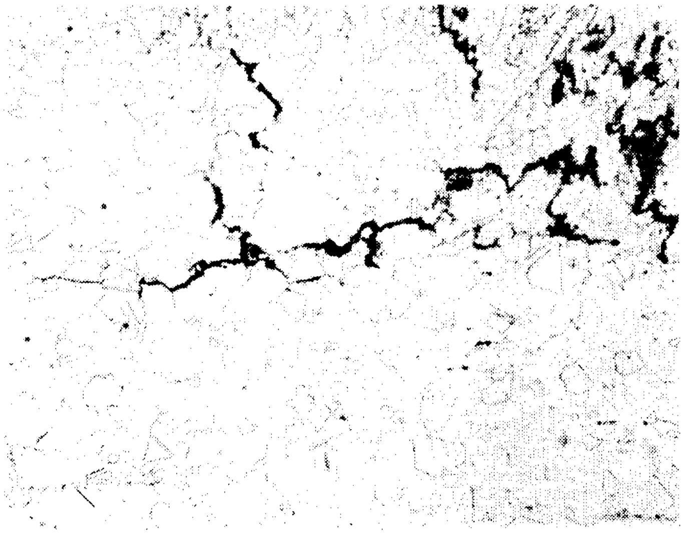


C. PARENT METAL

Note Cb Ti(C,N) formation

Magnification: 700X

FIGURE 53. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT J AT 1950 F ON 0.209-INCH MATERIAL



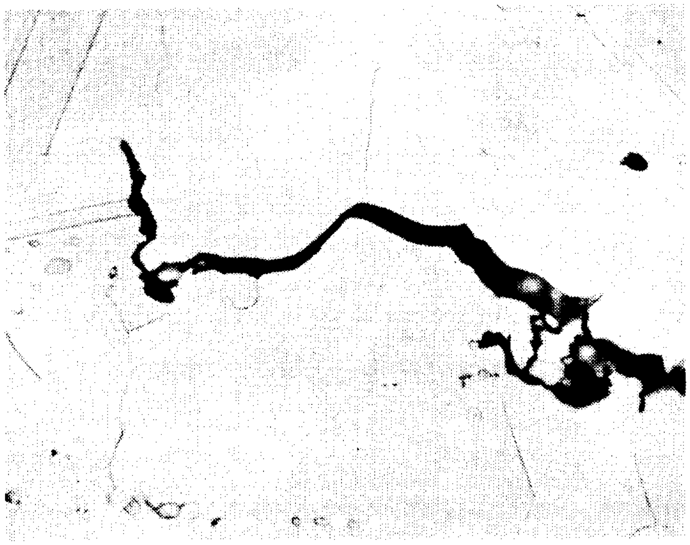
A. WELD/PARENT-METAL INTERFACE

Material: 0.250-inch Inconel 718 alloy.
Hopkins melted sample supplied
by Firth Sterling.

Heat No.: D562

Annealed: 1850 F

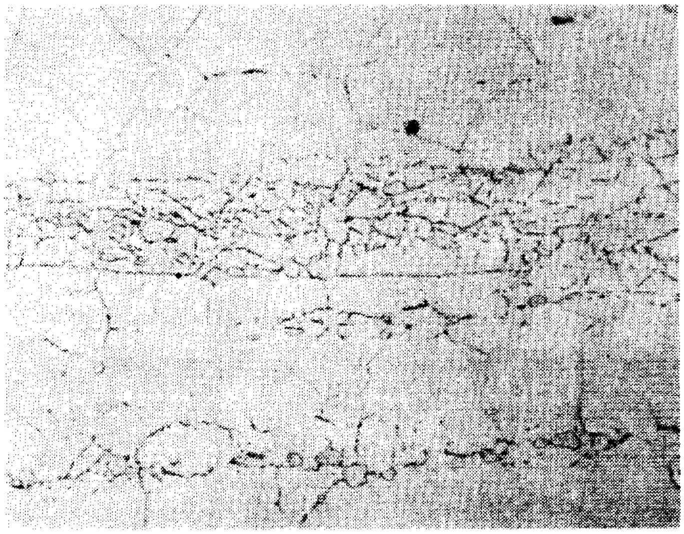
Magnification: 100X



B. HEAT-AFFECTED ZONE

Severe cracking follows Laves phase and Cb Ti(C,N) stringering.

Magnification: 700X



C. PARENT METAL

Note heavy Cb Ti (C,N) stringer formation

Magnification: 700X

FIGURE 54. MICROSTRUCTURAL STUDY OF VARESTRAINT SPECIMENS SHOWING EFFECT OF THERMAL TREATMENT C AT 1850 F ON 0.250-INCH MATERIAL

It is apparent from examination of these figures that significant structure changes have occurred in the heat-affected zone of the Inconel 718 Varestraint specimens welded in the fully heat-treated condition. Structure indicating the presence of a formerly liquid phase was found at grain boundaries in the heat-affected zone (Fig. 29, 32, 37, 38, 39, 40, 50, and 52). Observations of the photomicrographs at high magnifications showed that in addition to cracking in some areas, the material was being subjected to eutectic melting in the weld heat-affected zone. A similar phenomenon called coring has been described in the case of resistance welding nickel-base alloys where melting along the grain boundaries takes place in critical electrode pressure areas. The present investigation did not firmly establish whether this phenomenon results from melting along the grain boundaries or the feeding of liquid metal from the resorvoir of the weld pool. The latter would occur after boundaries are opened in the heat-affected zone by the stresses induced during welding. However, electron microprobe analysis (Section 2.10) indicated that an increased amount of grain-boundary segregation had taken place near grain-boundary eutectic melting sites. This would, therefore, suggest that the grain-boundary liquid phase is also due to eutectic melting.

Another structure related to stringer formation was detected at random locations in and through grain boundaries. The foreign material, later identified as CbTi(C, N) particles interdispersed with some Laves phase were aligned in the direction of rolling. This stringer formation was found to be prevalent on the double vacuum melted 0.209-inch material, Heat No. 95224 and in the Hopkins-melted material, Heat No. D562. Figures 52 through 54 show that cracking in the heat-affected zone of the double vacuum and Hopkins-melted materials followed the general pattern of the stringer formations.

Some areas of the double vacuum melted Heat No. 95224 and the Hopkins-processed Heat D562 also exhibited a banded structure showing areas with higher than normal density of the precipitating phases interspersed with regions having relatively few precipitates. The banded appearance as well as the stringer formation is evidence that alloy segregation during the solidification of the ingot was not completely distributed by the hot working and elevated temperature thermal treatments. This, undoubtedly, has adversely affected the cracking susceptibility of those two heats.

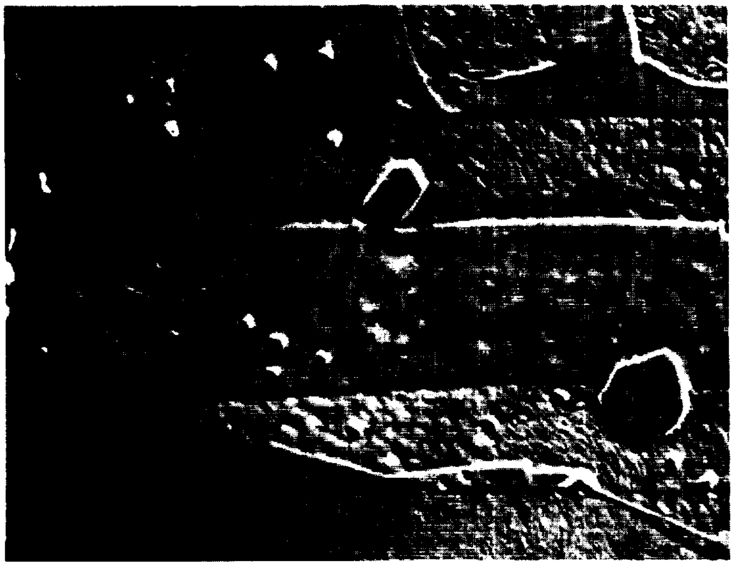
2.9 ELECTRON MICROSCOPY

An electron microscopic study of specimens of Inconel 718 was undertaken in an attempt to correlate changes in microstructure with the serious weld heat-affected zone cracking heretofore described. A systematic investigation was made in which changes in microstructure resulting from various heat treatments were recorded and analyzed. This investigation was conducted for both the 0.040- and the 0.209-inch material and they were subsequently compared. The results for the two thicknesses are similar in most cases. Where major differences were noted, the differences are described.

The microstructural changes, accompanying every step in each heat-treat cycle studied, were determined. The various specimens examined (for each thickness) are listed below:

- As-received
- Annealed 1750 F
- Annealed 1750 F - aged 8 + 8
- Annealed 1750 F - aged 8 + 8 weld (heat-affected zone examined)
- Annealed 1850 F
- Annealed 1850 F - aged 8 + 8
- Annealed 1850 F - aged 8 + 8 + weld (heat-affected zone examined)
- Annealed 1900 F - aged 8 + 8
- Annealed 1900 F - aged 8 + 8 + weld (heat-affected zone examined)
- Annealed 1950 F
- Annealed 1950 F - aged 10 + 10
- Annealed 1950 F - aged 10 + 10 + weld (heat-affected zone examined)

Representative electron micrographs of the as-received Inconel 718 alloy are seen in Figure 55. The as-received material shows a random distribution of carbides, both small and large, and some Laves phase in the matrix. Slip lines and twins are in evidence, and, as expected, are more numerous in the 0.040-inch material. No gamma prime phase is detectable in the as-received material in either thickness.
The low-temperature anneal (1750 F) did not have much effect on the Inconel 718 alloy. Work by Raymond (Ref. 10) revealed that this temperature was not a solutioning



Structure: Random distribution of carbides in addition to slip lines and twinning.

Material: 0.040-inch Inconel 718 alloy

Magnification: 4000X

Structure: Random distribution of carbides in addition to a few slip lines.

Material: 0.209-inch Inconel 718 alloy

Magnification: 4000X

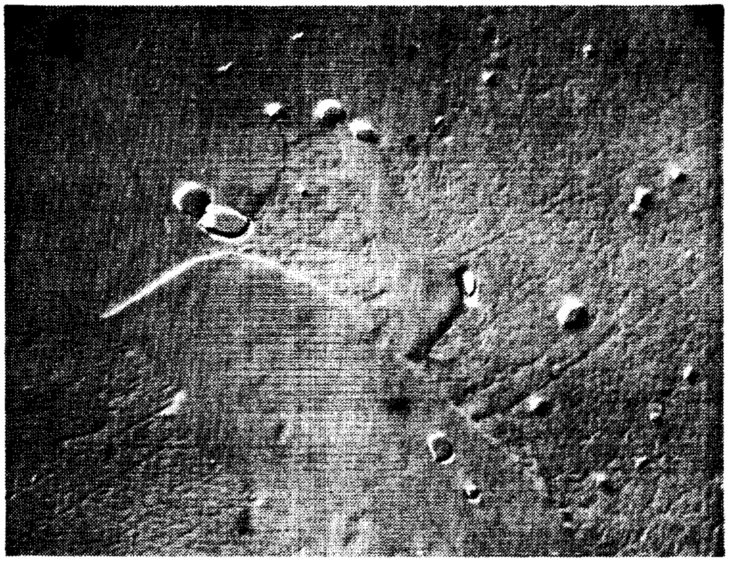
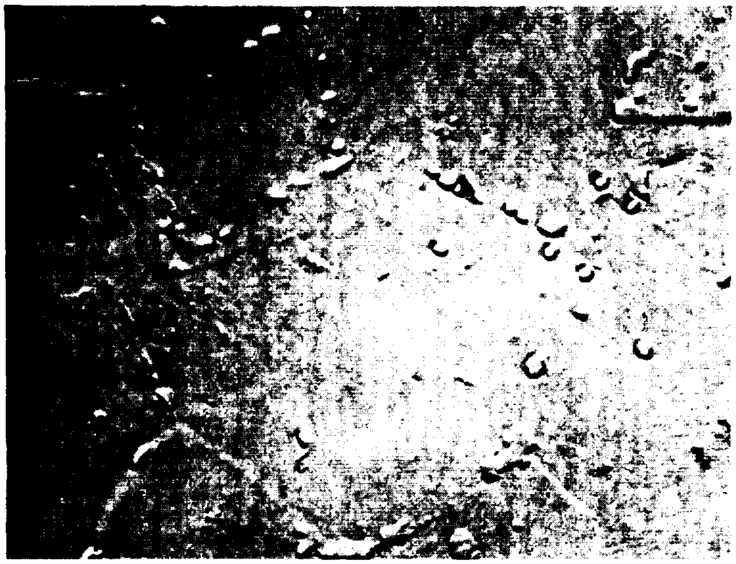


FIGURE 55. ELECTRON MICROGRAPHS OF AS-RECEIVED INCONEL 718 ALLOY

temperature. Raymond concluded that the direct result of an 1750 F anneal was the precipitation of the columbium-rich Laves phase and columbium carbides or carbonitrides in the grain interiors and grain boundaries. The same phenomenon was noted in this present work and may be seen in Figure 56. The aging thermal cycle left the material treated at 1750 F with many grain boundary carbides and Laves phase with some second-phase particles distributed throughout the matrix. A few areas contained several individual or paired gamma prime platelets. The heat-affected zone in a welded specimen which had previously been processed with the 1750 F



Structure: Grain boundary carbides and Laves phase with second phase particles distributed throughout the matrix.

Material: 0.040-inch Inconel 718 alloy

Magnification: 4000X

FIGURE 56.

ELECTRON MICROGRAPH OF 0.040-INCH MATERIAL; ANNEALED AT 1750 F, 8 + 8 AGING CYCLE

anneal followed by the 8 + 8 age (8 hours at 1325 F, furnace cool to 1150 F, 8 hours at 1150 F) did not differ much from the parent metal. The short (5 minutes) anneal at 1750 F resulted in some carbide and Laves phase precipitation as seen in Figure 57.

The 1850 F annealing treatment resulted in minor solutioning of the carbides with subsequent grain boundary and matrix precipitation on aging.

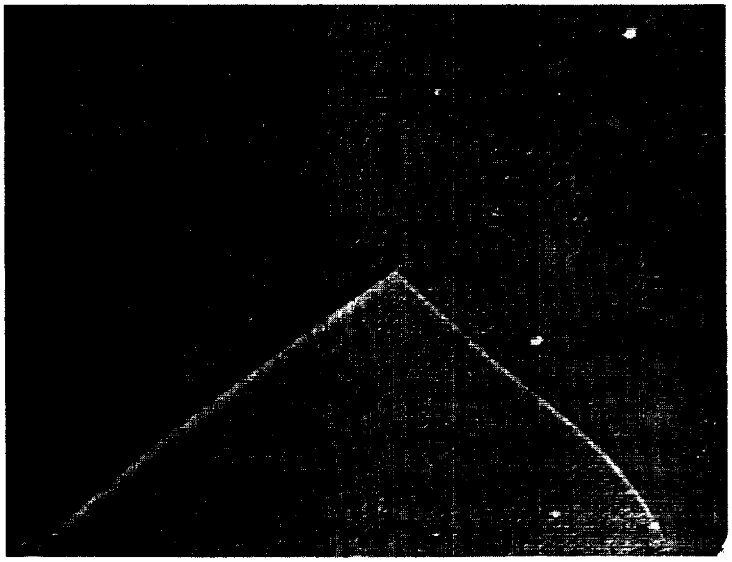
Both the 1900 and the 1950 F anneals had marked effects on the Inconel 718 microstructure. A representative photomicrograph is seen in Figure 58. A triple point may be noted and the difference in matrix appearance of the grains may be attributed to differential grain etching due to crystallographic orientation. Solutioning of carbides and Laves phase has occurred and the structure has been cleaned considerably leaving scattered clusters of small carbides. Considerable grain growth was in evidence in the specimens which generally exhibited large areas devoid of precipitates or second-phase particles, some scattered carbides, and Laves phase.

The material annealed at 1950 F was given a longer and higher temperature age than the specimens heretofore discussed. The aging treatment consisted of 10 hours at 1400 F, a furnace cool to 1200 F followed by sufficient time at 1200 F to give a total aging time of 20 hours. This heat-treat cycle resulted in a marked change in the microstructural appearance of the Inconel 718 alloy. The 1950 F anneal followed by the 10 + 10 age was the only treatment to yield massive, resolvable gamma prime

Structure: Carbides and Laves phase.
Material: 0.040-inch Inconel 718 alloy
Magnification: 4000X

FIGURE 57.

ELECTRON MICROGRAPH OF 0.040-INCH MATERIAL ANNEALED AT 1750 F FOR FIVE MINUTES



Structure: Triple point showing primarily clean grain boundaries. Grain growth is also evident.
Material: 0.209-inch Inconel 718 alloy
Etchant: Kallings
Magnification: 4000X

FIGURE 58.

ELECTRON MICROGRAPH OF 0.209-INCH MATERIAL; Triple-Point Structure

precipitate within the metal matrix. A low magnification photomicrograph of the typical structure is seen in Figure 59. Grain boundary Laves phase and carbides can be seen, but at this magnification (3000X) the gamma prime is not resolvable. A higher resolution photomicrograph (Fig. 60) clearly shows the massive gamma prime in the matrix with some Laves phase precipitated in the grain boundary and a large CbTi(C) particle at the lower left. Although not particularly evident in Figure 60, a grain boundary phenomenon occurred in the material annealed at 1950 F and double aged at 1400 and 1200 F. This effect is more clearly shown in Figures 61 and 62 where the areas of interest are outlined.

Structure: Grain boundary Laves phase and carbides.

Material: 0.209-inch Inconel 718 alloy

Etchant: Kallings

Magnification: 3000X

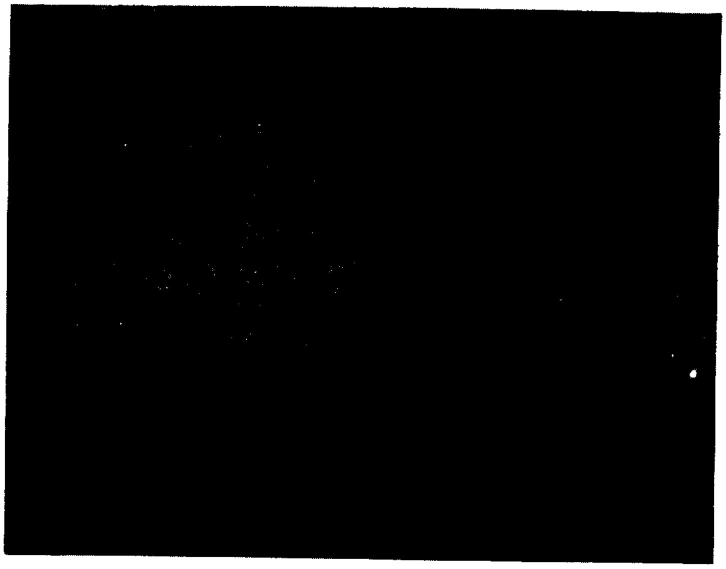
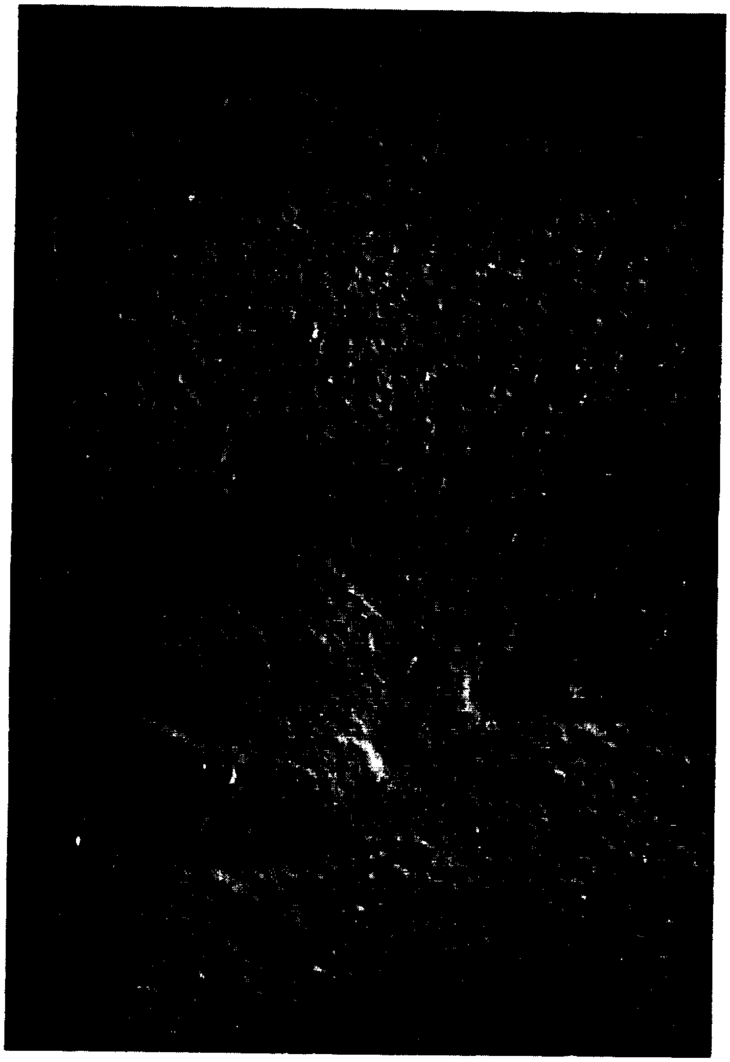


FIGURE 59.

ELECTRON MICROGRAPH OF 0.209-INCH MATERIAL; Aged with 10 + 10 Cycle



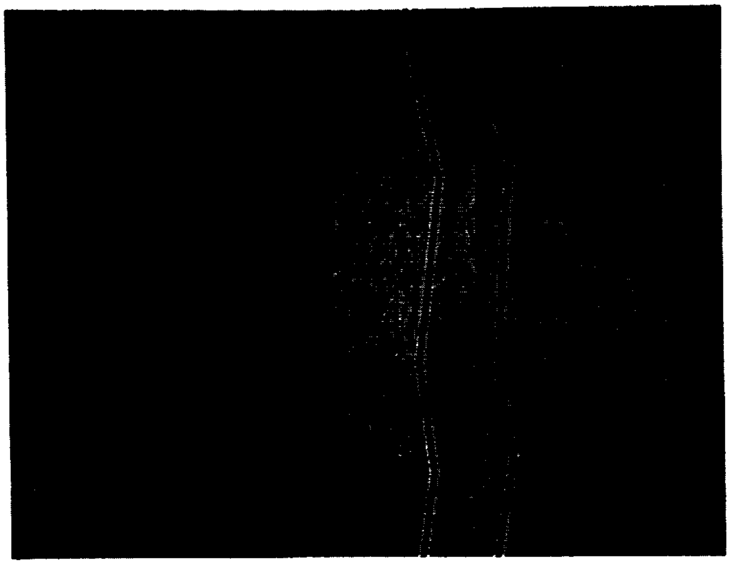
Material: 0.209-inch Inconel 718 alloy

Etchant: Kallings

Magnification: 22,000X

FIGURE 60.

ELECTRON MICROGRAPH OF 0.209-INCH MATERIAL; Massive Gamma Prime and Large Cb Ti (c) Particle Structure



Structure: Heavy gamma prime precipitate and some small Laves phase particles in the grain boundaries. Large carbide particles are marked with the letter C.

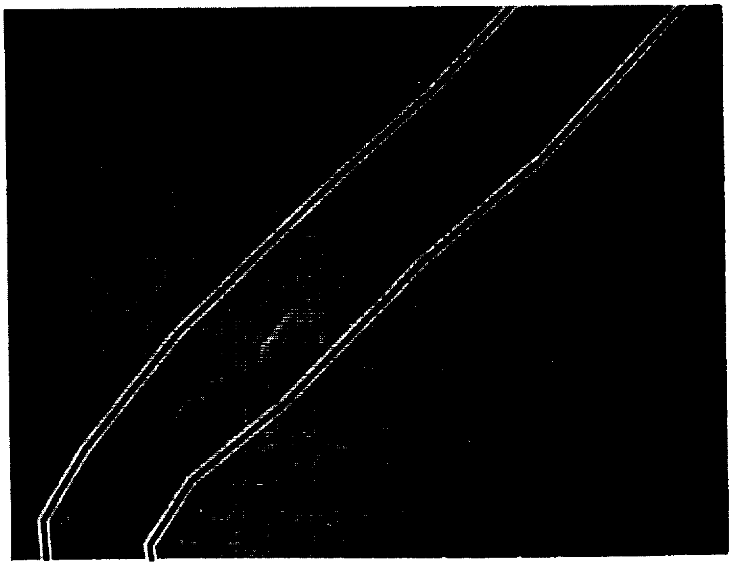
Material: 0.209-inch Inconel 718 alloy

Etchant: Kallings

Magnification: 10,000X

FIGURE 61.

ELECTRON MICROGRAPH OF 0.209-INCH MATERIAL WITH DENUDED GRAIN BOUNDARY ZONE; 10,000X



Structure: Heavy gamma prime precipitate and some Laves phase particles in the grain boundaries.

Material: 0.209-inch Inconel 718 alloy

Etchant: Kallings

Magnification· 22,000X

FIGURE 62.

ELECTRON MICROGRAPH OF 0.209-INCH MATERIAL WITH DENUDED GRAIN BOUNDARY ZONE; 22,000X

Figures 61 and 62 show a matrix with a heavy gamma prime precipitate and some small Laves phase particles in the grain boundaries. Larger carbides are marked with the letter C. Close examination of these figures reveals that the areas immediately adjacent to the grain boundaries are devoid of gamma prime precipitates or denuded. This effect was not seen in specimens that had been solution annealed at a lower temperature and given the 8 + 8 aging treatment. Figure 63 is representative of the absence of this denudation effect in both thicknesses of material. It should be noted that no gamma prime precipitate is in evidence in either specimen. In most specimens examined no resolvable gamma prime was found. This fact was explained

Material: 0.040-inch Inconel 718 alloy

Note absence of denuded zone along grain boundaries.

Magnification: 10,000X

Material: 0.209-inch Inconel 718 alloy

Note absence of denuded zone along grain boundaries.

Magnification: 15,000X

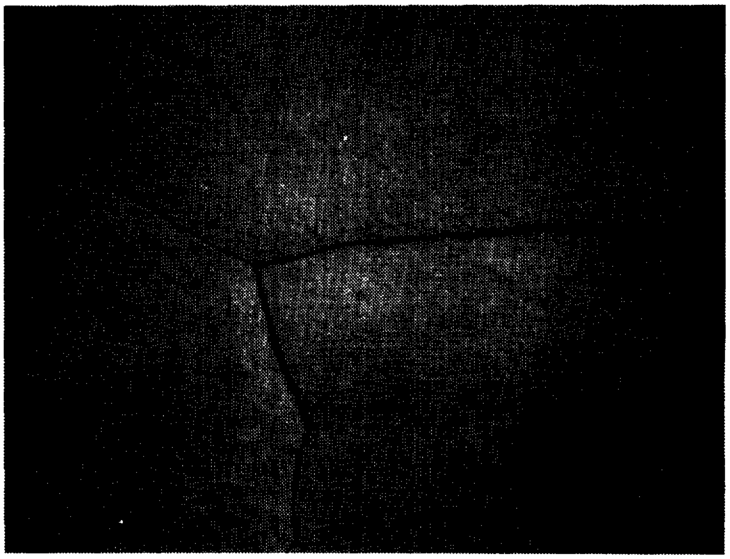
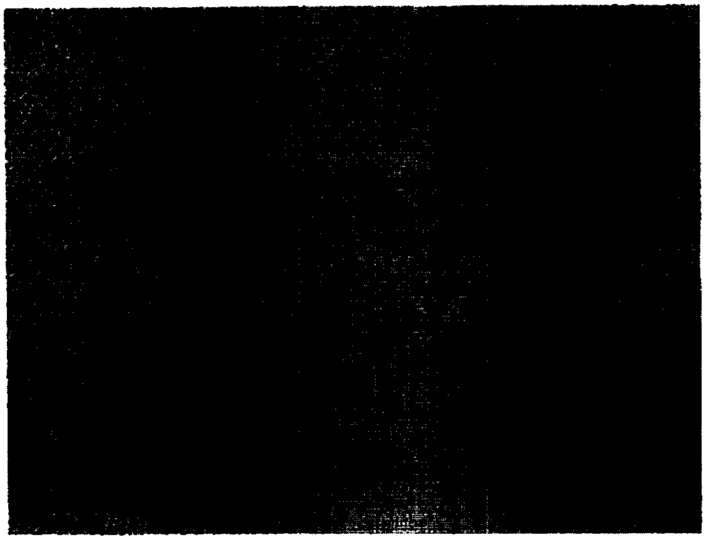


FIGURE 63. ELECTRON MICROGRAPH OF 0.040- AND 0.209-INCH MATERIAL; ANNEALED AT 1750 F, AGED IN 8 + 8 CYCLE

in a private communication with Mr. E. T. Raymond of Huntington (Ref. 3). He found that except in cases where gamma prime had sufficient opportunity for growth (higher aging temperature and longer aging times) that gamma prime was difficult to resolve by the two-stage, carbon-replica technique and frequently could be resolved only by thin foil transmission microscopy. In the present study the only specimens that showed heavy gamma prime precipitate were those that had been aged for a total of 20 hours at 1400 and 1200 F, respectively. The other aging treatments most likely precipitated a very fine gamma prime not resolvable by replica techniques.



Crack shown in circled area.
Specimen annealed at 1950 F
with 10 + 10 age.

Magnification: 100X

FIGURE 64.

INCIPIENT GRAIN BOUNDARY MELINT IN HEAT-AFFECTED ZONE ADJACENT TO FUSION ZONE

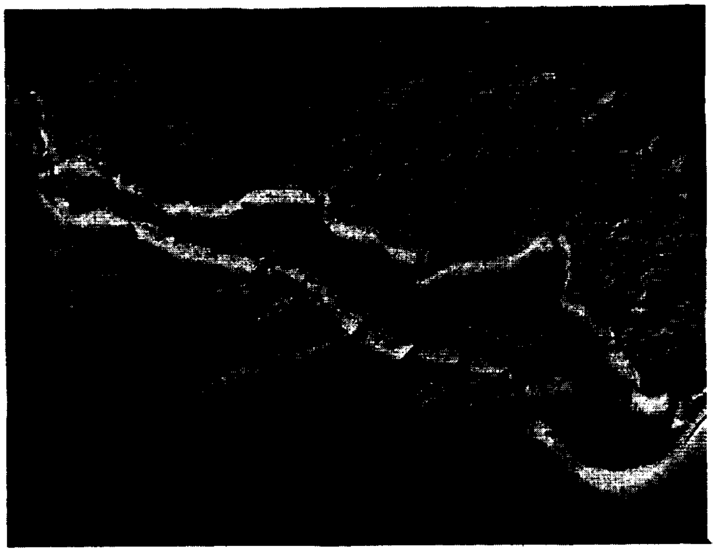
The denudation effect was noted in the parent material and in the portion of the heat-affected zone closer to the parent material than the fusion zone. Although some cracks were seen to originate in this area of the heat-affected zone, most of the cracking was found in the area adjacent to the fusion zone as described in Paragraph 2.8.1. The cracking was intergranular in most cases with some cracks originating in the weld zone and propagating into the heat-affected zone. Initial optical microscopic examination of heat-affected zone cracking in the area adjacent to the weld zone showed evidence of incipient grain boundary melting. A low magnification optical micrograph (Fig. 64) shows a small fissure (circle) and indications of boundary melting in a typical area in which heat-affected zone cracking was found. An electron microscopic examination of such areas was made in an effort to more clearly determine the nature of the cracking.

A crack origin in the area of grain boundary liquation is shown in Figure 65. The grain boundary phase is probably Laves phase. A higher magnification micrograph (Fig. 66) shows this same type of cracking in the grain boundary. Partial gross melting of the Laves phase is indicated by arrows. None of the carbo-nitrides (Fig. 67) showed any evidence of melting. Figure 67 shows a crack propagating around a carbo-nitride particle in a grain boundary. It should also be noted that no gamma prime precipitate is seen in Figure 66. The absence of gamma prime in the

Same specimen as Figure 64.
Magnification: 3900X

FIGURE 65.

CRACK ORIGINATING IN AREA OF INCIPIENT GRAIN BOUNDARY MELTING



Same specimen as Figure 64.
Magnification: 10,000X

FIGURE 66.

CRACK IN AREA OF INCIPIENT GRAIN BOUNDARY MELTING; Partial Melting of Laves Phase Indicated by Arrows

Magnification: 10,000X

FIGURE 67.

CRACK PROPAGATING AROUND A CARBO-NITRIDE PARTICLE area of the heat-affected zone adjacent to the weld was found in all cases. This condition might be expected because solutioning of gamma prime begins at 1600 F (Ref. 5, 6), and this region adjacent to the weld experienced temperatures considerably above that evidenced by the Laves phase melting. The gamma prime density increases with increasing distances from the weld with massive gamma prime developing approximately 0.040 inch from the weld heat-affected zone interface. At this point, the denudation effect becomes evident.

The major cause of cracking then appears to be related to the precipitation of low-melting Laves phase in grain boundaries. This precipitation does not occur unless solutioning of the Laves phase takes place during the annealing treatment. Subsequent aging results in the grain boundary appearance of the Laves phase and incipient melting during welding. Imposing a stress on a hot specimen with a liquid phase in the grain boundaries results in opening of the material along these boundaries.

The nature of the denuded zone adjacent to the grain boundaries and its relation to the secondary cracking may now be examined. As mentioned earlier, the appearance of the denuded zone was noted only in that material which had been annealed at 1950 F. Electron microscopy indicated the solutioning temperature for carbides and probably Laves phase in the Inconel 718 alloy to be between 1850 and 1900 F. It was also found that the grain boundary effect (denudation) was evident only in the material in which the carbides and Laves phase had been taken into solid solution in the matrix, and subsequently preferentially precipitated in the grain boundaries during the aging cycle. The Laves phase in the Inconel 718 alloy has been found to be isomorphous with Fe_2Ti and can be simply described as $Fe_2(Cb, Ti)$ (Ref. 11). Other work presented in the literature indicated the Laves phase to be high in columbium (Ref. 12). The carbides are of the form CbTi(C) and are also rich in columbium. The gamma prime, on the other hand, precipitates in a meta-stable form corresponding to $Ni_3(Cb, Al, Mo, Ti)$ (Ref. 11, 12, 13) which is again columbium-rich and transforms to a stable Ni_3Cb on long-time or high-temperature aging.

When the carbides and Laves phase are taken into solution prior to aging they precipitate in the grain boundaries on aging with concomitant depletion of the adjacent areas of columbium. As the gamma prime precipitates in the matrix on further aging, it is unable to form in the areas adjacent to the grain boundaries resulting in a denuded zone. Although carbides and Laves phase precipitate in the grain interior and grain boundaries during the 1750, 1800, and 1850 F anneals, no apparent solute depletion of the grain boundary areas occurs. The depletion effect resulting from the solution anneal at 1950 F might possibly be attributed to a morphology change in the grain boundary precipitate. This phenomenon had been seen and described earlier by Raymond in his work at Huntington (Ref. 10).

The relationship between secondary cracking in this area of the heat-affected zone and the denuded grain boundary zones can be seen more clearly by considering the strengthening mechanism in the Inconel 718 alloy. Gamma prime precipitates by an exchange transformation reaction in an ordered, body-centered tetragonal form with lattice constants very similar to the face centered cubic matrix (Ref. 12). The strengthening of the alloy results from the coherency strains between precipitate and matrix. The uniform dispersion of gamma also accounts for the high-temperature strength of the alloy. The unaged alloy (without a gamma prime dispersion) is relatively weak particularly at elevated temperatures as would be found in a heat-affected zone during a welding operation. The denuded zone acts similarly to the unaged alloy and the tensile or shear strength of the material in these zones is exceeded much before that of the matrix.

Although no denuded zone or gamma prime precipitate was seen in the material annealed at 1800 or 1850 F and aged with the 8 + 8 cycle, the denudation effect may be present on a much smaller scale not capable of being resolved by replica techniques.

2.10 ELECTRON MICROPROBE ANALYSIS

To better understand the changes that were observed with the light and electron microscopes, two specimens, metallographic Mount Numbers 7825 and 7829. were submitted for microprobe analysis. Specimen 7825 was representative of specimens annealed at 1950 F and double aged for 20 hours. The analyses to be performed were:

- Investigate and/or analyze low-melting eutectic in crack area (Mount 7825) and identify elements and/or compound phase present.
- For Mount 7829, analyze small globular phases in denuded area and determine composition and phase.

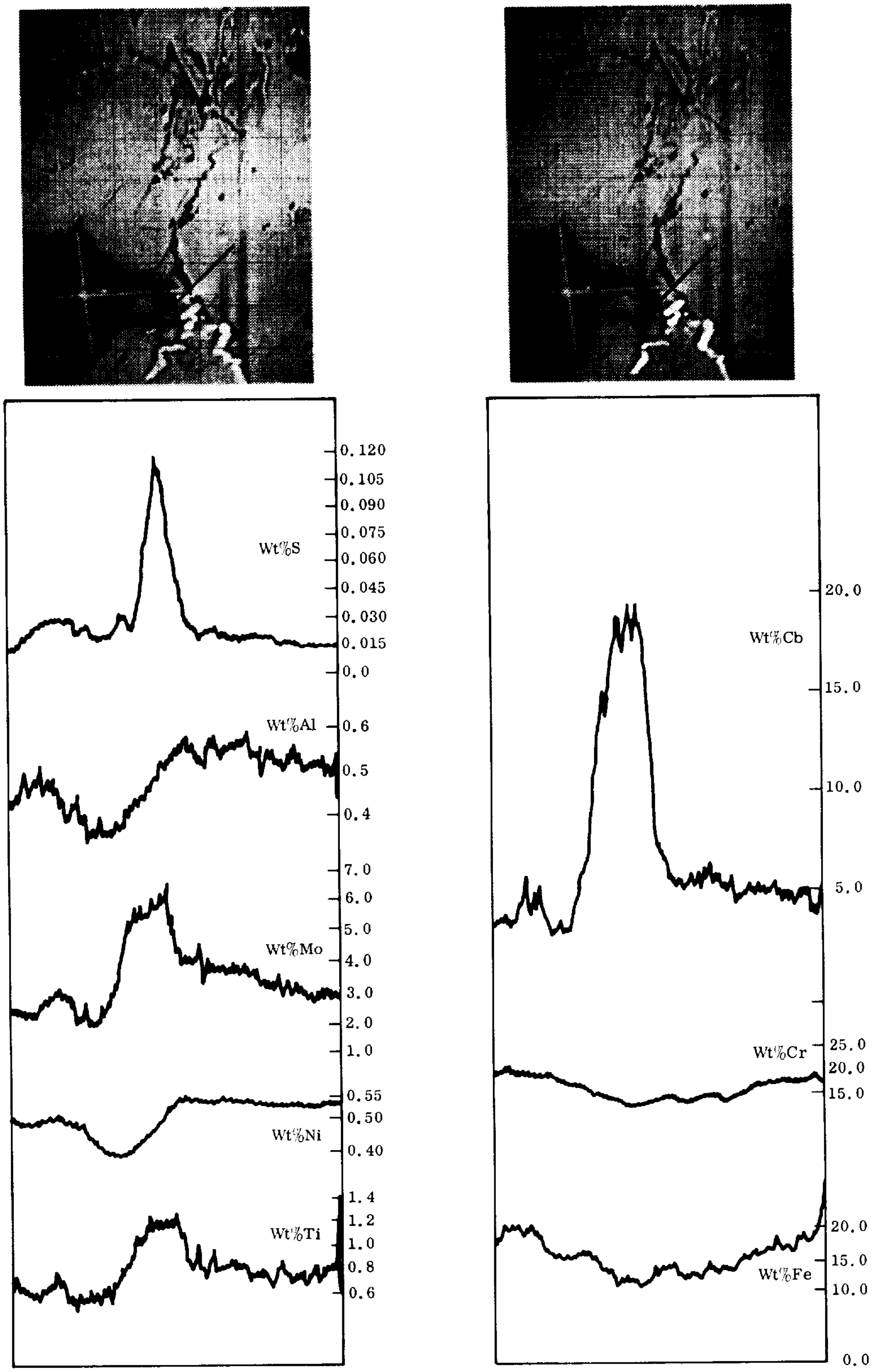


FIGURE 68. ELECTRON MICROPROBE TRACE ON LOW MELTING EUTECTIC

2.10.1 Method Used for Analyses

For Item 1, a traverse of the crack and adjacent area was made for sulfur gradients (Fig. 68). Elemental scans of the unaffected area and crack were also made to identify all elements present in both areas, and to determine the amount present relative to the unaffected area of the sample.

For Item 2, elemental scans were made of the small globular phase and the unaffected area. Identification of the elements present and the amount relative to the unaffected area were determined.

Results of Microprobe Analyses

Mount 7825 - Crack at point of high columbium and sulfur concentration.

	Fe	Cr	Cb	Ti	Ni	Co	Mo	Al	Cu	S	Ta	Si	%
Crack Area	12.0	15.0	20.0	1.4	44.0	0.8	6.0	0.5	0.08	0.115	NA	NA	99.8
Unaffected Area	18.0	18.0	5.0	0.8	53.0	0.1	3.0	0.5	0.1	0.015	0.3	0.3	99.0

Mount 7829 - Small globular phase inclusion in denuded area.

	Fe	Cr	Cb	Ti	Ni	Co	Mo	Al	Cu	S	Ta	Si	%
Phase	6.0	6.3	47.5	4.0	21.7	NA	2.6	0.32	NA	0.02	0.1	0.5	89.3
Unaffected Area	18.0	18.0	5.0	0.8	53.0	0.1	3.0	0.5	0.1	0.015	0.3	0.3	96.1

NA - Not analyzed

Compositions of the areas of interest differed, in nearly all respects, to those of the unaffected reference areas.

The amount of sulfur increased only slightly in the globular phase (from 0.015 to 0.020%) and appreciably in the crack area (0.015 to 0.115%). Relating the sulfur content to a particular compound such as sulfide was not possible with the limited amount of data collected.

Iron, chromium, and nickel decreased while columbium increased in both samples. The magnitude of the concentration changes was greater in the globular phase, and its composition corresponds closely to Laves phase residues extracted from forgings and reported by Eiselstein (Ref. 5).

Composition of this phase, reported by Eiselstein, extracted from forgings with different heat treatments was very similar to the globular phase examined with the microprobe and shown in the following tabulation:

	Composition					
Heat Treatment (Ref. 5)	Ni	Fe	Cr	Ti	Cb	Mo
1900 F/1 hr, WQ + 1700 F/50 hr, WQ	27	6	4	2	55	6
2200 F/1 hr, WQ + 1700 F/50 hr, WQ	31	8	7	3	48	3
Microprobe Mount 7829	27	6	6.3	4	47.5	2.6

Chemical composition of the low-melting phase (Mount 7825, 1950 F anneal) did not correlate readily with any particular phase associated with those reported by Eiselstein. Two reasons may account for this lack of correlation.

- Size of phase too small for a one-micron beam to resolve and to be free of interferences by overlap of matrix material
- Analysis is typical of chemical composition in crack and a discrete phase was not present.

Assuming resolution was obtained on a separate phase in the crack, Fe_2Ti or (FeCb)Ti could be present equally as well as gamma, eta, beta, sigma, and orthorhombic by assessing the microprobe concentration data. Thus, for positive determination and identification of the phase or phases would require their extraction and subsequent diffraction studies. Since this was not feasible with the present program, reconsideration of the microprobe data could show the various probable phases and compositions as shown in the following tabulation:

	Fe	Cr	Cb	Ti	Ni	Mo	S	Al
Weight Percent Found	12.0	15.0	20.0	1.4	44.0	6.0	0.115	0.5
Gram Atoms	0.21	0.29	0.21	0.33	0.75	0.063	0.0036	
Normalized to base Fe = 1	1.0	1.45	1.05	0.15	3.75	0.35	0.0180	

It can be seen that sufficient nickel is present to form both Ni_3Cb and Ni_3Ti and that sigma (FeCr) are all obviously possible entities. Assessing the data will show the only major abnormality that will stand alone is the high sulfur content. The concentration of sulfur at this area was a little greater than six times the nominal maximum for the alloy. Because of the abnormal amount of sulfur present in Mount 7825, an additional mount was submitted for verification. Subsequent microprobe analysis on a specimen annealed in accordance with AMS 5596 and Varestraint tested, again indicated the presence of sulfur six times the nominal for the alloy in areas where a formerly liquid phase had existed. Alloy segregation of compounds high in sulfur could certainly account for the presence of low-melting eutectic noted in the heat-affected zone of most Varestraint specimens.

2.11 HEAT-AFFECTED ZONE CRACKING TEMPERATURE RANGE

An effort was made to determine the range of temperatures over which cracking occurs on Varestraint test specimens in relation to the augmented strain used. It was felt that the temperature-time relationship at the instant of application of the augmented strain could be converted into a temperature-distance relationship. By determining the maximum crack length relative to the measured temperature distribution along the heat-affected zone, the temperature range over which the Inconel 718 material is sensitive to hot cracking could then be determined. Initial attempts to experimentally measure the temperature distribution during TIG welding of Varestraint specimens by the use of fine diameter thermocouples and/or the use of optical pyrometers indicated that temperatures could not be measured accurately by these procedures. Measurements are difficult to make because of stray currents, arc glare, the small area, and the short time involved. An analytical approach, while limited by the degree to which the equations used described actual welding conditions, would enable the calculation of the temperature distribution as a function of space and time. Consequently, an analysis was made with particular regard for the temperature distribution on Varestraint specimens during the welding cycle. The analysis included the complex interaction between the speed of welding, dimensions of the test specimens, and the temperature-dependent thermal and electrical properties of the material. For this analysis, the temperature at the edge of the fusion zone was assumed to be 2450 F. A digital computer was used to give a solution. The analytical method used to plot a temperature-distance relationship is described in Reference 14.

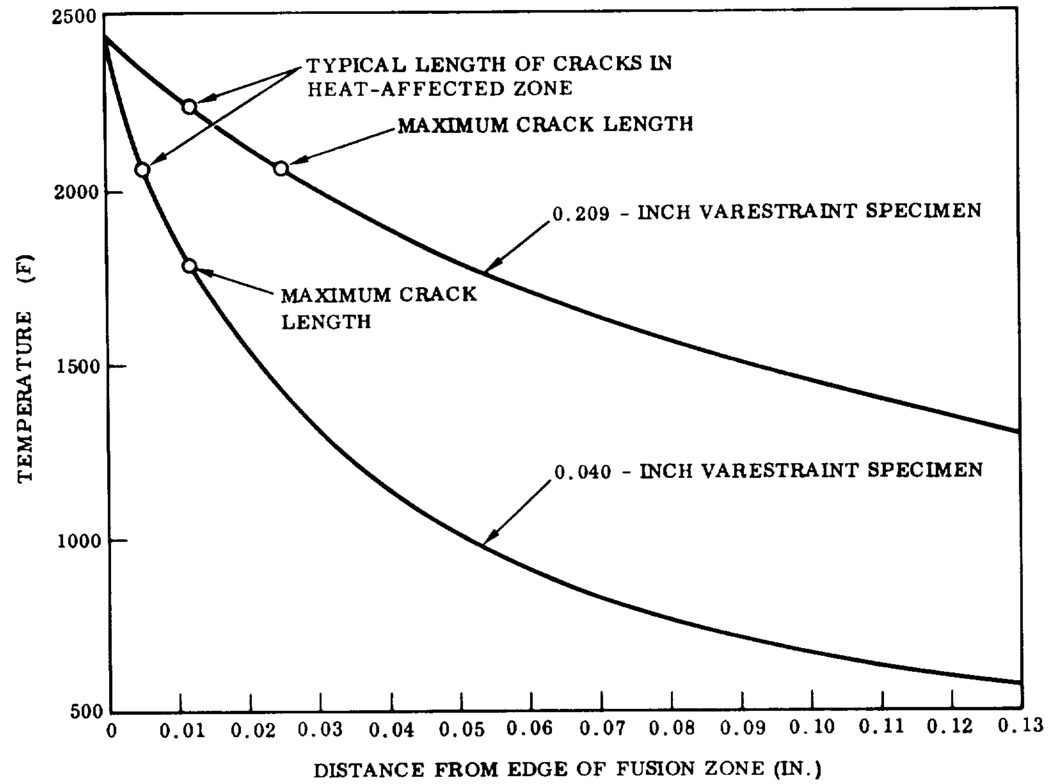


FIGURE 69. CALCULATED TEMPERATURE DISTRIBUTION ON VARESTRAINT SPECIMENS

Figure 69 shows the resultant temperature-distance relationship pertaining to the 0.040- and 0.209-inch Inconel 718 materials. Maximum single-crack length for the 0.209-inch material was found to measure 0.0248 inch which corresponds to a temperature of approximately 2070 F. The maximum single-crack length for the 0.040-inch material was measured and found to be 0.012 inch which corresponds to a temperature of approximately 1800 F. It can, therefore, be assumed that the cracking temperature range for the 0.040-inch Inconel 718 alloy extends to 1800 F when subjected to an augmented strain of 2.0, and 2070 F for the 0.209-inch material at 2.6 augmented strain.

3

PHASE II DEVELOPMENT

3.1 OBJECTIVES

To apply and demonstrate the optimum heat-treating process chosen from Phase I study. This was to determine the effects on weld properties resulting from welding fully heat treated high mass Inconel 718 material to low mass AISI Type 321 Stainless Steel and age-hardened Inconel 718 materials.

To develop information on the effect of time-temperature variations on annealed and fully heat treated Inconel 718 specimens relative to:

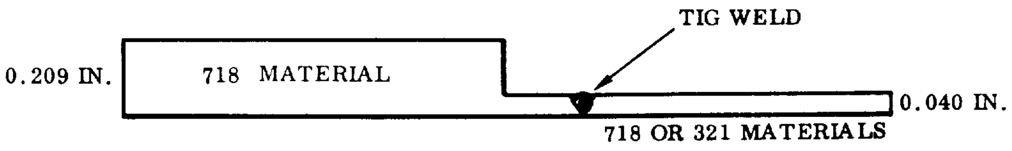
- Strength properties
- Width of heat-affected zone
- Grain size changes in heat-affected zone
- Precipitation of microconstituents
- porosity
- Cracking susceptibility
- Fatigue life.

3.2 WELDING HEAVY SECTIONS TO LIGHT SECTIONS

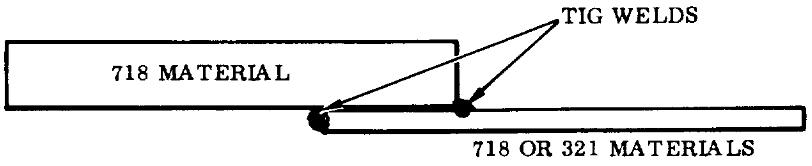
Sets of typical weld joints (lap and butt), in the appropriate mass ratio of bellows thickness to thick gimbal flange sections, were welded in the fully heat-treated condition using the optimum thermal treatment chosen from Phase I study. Strength properties, joint integrity, and fatigue properties were determined.

3.3 TENSILE STRENGTH

Test specimens for this evaluation were fully heat treated using the Pratt & Whitney thermal cycle in accordance with AMS 5596. Tensile specimens were of the flat type with the fusion zone located at the midspan of the specimen (Fig. 70). Specimens were welded in the fully heat-treated condition. It was, therefore, expected that an area in the heat-affected zone would be devoid of gamma prime precipitate



BUTT JOINT SPECIMEN



LAP JOINT SPECIMEN

FIGURE 70. TENSILE AND FATIGUE SPECIMEN CONFIGURATION: Phase II Evaluation

because of exposure to possible solutioning resulting from the high temperature in that region. As a result, strength properties were expected to be somewhat lower.

Tensile test results are contained in Table XIX and, as expected, show that stress at failure on the Inconel 718 to 718 joints is only slightly higher than annealed properties. Ultimate tensile stress ranged from 128.5 to 167.0 ksi. Cryogenic (-320 F) strength values ranged from 170.0 to 204.5 ksi. The Inconel 718 to AISI 321 joints failed at a stress level equivalent to the ultimate strength of the AISI 321 material. Stress at failure ranged from 84.5 to 92.0 ksi at ambient temperature, and 151.0 to 180.5 ksi at the cryogenic temperature of -320 F.

In the case of the Inconel 718 to 718 joints, specimens exhibited only localized heat-affected zone yielding prior to failure. Failure in the Inconel 718 to AISI 321 joints occurred in the AISI 321 side at some distance removed from the fusion joint.

3.4 FATIGUE TEST RESULTS

Flat-type butt and lap-joint specimens similar to the tensile specimen shown in Figure 66 were tested in the Calidyne Vibrator (Fig. 71). Specimens were fatigue tested using the stair-step method of increasing the amplitude after each step of 10^6 cycles. This procedure is repeated at successively higher amplitudes until failure occurs. For each joint design, a calibration of amplitude versus stress at the section change was done using strain gages.

TABLE XIX

WELDING OF AGE HARDENED HIGH MASS 718 ALLOY TO LOW MASS AGE HARDENED 718 AND TYPE AISI 321 MATERIALS

Type of Joint	Materials	Heat No.	Ambient Temperature F_{tu} (ksi)	Ambient Temperature Location of Failure	Cryogenic -320 F F_{tu} (ksi)	Cryogenic -320 F Location of Failure
Lap	718 to 718	6518	133.5	HAZ	172.8	HAZ
		6518	137.6	HAZ	177.2	HAZ
		6790	167.0	HAZ	188.8	HAZ
		6790	157.0	HAZ	194.3	HAZ
		6394	154.0	HAZ	187.0	HAZ
		6394	154.0	HAZ	198.7	HAZ
		6300	161.0	HAZ	189.5	HAZ
		6300	156.0	HAZ	204.5	HAZ
Butt	718 to 718	6518	132.0	HAZ	172.0	HAZ
		6518	128.5	HAZ	170.0	HAZ
		6790	136.0	HAZ	182.5	HAZ
		6790	136.0	HAZ	177.0	HAZ
		6394	134.0	HAZ	178.0	HAZ
		6394	135.0	HAZ	183.8	HAZ
		6300	136.0	HAZ	180.0	Weld
		6300	134.0	HAZ	177.1	HAZ
Lap	718 to 321		86.0	PM of 321	180.5	HAZ of 321
			86.4	PM of 321	179.5	HAZ of 321
			84.5	PM of 321		
			85.0	PM of 321		
Butt	718 to 321		92.0	PM of 321	153.0	HAZ of 321
			89.0	PM of 321	151.0	HAZ of 321
			89.6	PM of 321		
			88.0	PM of 321		

Legend:

PM - Parent Metal.
HAZ - Heat-Affected Zone.

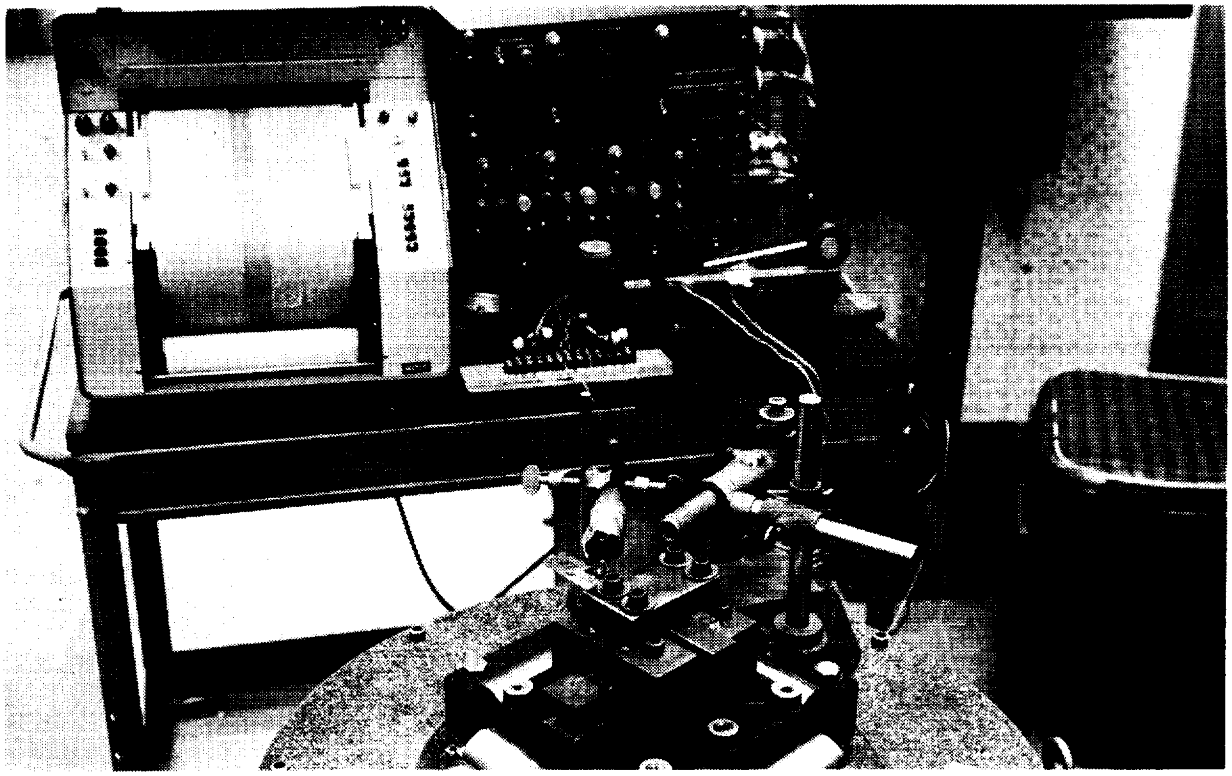


FIGURE 71. CALIDYNE VIBRATOR

Test results are summarized in Table XX and Figures 72 and 73. Examination and analysis of the fatigue data indicate that fatigue life is an independent variable in the range of stresses applied (60 to 80 ksi).

For the configuration tested, i.e., the low-mass section, approximately 0.042 inch thick, 0.95 inch wide, and 2.50 inches long, it appears that the mean fatigue life for the butt welded Inconel 718 to 718 type is 1.66 x 10^6 cycles with a 95 percent lower boundary of 0.666 x 10^6 cycles on the average. The Inconel 718 to 718 lap weld mean appears to be 1.064 x 10^6 cycles with a 95 percent lower boundary of 0.554 x 10^6 cycles. These estimates are based on analysis using the Weibull technique (Ref. 8 and 9).

It was not possible to statistically analyze the limited Inconel 718 to AISI 321 data obtained during this evaluation. However, Table XX does show the total number of cycles to failure on the Inconel 718 to AISI 321 specimens tested. Lap joint specimens exhibited a fatigue life of 0.112 x 10^6 to 1.289 x 10^6 cycles. Fatigue life of the butt-joint specimens ranged from 0.137 x 10^6 to 1.477 x 10^6 cycles.

TABLE XX

FATIGUE PROPERTIES OF AGE HARDENED AND WELDED HIGH MASS INCONEL 718 ALLOY JOINED TO LOW MASS INCONEL 718 AND AISI 321 MATERIALS

Joint Design	Specimen Number	Frequency (cps)	Cycles at 60 (ksi)	Cycles at 70 (ksi)	Cycles at 80 (ksi)	Total Cycles at Failure
Type I Lap Joint Inconel 718 to 718	1	283	10^6	10^6	10^6	3 x 10^6
	2	214	898,800	-	-	0.898 x 10^6
	3	217	10^6	194,400	-	1.194 x 10^6
	4	210	567,000	-	-	0.567 x 10^6
	5	215	10^6	154,800	-	1.154 x 10^6
	6	217	10^6	937,440	-	1.937 x 10^6
	7	207	645,840	-	-	0.645 x 10^6
	8	214	706,200	-	-	0.706 x 10^6
	9	211	10^6	443,100	-	1.443 x 10^6
	10	216	686,880	-	-	0.686 x 10^6
	11	211	949,500	-	-	0.949 x 10^6
	12	216	673,920	-	-	0.673 x 10^6
Type II Lap Joint Inconel 718 to AISI 321	13	213	10^6	289,800	-	1.289 x 10^6
	14	208	886,080	-	-	0.886 x 10^6
	15	253	112,520	-	-	0.112 x 10^6
	16	214	770,400	-	-	0.770 x 10^6
Type III Butt Joint Inconel 718 to 718	17	209	873,600	-	-	0.873 x 10^6
	18	213	10^6	830,700	-	1.830 x 10^6
	19	209	10^6	62,700	-	1.062 x 10^6
	20	207	683,320	-	-	0.683 x 10^6
	21	210	982,800	-	-	0.982 x 10^6
	22	208	10^6	187,200	-	1.187 x 10^6
	23	219	10^6	893,520	-	1.893 x 10^6
	24	227	10^6	476,700	-	1.476 x 10^6
	25	222	10^6	10^6	520,400	2.520 x 10^6
	26	207	10^6	10^6	906,600	2.906 x 10^6
	27	204	1 10^6	10^6	353,220	2.353 x 10^6
	28	204	10^6	856,800	-	1.856 x 10^6
Type IV Butt Joint Inconel 718 to AISI 321	29	204	10^6	477,360	-	1.477 x 10^6
	30	208	759,600	-	-	0.759 x 10^6
	31	207	137,260	-	-	0.137 x 10^6
	32	210	10^6	-	-	1.0 x 10^6

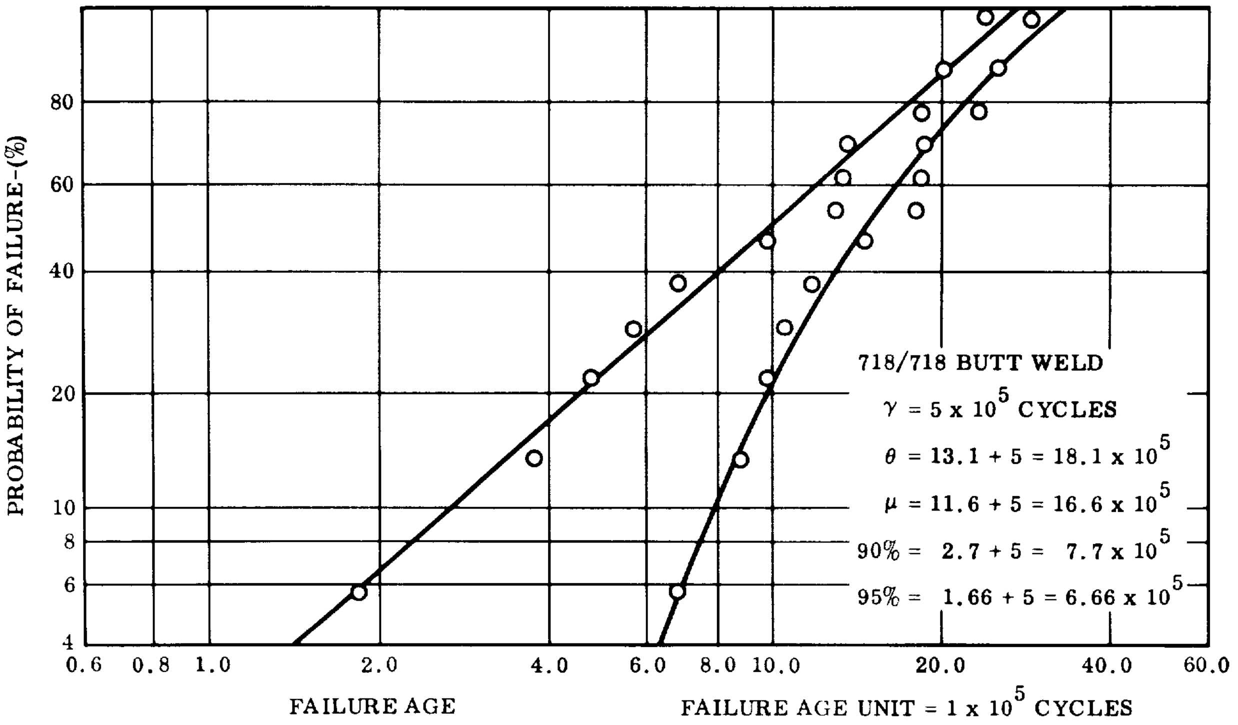


FIGURE 72. WEIBULL PROBABILITY PLOT; 718/718 Butt Weld

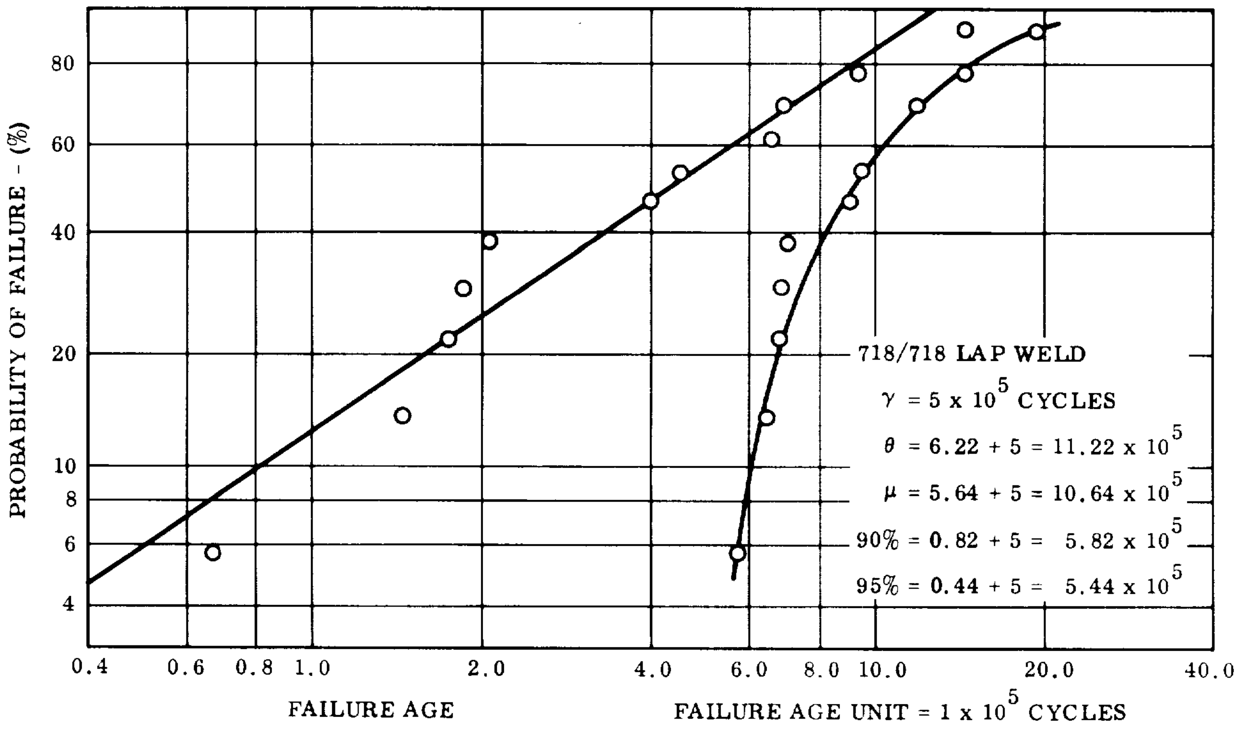
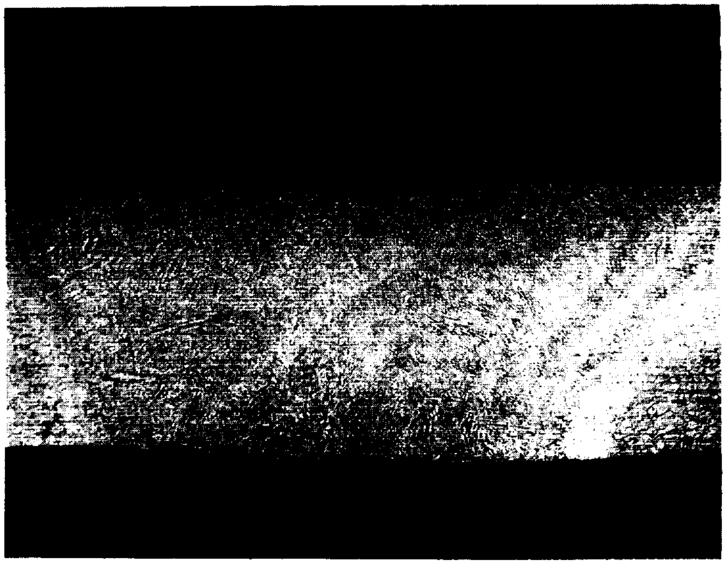


FIGURE 73. WEIBULL PROBABILITY PLOT; 718/718 Lap Weld



Etchant: Kallings

Magnification: 35X

FIGURE 74.

TYPICAL BUTT JOINT ON 718/718 FATIGUE SPECIMEN

Etchant: 10% oxalic electrolytic

Magnification: 35X

Note fatigue crack propagation in heat-affected zone of the AISI 321 side of the specimen.

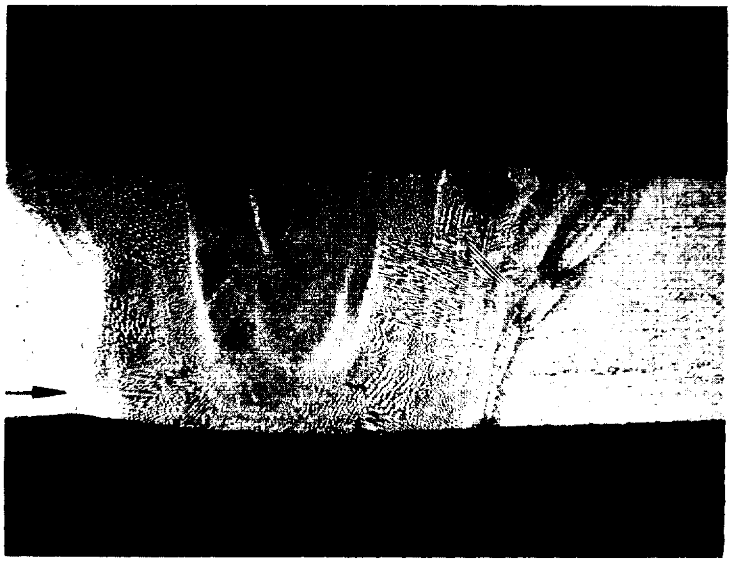


FIGURE 75.

TYPICAL BUTT JOINT ON 718/AISI 321 FATIGUE SPECIMEN

3.5 FUSION WELDS

The integrity of the fusion welds was determined by dye-penetrant, radiographic, and metallographic techniques. No cracks were found by any of the aforementioned techniques . Radiographic examination revealed some denser areas in the dissimilar joints (Inconel 718 to AISI 321). Those dark indications appeared on X-ray film with a lower density than the surrounding metal. Subsequent microscopic examination did not reveal any weld defect in the areas indicated on the X-ray film. Typical structure of the butt and lap welds of the Inconel 718 to 718, and Inconel 718 to AISI 321 are shown in Figures 74 through 77. The alignment of the dendrites is more pronounced in the dissimilar joints of the Inconel 718 to AISI 321 materials. Orientation of dendrites in directional colonies as seen in Inconel 718 to AISI 321 joints,

Arrow points to fatigue crack in Heat-Affected Zone

Etchant: Kallings

Magnification: 35X

FIGURE 76.

TYPICAL LAP JOINT ON 718/718 FATIGUE SPECIMEN

Etchant: Oxalic 10 percent electrolytic

Magnification: 35X

FIGURE 77.

TYPICAL LAP JOINT ON 718/AISI 321 FATIGUE SPECIMEN

particularly when aligned parallel to the source of radiation, apparently offer less resistance to the passage of the X-rays. This coarser and segregated orientation of dendrites evidently causes the appearance of these darker blotches in the X-ray film.

3.6 TIME-TEMPERATURE VARIATIONS

Unusual combinations of temperature and time must be dealt with in welding. The temperature changes in welding are, therefore, seldom looked upon as favorable. It sometimes appears that the harmful effects of applying heat for welding greatly outnumber the benefits. Nevertheless, to capitalize on one of the most effective benefits of heating, that of obtaining fusion and coalescence, the unwanted effects must be endured. The most logical means of dealing with the undesirable side effects of heat is to know what metallurgical changes occur as a result of metal temperature levels and the time they exist. In this connection, the fusion zone often is not the primary interest.

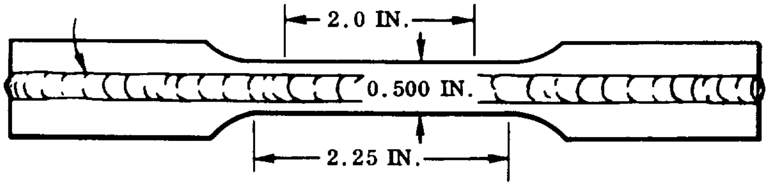


FIGURE 78. SPECIMEN CONFIGURATION: Tensile Testing Welds with Time-Temperature Variations

Rather, the heat-affected base metal adjacent to the weld may be prone to develop an undesirable metallurgical condition. Consequently, the effects of variations in welding parameters on the width of the heat-affected zone, grain size, porosity, cracking susceptibility, fatigue, and strength properties were determined.

Tensile specimens with the weld parallel to the tensile axis (Fig. 78) were welded with variations in energy input. Welds were made on material in two conditions: annealed and fully heat treated in accordance with AMS 5596. Two thicknesses and four heats were evaluated; four heats of the 0.040-inch and four heats of the 0.209-inch material. In addition, variations in surface preparations as well as double-pass welds were evaluated. A flow chart for this phase of the evaluation is as follows.

TIME-TEMPERATURE VARIATIONS

Material: Inconel 718 Alloy - 0.040- and 0.209-inch thick

Condition: 1. Annealed - Welded - Tested
2. Aged - Welded - Tested

Time-Temperature Variations: 1 through 7

1. Varestraint test to determine cracking sensitivity relative to variations in energy input
2. Tensile tests relative to time-temperature variations
3. Microstructural examination relative to time-temperature variations
4. Fatigue tests (0.040-inch material only) relative to time-temperature variations

3.7 VARESTRAINT TEST RESULTS

Varestraint test results with variations in energy input are shown in Tables XXI and XXII and Figures 79 and 80. Solar's standard production schedule for Inconel 718 components was identified as Time-Temperature Variation No. 1. The energy unit/ linear inch of weld joint on Solar's welding schedule for the 0.040-inch material is 900 Joules. This particular welding schedule resulted in the least heat-affected zone cracking of the 0.040-inch material. Heat-affected zone cracking sensitivity increased as the energy input increased to 1155 Joules/inch. A slight reversal, however, was noted when the energy input was increased to 1800 Joules/minute.

Manually welded 0.040-inch Varestrain specimens resulted in somewhat higher cracking susceptibility than the standard automatic schedule even though the average energy input was lower.

Test results did not indicate any advantage in reducing heat-affected zone cracking by the use of manual cleaning with Oakite Alkaline Cleanser. The use of a nitric-hydrofluoric acid pickle followed by a manual Oakite alkaline cleaning operation did not show its usual advantage in reducing heat-affected zone cracking over a straight acid pickle. This small advantage could very well be the result of added changes induced by variations in heat input.

Variations in energy input on the 0.209-inch Varestraint test specimens increased the heat-affected zone cracking sensitivity as the energy input is increased from 9000 to 15,000 Joules/minute, Table XXII, Figure 80.

The effect of a double-pass weld on specimens subjected to the energy input of 9000 Joules/minute is to effectively increase the heat-affected zone cracking sensitivity of the 0.209-inch specimens. However, as the heat input is raised to 11,250 Joules/minute, this effect of a double pass on cracking sensitivity is minimized and partially reversed.

A slight decrease in heat-affected zone cracking was noted by the use of an alkaline cleansing operation just prior to welding. This effect may be noted on heat energy variation No. 4 and No. 7. The energy input on both cycles are identical, with the only difference being in the manner of surface preparation. The specimens given the extra cleaning operation resulted in the slightly lower heat-affected zone cracking sensitivity.

TABLE XXI

TIME-TEMPERATURE RELATIONSHIPS (Varestraint Testing to Determine Cracking Sensitivity of the 0.040-Inch Thick Material in Relation to Variations in Energy Input)

Time-Temperature Variation Number	Specimen Number	Heat Number	Condition	Total Heat-Affected Zone Crack Length (in.)	Average for 5 Tests (in.)
1. 900 Joules/inch (Std. Production Schedule) 20 amp, 13.5 v, 18 ipm, helium 75 argon 25 at 30 cfh, HNO_3-HF pickle. Manual scrub with Oakite Cleanser.	1-1-W-1	6300	Annealed	0.0220	
	1-2-X-1	6790	Annealed	0.0080	
	1-3-Y-1	6518	Annealed	0.0328	
	1-4-Z-1	6394	Annealed	0.0364	
	1-5-W-1	6300	Annealed	0.0224	0.0243
	1-11-W-2	6300	Aged	0.0060	
	1-12-X-2	6790	Aged	0.0020	
	1-13-Y-2	6518	Aged	0.0324	
	1-14-Z-2	6394	Aged	0.0040	
	1-15-W-2	6300	Aged	0.0476	0.0184
2. 1085 Joules/inch, 14 amp, 15.5 v, 12 ipm, helium 75 argon 25 at 30 cfh, HNO_3-HF pickle. Manual scrub with Oakite Cleanser.	2-1-W-1	6300	Annealed	0.0464	
	2-2-X-1	6790	Annealed	0.0652	
	2-3-Y-1	6518	Annealed	0.0536	
	2-4-Z-1	6394	Annealed	0.0658	
	2-5-X-1	6790	Annealed	0.0512	0.0548
	2-11-W-2	6300	Aged	0.0452	
	2-12-X-2	6790	Aged	0.0436	
	2-13-Y-2	6518	Aged	0.0632	
	2-14-Z-2	6394	Aged	0.0528	
	2-15-X-2	6790	Aged	0.0496	0.0508
3. 1155 Joules/inch, 11 amp, 14 v, 8 ipm, helium 75 argon 25 at 30 cfh, HNO_3-HF pickle. Manual scrub with Oakite Cleanser.	3-1-W-1	6300	Annealed	0.0980	
	3-2-X-1	6790	Annealed	0.0948	
	3-3-Y-1	6518	Annealed	0.0836	
	3-4-Z-1	6394	Annealed	0.0976	
	3-5-Y-1	6518	Annealed	0.1060	0.0960
	3-11-W-2	6300	Aged	0.0724	
	3-12-X-2	6790	Aged	0.1004	
	3-13-Y-2	6518	Aged	0.1024	
	3-14-Z-2	6394	Aged	0.0988	
	3-15-Y-2	6518	Aged	0.0820	0.0912
4. 1800 Joules/inch, 6 amp, 20 v, 4 ipm, helium 75 argon 25 at 30 cfh, HNO_3-HF pickle. Manual scrub with Oakite Cleanser.	4-1-W-1	6300	Annealed	0.0456	
	4-2-X-1	6790	Annealed	0.0416	
	4-3-Y-1	6518	Annealed	0.0624	
	4-4-Z-1	6394	Annealed	0.0232	
	4-5-Z-1	6394	Annealed	0.0396	0.0424
	4-11-W-2	6300	Aged	0.0302	
	4-12-X-2	6790	Aged	0.0284	
	4-13-Y-2	6518	Aged	0.0568	
	4-14-Z-2	6394	Aged	0.0264	
	4-15-Z-2	6394	Aged	0.0188	0.0321
5. 900 Joules/inch, 20 amp, 13.5 v, 18 ipm, helium 75 argon 25 at 30 cfh, HNO_3-HF pickle only.	5-1-W-1	6300	Annealed	0.0288	
	5-2-X-1	6790	Annealed	0.0472	
	5-3-Y-1	6518	Annealed	0.0756	
	5-4-Z-1	6394	Annealed	0.0444	0.0456
	5-11-W-2	6300	Aged	0.0040	
	5-12-X-2	6790	Aged	0.0040	
	5-13-Y-2	6518	Aged	0.0296	
	5-14-Z-2	6394	Aged	0.0040	
	5-15-W-2	6300	Aged	0.0060	0.0095
6. 1155 Joules/inch, 11 amp, 14 v, 8 ipm, helium 75 argon 25 at 30 cfh, HNO_3-HF pickle only.	6-1-W-1	6300	Annealed	0.0412	
	6-2-X-1	6790	Annealed	0.0436	
	6-3-Y-1	6518	Annealed	0.0736	
	6-4-Z-1	6394	Annealed	0.0480	
	6-5-X-1	6790	Annealed	0.0772	0.0567
	6-11-W-2	6300	Aged	0.0464	
	6-12-X-2	6790	Aged	0.0412	
	6-13-Y-2	6518	Aged	0.0620	
	6-14-Z-2	6394	Aged	0.0272	
	6-15-X-2	6790	Aged	0.0576	0.0468
7. Manual weld 660 Joules/inch, 8 amp, 11 v, 8 ipm, helium 75 argon 25 at 25 cfh, HNO_3-HF pickle. Manual scrub with Oakite Alkaline Cleanser.	7-1-W-1	6300	Annealed	0.0396	
	7-2-X-1	6790	Annealed	0.0512	
	7-3-Y-1	6518	Annealed	0.1081	
	7-4-Z-1	6394	Annealed	0.0616	
	7-5-Y-1	6518	Annealed	0.0888	0.0698
	7-11-W-2	6300	Aged	0.0716	
	7-12-X-2	6790	Aged	0.0236	
	7-13-Y-2	6518	Aged	0.0536	
	7-14-Z-2	6394	Aged	0.0196	
	7-15-Y-2	6518	Aged	0.0444	0.0425

TABLE XXII

TIME-TEMPERATURE RELATIONSHIPS ON VARESTRAINT TESTS

Varestraint Testing to Determine Cracking Sensitivity in the 0.209-Inch Material in Relation to Variations in Energy Input

Time-Temperature Variation Number	Specimen No.	Heat No.	Condition	Total HAZ Crack Length (in.)	Average for 4 Tests (in.)
1. 9,000 Joules 200 amp, 12 volts, 16 ipm 0.125 in. dia. electrode 75 helium, 25 argon, pickled and manually cleaned with Oakite Alkaline Cleanser.	S-1-6	6518	Annealed	0.138	
	T-1-8	6394	Annealed	0.048	
	U-1-9	6790	Annealed	0.163	
	V-1-10	95224	Annealed	0.085	0.108
	S-1-17	6518	Aged	0.031	
	T-1-18	6394	Aged	0.021	
	U-1-19	6790	Aged	0.033	
	V-1-20	95224	Aged	0.066	0.042
2. 11,250 Joules double pass, bend on second pass. 250 amp, 12 volts, 16 ipm 0.125 in. dia. electrode 75 helium, 25 argon, pickled and manually cleaned with Oakite Alkaline Cleanser.	S-2-7	6518	Annealed	0.201	
	T-2-8	6394	Annealed	0.047	
	U-2-9	6790	Annealed	0.126	
	V-2-10	95224	Annealed	0.155	0.132
	T-2-16	6394	Aged	0.061	
	S-2-17	6518	Aged	0.144	
	U-2-19	6790	Aged	0.060	
	V-2-20	95224	Aged	0.084	0.087
3. 13,900 Joules double pass, bend on second pass. 250 amp, 13 volts, 14 ipm 0.125 in. dia. electrode 75 helium, 25 argon, pickled and manually cleaned with Oakite Alkaline Cleanser.	S-3-7	6518	Annealed	0.180	
	T-3-8	6394	Annealed	0.126	
	U-3-9	6790	Annealed	0.173	
	V-3-10	95224	Annealed	0.197	0.169
	U-3-16	6790	Aged	0.173	
	S-3-17	6518	Aged	0.150	
	T-3-18	6394	Aged	0.106	
	V-3-20	95224	Aged	0.167	0.149
4. 15,000 Joules 250 amp, 14 volts, 14 ipm 0.125 in. dia. electrode 75 helium, 25 argon, pickled and manually cleaned with Oakite Alkaline Cleanser.	V-4-6	95224	Annealed	0.206	
	S-4-7	6518	Annealed	0.134	
	T-4-8	6394	Annealed	0.112	
	U-4-9	6790	Annealed	0.132	0.146
	S-4-17	6518	Aged	0.069	
	T-4-18	6394	Aged	0.160	
	U-4-19	6790	Aged	0.050	
	V-4-20	95224	Aged	0.134	0.103

TABLE XXII (Cont.)

TIME-TEMPERATURE RELATIONSHIPS ON VARESTRAINT TESTS

Varestraint Testing to Determine Cracking Sensitivity in the 0.209-Inch Material in Relation to Variations in Energy Input

Time-Temperature Variation Number	Specimen No.	Heat No.	Condition	Total HAZ Crack Length (in.)	Average for 4 Tests (in.)
5. 9,000 Joules Double Bead, bend on second pass. 200 amp, 12 volts, 16 ipm, pickled and manually cleaned with Oakite Alkaline Cleanser	S-5-6	6518	Annealed	0.160	
	T-5-8	6394	Annealed	0.149	
	U-5-9	6790	Annealed	0.150	
	V-5-10	95224	Annealed	0.205	0.166
	S-5-17	6518	Aged	0.080	
	T-5-18	6394	Aged	0.067	
	U-5-19	6790	Aged	0.165	
	V-5-20	95224	Aged	0.068	0.095
6. 11,250 Joules 250 amp, 12 volts, 16 ipm pickled only	S-6-7	6518	Annealed	0.181	
	T-6-8	6394	Annealed	0.121	
	U-6-9	6790	Annealed	0.146	
	V-6-10	95224	Annealed	0.119	0.141
	S-6-17	6518	Aged	0.131	
	T-6-16	6394	Aged	0.095	
	U-6-19	6790	Aged	0.140	
	V-6-20	95224	Aged	0.104	0.117
7. 15,000 Joules 250 amp, 14 volts, 14 ipm, pickled only.	U-7-6	6790	Annealed	0.186	
	S-7-7	6518	Annealed	0.161	
	T-7-8	6394	Annealed	0.142	
	V-7-10	95224	Annealed	0.210	0.177
	U-7-16	6790	Aged	0.115	
	S-7-17	6518	Aged	0.186	
	T-7-18	6394	Aged	0.118	
	V-7-20	95224	Aged	0.098	0.154

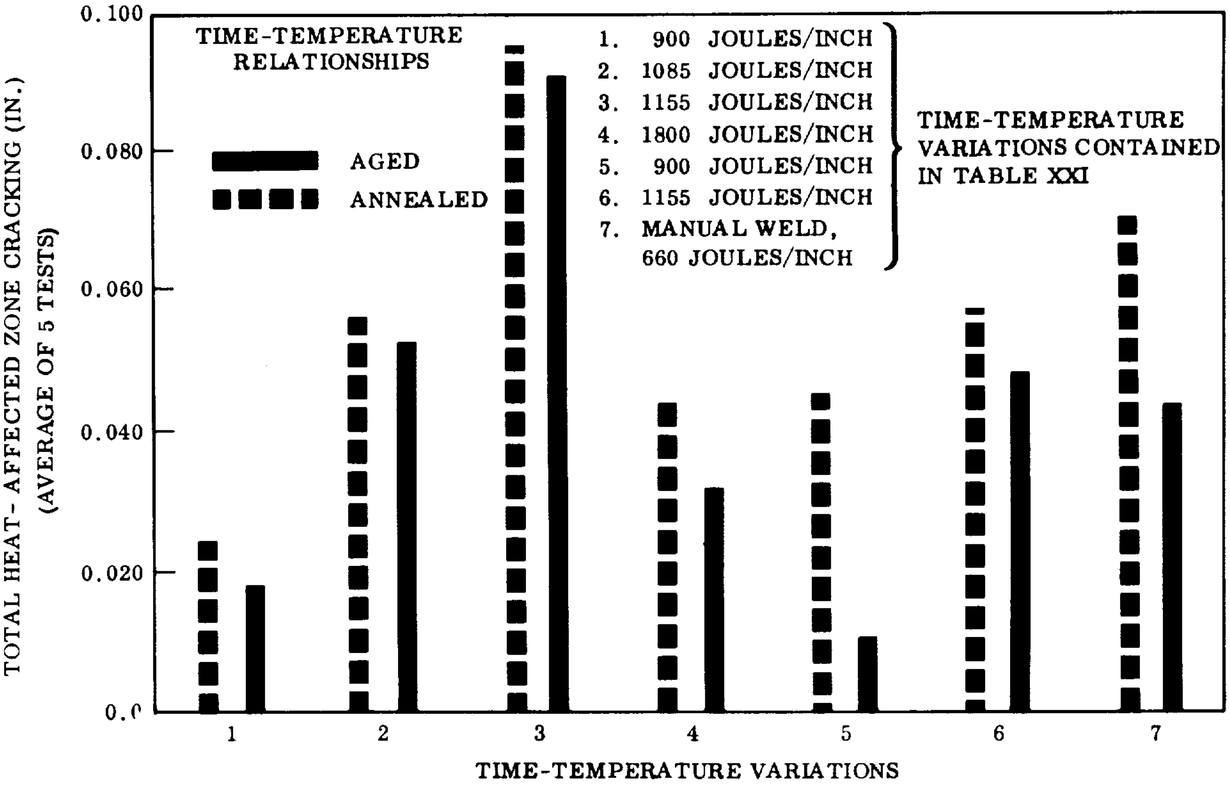


FIGURE 79. VARESTRAINT TESTING TO DETERMINE CRACKING SENSITIVITY OF 0.040-INCH MATERIAL IN RELATION TO VARIATIONS IN ENERGY INPUT

3.8 MICROSTRUCTURE

Specimens with variations in welding parameters were examined with a metallurgical microscope to determine the effects of time-temperature variations on the width of the heat-affected zone, grain size changes in the heat-affected zone, precipitation of microconstituents, porosity, and cracking sensitivity. Specimens of the 0.040-inch material, representative of all seven variations and both conditions (annealed and aged), were examined. Figures 81 and 82 show the typical cracking found in Varestraint specimens welded with variations in energy input. Figure 81 shows the interdendritic cracking pattern in the fusion zone, while Figure 82 shows

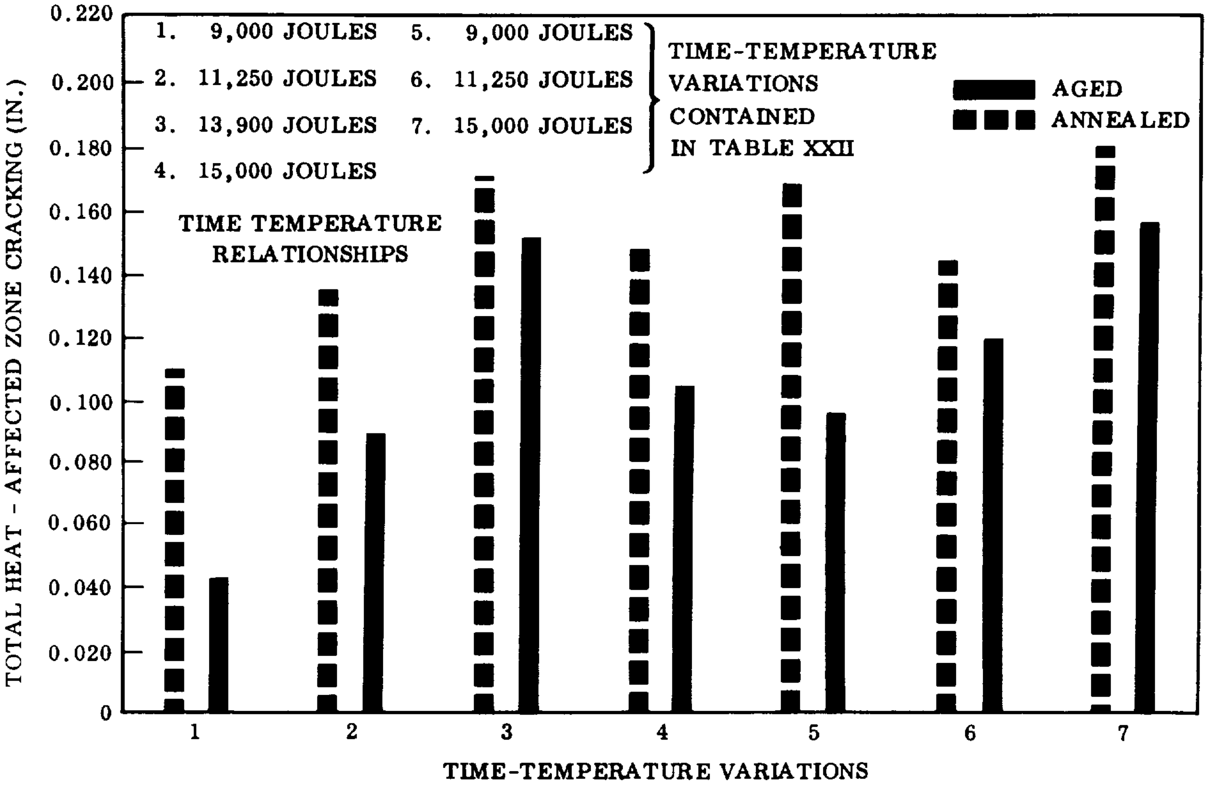


FIGURE 80. VARESTRAINT TESTING TO DETERMINE CRACKING SENSITIVITY OF 0.209-INCH MATERIAL IN RELATION TO VARIATIONS IN ENERGY INPUT

the intergranular cracking pattern in the heat-affected zone. Results of the examination showed that the width of the heat-affected zone does vary with variation in heat energy input. The following tabulation shows that the width of the heat-affected zone varies from 0.0086 to 0.0159 inch from time-temperature variation No. 1 to No. 7. There is also a tendency for slight grain growth to occur in the heat-affected zone. In addition, the welding operation resulted in the disappearance of precipitates and some carbides, and a general cleaning of grain boundaries in the heat-affected zone. No porosity was evident in any of the specimens examined.

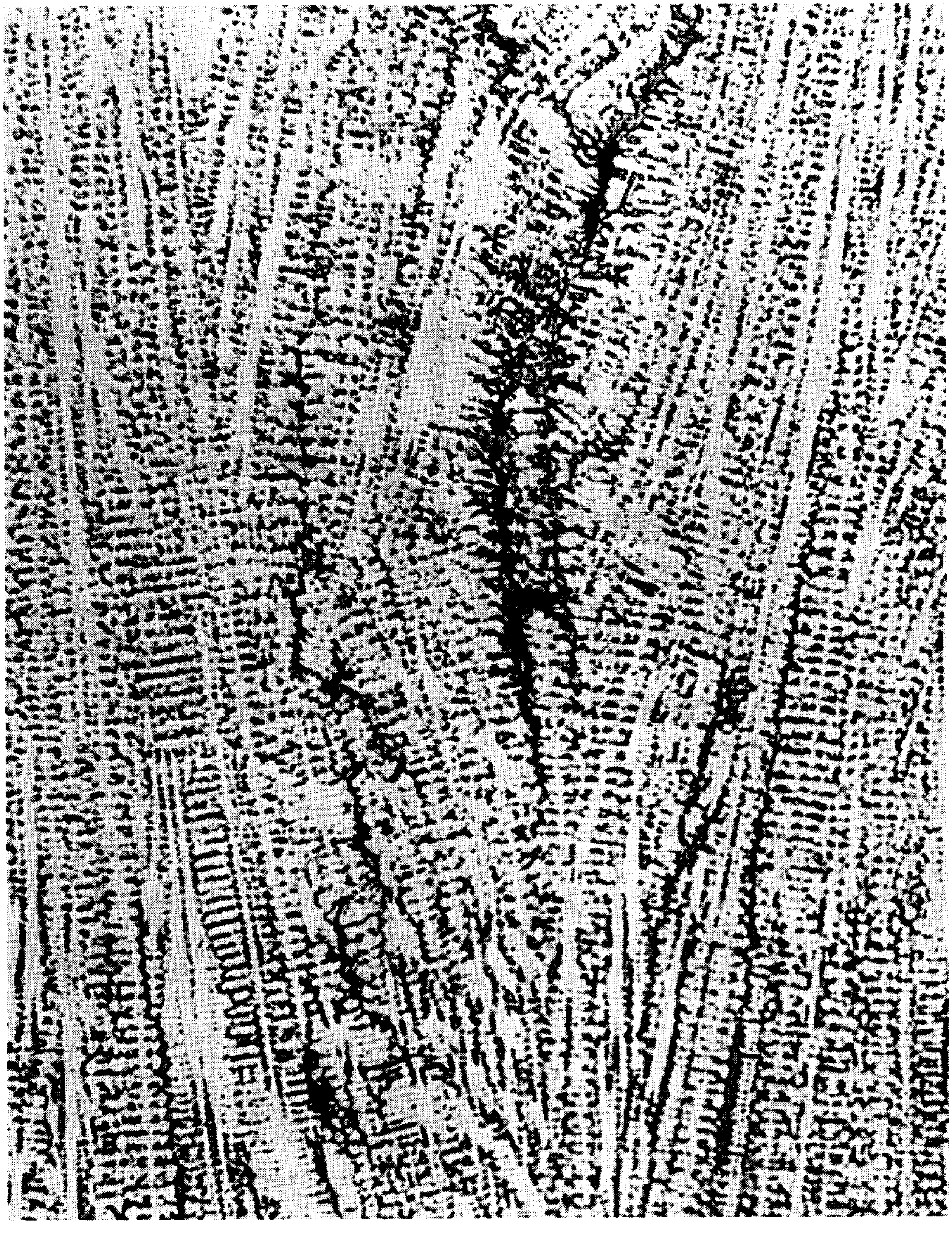


FIGURE 81. INTERDENDRITIC CRACKING IN FUSION ZONE OF 0.209-INCH 718 SPECIMEN

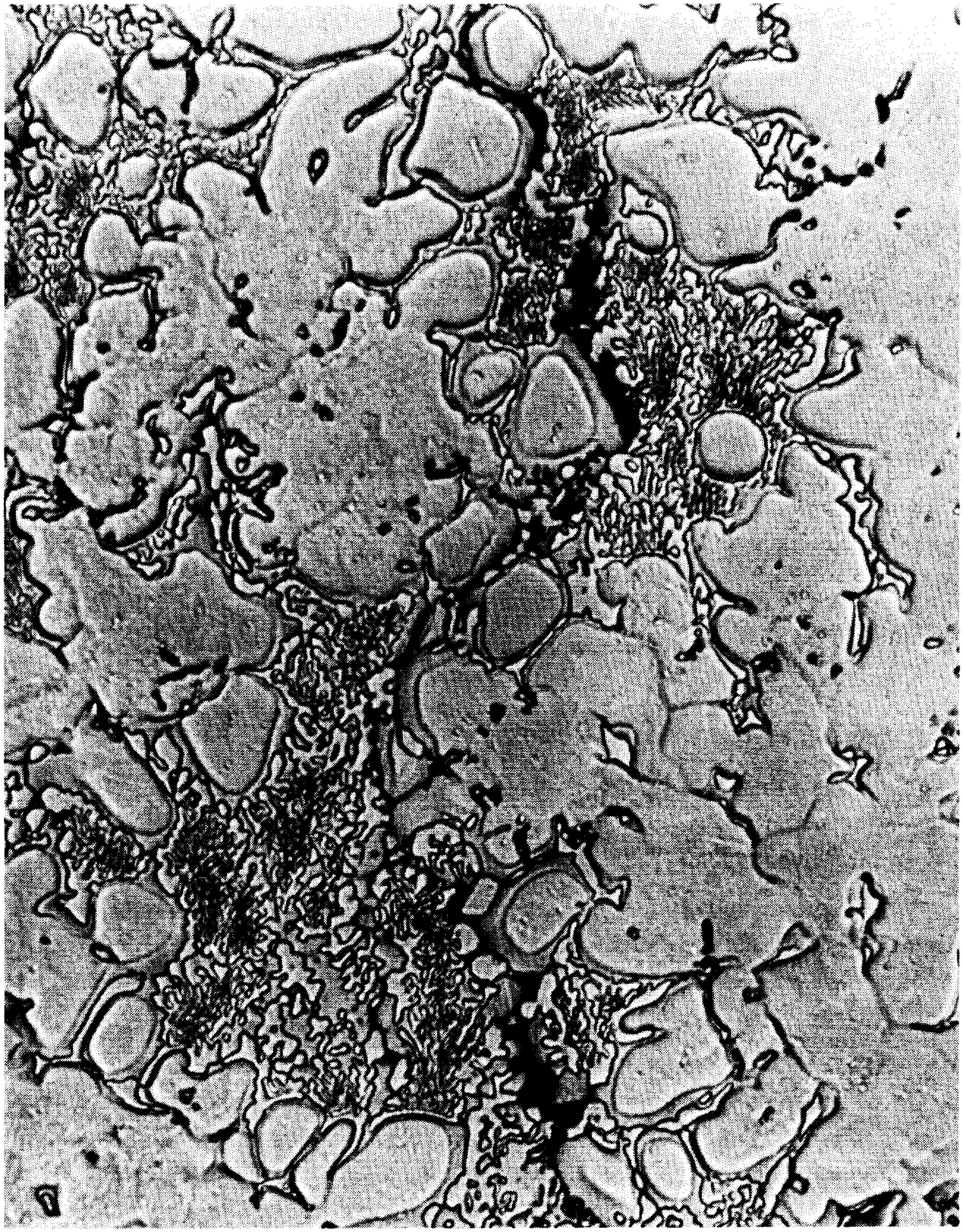


FIGURE 82. LOW MELTING INTERGRANULAR EUTECTIC PHASE IN HEAT-AFFECTED ZONE OF INCONEL 718 SPECIMEN

Time-Temperature Variation and Condition	Width of Heat-Affected Zone (10^{-3} in.)	Grain Size (ASTM)	
		Heat-Affected Zone	Parent Metal
900 Joules/in.			
No. 1 annealed	8.6	5	6
No. 1 aged	9.8	6	6
1085 Joules/in.			
No. 2 annealed	11.0	6	6
No. 2 aged	11.3	6	6
1155 Joules/in.			
No. 3 annealed	12.3	6	6
No. 3 aged	12.1	5	6
1800 Joules/in.			
No. 4 annealed	13.8	5	6
No. 4 aged	13.6	5	6
900 Joules/in.			
No. 5 annealed	9.6	6	6
No. 5 aged	10.7	5	6
1155 Joules/in.			
No. 6 annealed	10.5	6	6
No. 6 aged	10 6	5	6
Manual Weld			
No. 7 annealed	14.9	5	6
No. 7 aged	15.9	5	6

3.9 TENSILE TESTS

Mechanical test data on the 0.040- and 0.209-inch specimens with the weld parallel to the tensile axis which had been subjected to variations in energy input is shown in Tables XXIII and XXIV.

Test results indicate that variations in energy input or surface preparation techniques do not have any particular effect on mechanical properties on specimens welded in the annealed condition. In addition, no particular effect in strength properties was noted on specimens with a double-pass weld.

As expected, welding of specimens in the age-hardened condition resulted in some loss in strength properties. Yield strength values were particularly affected, with values decreasing as the energy input was increased from 900 to 1155 Joules on the 0.040-inch material and 9000 to 13,900 Joules on the 0.209-inch material. There does, however, appear to be a threshold where a higher increase in energy input will result in a slight increase in yield strength values.

TABLE XXIII

EFFECT OF TIME-TEMPERATURE VARIATIONS ON MECHANICAL PROPERTIES OF WELDED 0.040-INCH THICK SPECIMENS

Welded in the Annealed Condition				Welded in the Age-Hardened Condition			
Time-Temperature Variation Number	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches	Heat Number	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches
1. 900 Joules, HNO_3-HF pickle, Oakite cleaned	143.5	77.0	38.5	6300	190.0	152.0	22.5
	132.4	73.2	26.0	6790	189.0	152.0	20.5
	127.0	65.0	43.0	6518	180.0	114.0	24.5
	141.0	74.0	41.5	6394	195.0	160.0	20.0
Average	136.5	72.5	37.5		188.5	147.0	22.0
2. 1085 Joules	143.0	72.3	39.0	6300	192.5	149.0	21.5
	139.0	72.3	38.5	6790	191.5	143.0	21.0
	130.0	66.5	44.5	6518	176.0	111.0	27.0
	140.5	74.0	36.5	6394	192.0	131.0	20.5
Average	138.0	71.5	39.5		188.0	133.5	22.5
3. 1155 Joules	144.5	76.5	40.0	6300	179.0	123.5	26.0
	140.0	72.0	42.0	6790	171.5	125.0	24.0
	131.5	66.6	44.5	6518	172.0	109.0	27.0
	143.0	73.3	40.0	6394	189.0	130.0	22.0
Average	140.0	72.0	41.5		180.5	122.5	24.8
4. 1800 Joules	144.0	75.0	42.0	6300	195.0	141.0	21.0
	139.0	68.5	42.0	6790	195.0	132.0	22.5
	129.5	63.3	46.0	6518	182.0	128.5	26.0
	141.0	75.0	41.0	6394	195.5	124.0	21.0
Average	138.5	70.5	43.0		192.0	131.5	22.5
5. 900 Joules. HNO_3-HF pickle	146.5	77.0	39.0	6300	194.5	132.0	23.5
	139.5	71.5	40.5	6790	192.5		19.0
	131.0	67.0	45.0	6518	183.0	114.0	27.0
	137.5	77.5	31.0	6394	197.0	147.0	20.0
Average	138.5	73.5	39.0		192.0	126.5	22.5
6. 1155 Joules, HNO_3 pickle	147.0	75.6	36.5	6300	190.0	143.0	21.0
	137.0	69.0	43.0	6790	190.5	128.0	22.0
	130.0	65.6	45.5	6518	179.0	129.0	27.5
	144.5	78.5	39.5	6394	195.0	156.0	18.5
Average	139.5	72.0	41.0		188.5	139.0	22.5
7. 660 Joules, Manual weld	148.0	77.5	41.0	6300	190.0	129.0	20.0
	140.0	71.6	41.0	6790	191.0	143.5	16.0
	130.5	66.4	42.5	6518	186.7	127.5	20.0
	143.5	80.2	40.5	6394	194.0	143.0	21.0
Average	140.5	74.0	41.5		190.5	136.0	19.5

TABLE XXIV

EFFECT OF TIME-TEMPERATURE VARIATIONS ON MECHANICAL PROPERTIES OF WELDED 0.209-INCH THICK SPECIMENS

Welded in the Annealed Condition				Welded in the Age-Hardened Condition			
Time-Temperature Variation Number	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches	Heat Number	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches
1. 9000 Joules, HNO_3-HF pickle, Oakite cleaned	126.4	62.4	47.5	6518	174.7	129.8	29.5
	116.7	60.8	52.0	6394	176.1	125.0	26.5
	136.5	70.1	32.5	6790	196.1	159.6	14.5
	125.6	62.9	40.5	95224	180.3	146.5	29.0
Average	126.2	64.0	43.0		181.5	140.0	25.0
2. 11,250 Joules, HNO_3-HF pickle, Oakite cleaned, double pass weld	136.4	68.2	38.5	6518	191.0	157.0	18.0
	122.4	60.6	52.5	6394	171.0	124.0	28.0
	143.2	78.6	41.0	6790	191.2	103.2	12.0
	123.7	66.9	47.0	95224	181.0	156.0	19.0
Average	132.5	68.5	44.5		183.5	135.0	19.0
3. 13,900 Joules, HNO_3-HF pickle, Oakite cleaned, double pass weld	123.0	60.4	43.5	6518	167.0	138.0	20.0
	122.6	60.5	37.0	6394	165.0	124.0	29.5
	131.0	67.5	22.0	6790	174.1	111.7	20.0
	127.0	63.8	37.0	95224	169.4	112.1	22.5
Average	125.5	63.2	35.0		168.5	121.3	23.0
4. 15,000 Joules, HNO_3-HF pickle, Oakite cleaned	125.8	62.9	44.5	6518	169.5	137.0	28.5
	126.2	60.7	42.5	6394	164.5	124.0	32.5
	141.5	70.1	32.0	6790	174.2	98.1	15.0
	124.6	61.8	37.5	95224	171.0	140.5	20.0
Average	129.3	63.8	39.0		169.8	124.8	24.0
5. 9000 Joules, double-pass weld HNO_3-HF pickle, Oakite cleaned	124.4	63.8	46.5	6518	177.0	141.3	29.0
	124.5	61.3	45.5	6394	164.9	132.4	25.0
	142.3	73.9	35.5	6790	195.5	128.3	10.5
	128.8	66.1	46.0	95224	182.6	145.0	24.5
Average	130.0	66.3	43.5		180.0	136.6	22.0
6. 11,250 Joules, HNO_3-HF pickle	133.3	66.0	32.5	6518	193.7	147.9	13.0
	126.0	62.2	48.0	6394	170.2	132.5	31.5
	131.2	57.7	48.0	6790	191.9	161.1	10.0
	126.6	57.8	38.5	95224	179.6	146.6	20.5
Average	129.2	61.0	41.5		183.8	147.0	18.5
7. 15,000 Joules, HNO_3-HF pickle	126.1	61.8	42.5	6518	164.3	138.8	17.0
	125.0	60.0	44.0	6394	161.9	121.2	25.5
	132.1	65.8	33.5	6790	177.1	131.9	16.5
	126.0	63.0	38.5	95224	168.6	130.4	23.5
Average	127.2	62.8	39.5		167.5	130.5	20.5

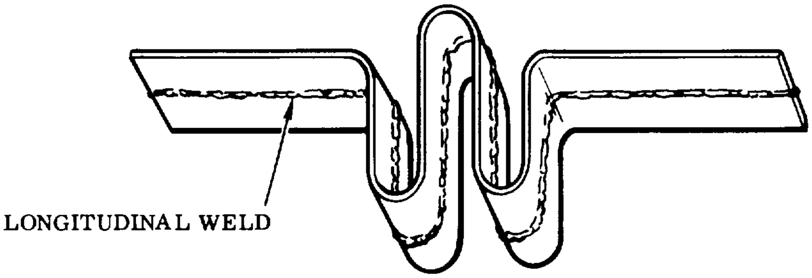


FIGURE 83. SIMULATED CONVOLUTED BELLOWS SPECIMEN

Strength values on the 0.209-inch age-hardened and welded specimens showed considerable scatter with variations in energy input. Yield strength values ranged from a low of 98,000 psi at 15,000 Joules input to 161,000 psi at 11,250 Joules input. Tensile values ranged from 161,900 psi at 15,000 Joules to 196,100 psi at 9000 Joules input.

Mechanical properties on the 0.040-inch age-hardened and welded specimens also showed considerable scatter. Yield strength values ranged from 109,000 psi at 1155 Joules to 152,000 psi at 900 Joules. Tensile strength values ranged from 172,000 psi at 1155 Joules to a high of 197,000 psi at 900 Joules input.

3.10 FATIGUE TESTS

Testing was conducted to determine the effects which occur from various welding and processing parameters on the cycle life of simulated bellows specimens. These tests were made for the purpose of determining if improved cycle life could be realized by close control of welding variables. It would have been more desirable to fabricate a limited number of bellows with variations in welding parameters and subject these bellows to axial fatigue tests. However, because so many factors exist which can contribute to premature fatigue failure in the longitudinal weld of a bellows, it would be too costly and time consuming to test actual bellows. Consequently, Solar designed a convoluted fatigue specimen which represents most of the conditions likely to occur in the longitudinal weld of a bellows. Figure 83 shows a sketch of the specimen used at Solar. Because of the simplicity of the test specimen, numerous test specimens were fabricated and tested with processing and welding variations at a relatively small cost. Results of the fatigue tests are shown in Tables XXV through XXIX.

TABLE XXV

AXIAL FATIGUE TESTS ON SIMULATED BELLOWS TEST SPECIMENS

Preliminary Data on Control Specimens to Determine the Effect of Specimen Preparation

Specimen Number	Cycles/Second	Amplitude (in.)	Surface Preparation	Cycles to Failure
1	10	0.120	None	16,569
2	10	0.120	Polished	13,154
3	10	0.120	Polished	19,307
4	10	0.120	None	21,500
5	10	0.120	Polished	22,496
6	10	0.120	Polished	11,670
7	10	0.120	Polished	17,428
8	10	0.120	None	15,367
9	10	0.120	None	19,734
10	10	0.120	None	19,242
11	10	0.120	Filed edges, sand blasted and vapor blasted surface	12,174
12	10	0.120	Filed edges, sand blasted and vapor blasted surface	19,844
13	10	0.120	Filed edges, sand blasted and vapor blasted surface	14,267
14	10	0.120	Filed edges, sand blasted and vapor blasted surface	19,526
15	10	0.120	Filed edges, sand blasted and vapor blasted surface	15,918
16	10	0.120	Beveled tip of edges	16,500
17	10	0.120	Beveled tip of edges	18,230
18	1	0.200	Rounded edges	1295
19	1	0.200	Rounded edges	1420
20	1	0.200	Rounded edges	1306
21	2	0.200	Rounded edges	1007
22	2	0.200	Rounded edges	1261
23	2	0.200	Rounded edges	1207
24	10	0.200	Rounded edges	1163
25	10	0.200	Rounded edges	1222
26	0.5	0.200	Rounded edges	1158
27	0.5	0.200	Rounded edges	1262
28	5	0.200	Square edge	1462
29	5	0.200	Square edge	1349
30	5	0.200	Square edge	1362

PROCESSING SEQUENCE: Annealed 1750 F and age hardened in accordance with AMS 5596

TABLE XXVI

AXIAL FATIGUE TESTS ON SIMULATED BELLOWS TEST SPECIMENS

Baseline Data on Parent Metal Specimens

Specimen Number	Cycles/Second	Amplitude (in.)	Cycles to Failure
1B	5	0.200	1402
2B	5	0.200	1381
3B	5	0.200	1408
4B	5	0.200	1390
5B	5	0.200	1383
6B	5	0.200	1482
7B	5	0.200	1359
8B	5	0.200	1365
9B	5	0.200	1397
10B	5	0.200	1433
11B	5	0.200	1427
12B	5	0.200	1362
13B	5	0.200	1349
14B	5	0.200	1462

Average cycles to failure ---1400

PROCESSING SEQUENCE: Annealed 1750 F and age hardened in accordance with AMS 5596

Preliminary test data on control specimens (unwelded) is shown in Table XXV. Variations in specimen preparation as well as testing parameters were made in an effort to obtain consistent results on control specimens. Test results indicated that fairly consistent results were obtainable by reducing the frequency to five cycles/second at 0.200 inch amplitude. To verify these results, fourteen additional control specimens were tested at five cycles/second and at an amplitude of 0.200 inch. Test results, as shown in Table XXVI show that good consistency was obtainable by the use of these testing parameters.

TABLE XXVII

AXIAL FATIGUE DATA ON WELDED SPECIMENS WITH TIME-TEMPERATURE VARIATIONS

Time-Temperature Variation Number	Type of Surface Preparation	Cycles to Failure
1. 2100 Joules	Weld planished - glass bead blasted.	343
2100 Joules	Weld planished - glass bead blasted.	313
2100 Joules	Weld planished - glass bead blasted.	368
	Average	341
2100 Joules	Weld not planished - glass bead blasted.	843
2100 Joules	Weld not planished - glass bead blasted.	832
2100 Joules	Weld not planished - glass bead blasted.	867
2100 Joules	Weld not planished - glass bead blasted.	792
2100 Joules	Weld not planished - glass bead blasted.	754
2100 Joules	Weld not planished - glass bead blasted.	786
	Average	812
2. 1917 Joules	Cleaned with Oakite Cleanser prior to welding. Weld planished - glass bead blasted.	390
1917 Joules	Cleaned with Oakite Cleanser prior to welding. Weld planished - glass bead blasted.	402
1917 Joules	Cleaned with Oakite Cleanser prior to welding. Weld planished - glass bead blasted.	396
	Average	396
1917 Joules	Weld not planished - glass bead blasted.	744
1917 Joules	Weld not planished - glass bead blasted.	699
1917 Joules	Weld not planished - glass bead blasted.	660
1917 Joules	Weld not planished - glass bead blasted.	639
1917 Joules	Weld not planished - glass bead blasted.	663
1917 Joules	Weld not planished - glass bead blasted.	591
	Average	666
3. 1917 Joules	Acid pickle prior to welding. Weld planished	395
1917 Joules	Acid pickle prior to welding. Weld planished	432
1917 Joules	Acid pickle prior to welding. Weld planished	324
	Average	383
1917 Joules	Weld not planished.	654
1917 Joules	Weld not planished.	654
1917 Joules	Weld not planished.	725
1917 Joules	Weld not planished.	589
1917 Joules	Weld not planished.	672
1917 Joules	Weld not planished.	692
	Average	664
Testing Parameters:	5 cycles/second, amplitude ± 0.200 inch	

TABLE XXVII (Cont.)

AXIAL FATIGUE DATA ON WELDED SPECIMENS WITH TIME-TEMPERATURE VARIATIONS

Time-Temperature Variation Number	Type of Surface Preparation	Cycles to Failure
4. 3120 Joules	Weld planished - glass bead blasted.	560
3120 Joules	Weld planished - glass bead blasted.	584
3120 Joules	Weld planished - glass bead blasted.	625
	Average	589
3120 Joules	As welded - glass bead blasted.	980
3120 Joules	As welded - glass bead blasted.	953
3120 Joules	As welded - glass bead blasted.	983
3120 Joules	As welded - glass bead blasted.	1,052
3120 Joules	As welded - glass bead blasted.	903
3120 Joules	As welded - glass bead blasted.	936
	Average	969
5. 2250 Joules	Weld planished - glass bead blasted.	372
2250 Joules	Weld planished - glass bead blasted.	325
2250 Joules	Weld planished - glass bead blasted.	273
	Average	323
2250 Joules	As welded - glass bead blasted.	769
2250 Joules	As welded - glass bead blasted.	745
2250 Joules	As welded - glass bead blasted.	770
2250 Joules	As welded - glass bead blasted.	754
2250 Joules	As welded - glass bead blasted.	754
2250 Joules	As welded - glass bead blasted.	718
	Average	751
6. 2550 Joules	Weld planished - glass bead blasted.	527
2550 Joules	Weld planished - glass bead blasted.	479
2550 Joules	Weld planished - glass bead blasted	502
	Average	502
2550 Joules	As welded - glass bead blasted.	839
2550 Joules	As welded - glass bead blasted.	866
2550 Joules	As welded - glass bead blasted.	816
2550 Joules	As welded - glass bead blasted.	854
2550 Joules	As welded - glass bead blasted.	901
2550 Joules	As welded - glass bead blasted.	892
	Average	861

NOTES: Type of joint - Bead on Plate, 5 cycles/second, amplitude ± 0.200 inch

Processing Sequence:

- Annealed 1750 F
- Welded
- Planished as indicated

- Annealed 1750 F
- Aged in accordance with AMS 5596
- Glass bead blasted
- Tested

TABLE XXVIII

EFFECT OF TIME-TEMPERATURE VARIATIONS USED FOR SIMULATED BELLOWS SPECIMENS ON MECHANICAL PROPERTIES OF WELDED SPECIMENS

Time-Temperature Variation Number	F_{tu} (ksi)	F_{ty} (ksi)	% Elongation in 2 inches
1. 2100 Joules	209.5	186.0	23.0
	210.0	180.0	24.0
2. 1917 Joules HNO_3 pickle	210.0	183.0	26.0
	210.0	184.0	24.0
3. 1917 Joules HNO_3 pickle Oakite cleaned	210.0	186.5	27.5
	210.0	183.5	27.0
4. 3120 Joules	207.0	181.5	19.0
	207.5	171.5	19.0
5. 2250 Joules	210.0	183.5	24.0
	209.5	182.5	24.0
6. 2550 Joules	209.0	180.5	22.0
	208.5	178.5	22.0
Processing Sequence:	• Annealed 1750 F • Welded • Annealed 1750 F • Aged in accordance with AMS 5596 • Tested		

Once the testing parameters were established, simulated convoluted specimens with six controlled time-temperature variations were axially fatigue tested. Test results are shown in Table XXVII. The fatigue test results do not clearly indicate an improved cycle life due to surface treatment, i.e., glass bead blasted surface versus acid pickled surface. However, fatigue life does increase as the heat input is increased from 1917 Joules/inch to 3120 Joules/inch.

Because of the low fatigue properties exhibited by specimens which had been planished after welding, it was decided that the annealing treatment used (1750 F for 5 minutes) was inadequate. Consequently, additional specimens with planished welds

TABLE XXIX

EFFECT OF ANNEALING CYCLES ON FATIGUE LIFE OF AGE HARDENED SPECIMENS WITH PLANISHED WELDS

Annealing Cycle	Cycles/Second	Amplitude (in.)		Cycles to Failure
1750 F 0.5 hour	5	0.200		416
1750 F 0.5 hour	5	0.200		371
1750 F 0.5 hour	5	0.200		382
1750 F 0.5 hour	5	0.200		451
			Average	450
1850 F 0.5 hour	5	0.200		1209
1850 F 0.5 hour	5	0.200		1212
1850 F 0.5 hour	5	0.200		1178
1850 F 0.5 hour	5	0.200		1198
			Average	1199
1950 F 0.5 hour	5	0.200		1043
1950 F 0.5 hour	5	0.200		954
1950 F 0.5 hour	5	0.200		915
			Average	970

Processing Sequence:

- Annealed 1750 F
- Welded
- Weld planished
- Annealed as indicated
- Aged in accordance with AMS 5596 with exception of 1950 F annealed specimens. 1950 F annealed specimens were double aged, i.e., 1400 F followed by 1200 F cycle.
- Tested.

were subjected to an annealing cycle of 30 minutes duration at 1750, 1850, and 1950 F. Specimens were subsequently double aged as indicated in Table XXIX and axially fatigue tested to failure.

Test data shown in Table XXIX indicate that an 1850 F anneal results in a substantial increase in fatigue life over the 1750 F annealed specimens. In addition, a 20 percent increase in fatigue life is realized by the use of an 1850 F anneal over a 1950 F anneal cycle.

4

CONCLUSIONS

- Variations in aluminum-titanium ratios within Solar's Inconel 718 material specification range did not appear to affect Varestraint crack susceptibility of the heats evaluated in this program.
- Increasing the thickness from 0.040 to 0.125 and/or 0.209 inch increases the Inconel 718 alloy's sensitivity to heat-affected zone cracking.
- It was established that the heat-affected zone cracking susceptibility of the Inconel 718 alloy is increased as the annealing temperature is raised from 1750 to 1950 F. Electron microscopy study revealed the presence of a denuded zone along the grain boundaries of material annealed at 1950 F and double aged. This denuded effect was not seen in specimens annealed at a lower temperature and double aged.
- The increased cracking susceptibility of one supplier's material over another was attributed to increased amounts of grain boundary segregation, particularly in areas of TiCb(C, N) particles interdespersed with some Laves phase aligned in the direction of rolling.
- Variations in welding parameters indicated that an increase in heat energy input resulted in an increase in heat-affected zone cracking susceptibility. However, axial fatigue tests of simulated bellows specimens indicated that increasing the heat energy input increased rather than decreased the fatigue life of simulated convoluted specimens.
- Significant structural changes occur in the heat-affected zone of Varestraint specimens. In addition to cracking, structures indicating the presence of a formerly liquid phase are present.
- Electron microprobe analysis has indicated that an increased amount of grain boundary segregation, high in sulfur content, takes place at grain boundary eutectic melting sites.
- Abbreviated aging cycles of only one to two hours duration result in high mechanical properties. In addition, introduction of 20 percent cold work will result in yield strengths above the 200 ksi level.
- The Pratt & Whitney thermal cycle in accordance with AMS 5596 was selected as the optimum thermal treatment for ducting application, because it apparently provides the best combination of weldability and strength properties. However, increased fatigue life of bellows may be obtained by interstage annealing at 1850 F after weld planishing and prior to aging.

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APPENDIX A

PRIMARY FABRICATION INFORMATION

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Huntington Produced Material (air melted, vacuum arc remelted)

Heats 6790E, 6394E, and 6518E (0.040-inch material)

1. Air melt and cast a 14-inch by 14-inch by 3300-pound ingot
2. Forge to 9.25-inch diameter
3. Rough grind
4. Vacuum-arc remelt to 12-inch diameter
5. Forge to 7 inches by 12 inches
6. Rough grind
7. Forge to 3 inches by 11 inches
8. Hot roll to approximately 0.290 inch
9. Anneal and pickle
10. Cold roll to 0.250 inch
11. Anneal at 1950 F and pickle
12. Roller level
13. Shear to 0.250 inch by 36 inches by 96 inches
14. Hot roll to approximately 0.050 inch
15. Cold roll to 0.040 inch
16. Shear to size

Heat 6300E (0.040 inch material)

1. Same as Heats 6790E, 6394E, and 6518E to Step No. 7
2. Hot roll to 0.185 inch
3. Anneal and pickle
4. Cold roll to 0.156 inch
5. Anneal at 1950 F and pickle
6. Roller level
7. Shear to 0.156 inch by 35 inches by 96 inches
8. Hot roll at approximately 0.050 inch

Heat 6300E (0.040 inch material) (Cont)

9. Cold roll to 0.040 inch
10. Shear to size

Heats 6790E, 6394E and 6518E (0.209-inch material)

1. Same as 0.040-inch material to Step No. 13
2. Cold roll to 0.209 inch by 36 inches by length
3. Shear to 0.209 inch by 34 inches by 96 inches

Eastern Furnished Material (double vacuum melted)

Heat 95221 (0.040-inch material)

1. Vacuum induction melted into a 10-inch diameter, 2300-pound ingot
2. Ground all over
3. Vacuum-arc remelted into a 12-inch diameter ingot
4. Ground all over
5. Hot rolled to 2 inches by 12 inches
6. Ground all over
7. Hot rolled to 0.350 inch
8. Sheared and spot ground
9. Hot roll to 0.055 inch
10. Sheared, annealed at 1950 F, pickled, and spot ground
11. Cold rolled to 0.040 to 0.044 inch
12. Degreased and sheared to size

The processing schedule for the 0.209-inch material, Heat 95224 is:

1. Vacuum induction melted into a 10-inch diameter, 2300-pound ingot
2. Ground all over
3. Vacuum-arc remelted into a 12-inch diameter ingot
4. Ground all over
5. Hot roll to 2 inches by 12 inches
6. Plasma cut to length
7. Ground all over
8. Hot rolled to 0.350 inch
9. Sheared and spot ground
10. Hot rolled to 0.263 inch

The processing schedule for the 0.209-inch material, Heat 95224 is: (Cont)

11. Annealed at 1950 F, pickled, spot ground
12. Cold rolled to 0.209 inch
13. Degreased and sheared to size

Firth Sterling Furnished Sample Material (Vacuum induction melted, remelted by the Hopkins Consumable Process)

Heat D-562 (Old Heat)

1. Hopkins melted into 11-inch diameter ingot
2. Forged to sheet bar 2 inches by 12 inches by 40 inches
3. Shipped to Eastern Stainless Steel Corporation.
4. Hot cross rolled to 0.375-inch plate
5. Cold rolled to 0.250 inch and annealed at 1800 F.

Heat A-786 (New Processing Procedure)

3 pieces - 0.25 inch by 4.125 inches by 28.0 inches

1 piece - 0.125 inch by 4.25 inches by 41.0 inches

1. Both items were out of a 11-inch by 20-inch slag ingot
2. Slab ingot was converted to 12-inch square.
3. A section of the 12-inch square was cross cogged to 0.75 inch by 4.0 inches
4. The 0.75-inch by 4.0-inch section was cogged to 0.488-inch and the 0.125-inch sample to 0.343 inch.
5. Conditioned
6. Hot rolled to 0.265 and 0.145 inch, respectively
7. Annealed and pickled
8. Cold rolled to final size

Armco Furnished Sample Material (double vacuum melted)

0.040- and 0.125-inch thick samples

1. Vacuum induction melt 17-inch diameter electrode
2. Vacuum arc remelt 20-inch diameter ingot
3. Press forge to 4-inch slab
4. Hot roll to 0.75-inch sheet bar
5. Cross roll to 0.060 inch/0.065 inch
6. Anneal 1950 F.

0.040- and 0.125-inch thick samples (Cont)

7. Cold roll to gage - two stage
8. Final anneal 1750 F
9. Flatten

The processing of the 0.125-inch thick strip is identical through Step 4.

5a. Cross roll to 0.150 inch in mill
6a. Anneal at 1950 F
7a. Cold roll to final gage 0.125 inch
8a. Final anneal in laboratory

APPENDIX B

RECOMMENDED THERMAL TREATMENTS FOR INCONEL 718 ALLOY USED IN BELLOWS AND GIMBAL STRUCTURES

APPENDIX B

RECOMMENDED THERMAL TREATMENTS FOR INCONEL 718 ALLOY USED IN BELLOWS AND GIMBAL STRUCTURES

PROCEDURES AND OPERATIONS

Heating

Rate of heating shall be suitably controlled to prevent injury to the parts.

Annealing

The Inconel 718 alloy should be annealed by heating to 1750 F ± 25 degrees F in a suitable protective atmosphere, holding at heat for not more than 30 minutes and cooled at a rate to produce the desired structure and mechanical properties.

Alternate Annealing Cycle

For bellows application, particularly after planishing of the weld prior to age hardening -- heat to 1850 F ± 25 degrees F hold at temperature for 0.5 hour or equivalent. Cool at a rate to produce the desired structure and mechanical properties.

Age Hardening

The Inconel 718 alloy should be hardened as follows: heat to 1325 ± 15 degrees F, hold at 1325 F for 8 hours, furnace cool 100 F/hour to 1150 F, hold at 1150 F ± 15 degrees F for 8 hours, and air cool.

As alternate procedures:

(a) Aging may be performed by heating to 1325 ± 15 degrees F, hold at heat for 8 hours, furnace cool to 1150 ± 15 degrees F, hold at 1150 F until a total aging time of 18 hours has been obtained, and air cool.

For many applications, an abbreviated aging cycle is recommended for time saving and economic reasons. The following abbreviated aging cycle resulted in comparable strength and weldability characteristics to thermal cycle in accordance with AMS 5596.

(b) Aging may be performed by heating to 1325 F ± 15 degrees F, hold at heat 4 hours, furnace cool to 1150 ± 15 degrees F, hold at 1150 F for 4 hours, and air cool.