NASA R-ME-IV-S-4

ESTABLISHMENT OF AN OPTIMUM HEAT TREATMENT FOR USE IN 718 ALLOY BELLOWS AND GIMBAL STRUCTURES

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SOLAR, A DIVISION OF INTERNATIONAL HARVESTER COMPANY
San Diego, California

Marshall Space Flight Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This report was prepared in the Research Laboratories of Solar, a Division of International Harvester Company, under Contract NAS 8-11282, Task Order R-ME-IV-S-4. The work is administered under the direction of the National Aeronautics and Space Administration, Manufacturing Engineering Laboratory, Huntsville, Alabama, with C. N. Irvine acting as Technical Supervisor.

This report covers work conducted from 1 August 1965 through 28 February 1966.

Personnel contributing to the Program and the compilation of this report are P. J. Valdez, Project Engineer; D. Jones, Mechanical Testing; and C. P. Davis, Welding. The Solar report number is RDR 1460.

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ILLUSTRATIONS

SECTION I

INTRODUCTION

This semi-annual report summarizes the work accomplished under Contract NAS 8-11282, Task Order R-ME-IV-S-4, Establishment of an Optimum Heat Treatment of the 718 Alloy for use in Bellows and Gimbal Structures. The report covers the work period from 1 August 1965 through 28 February 1966.

The objective of the program is to develop additional knowledge of the effects of thermal treatments on the 718 alloy and the relation of subsequent fabrication processes to the thermal treatments.

Microfissuring has constituted a problem in welding age-hardened 718 alloy components for the Saturn V Program. Although the mechanism of microcracking of the age-hardened 718 alloy is not adequately understood, it appears that both mechanical and metallurgical factors are involved. In an effort to get a better understanding of the mechanism involved in microcracking of the 718 alloy, a new test called the Varestraint Test is being used in this evaluation. This test is reported to provide a means to quantatively evaluate the hot cracking tendencies of metals and alloys.

In the initial phase of the study, the Varestraint Testing Apparatus was fabricated. It was designed to study the hot-cracking tendency of fusion welds in thin gage (0.040 inch) as well as thicker sections (up to 0.300 inch) of the 718 alloy. Evaluation of the Varestraint Testing Apparatus as to operation and performance has been completed.

The determination of cracking tendencies of the 718 alloy relative to variations in thermal treatments is currently in progress. Difficulty in obtaining material to our restrictive chemical composition has delayed the over-all program. Initial test results on available 0.040-inch material have demonstrated the versatility and potential of the Varestraint Test in evaluating the cracking susceptibility of the 718 alloy in regard to controlled variations, such as welding speed, and prior heat treatment.

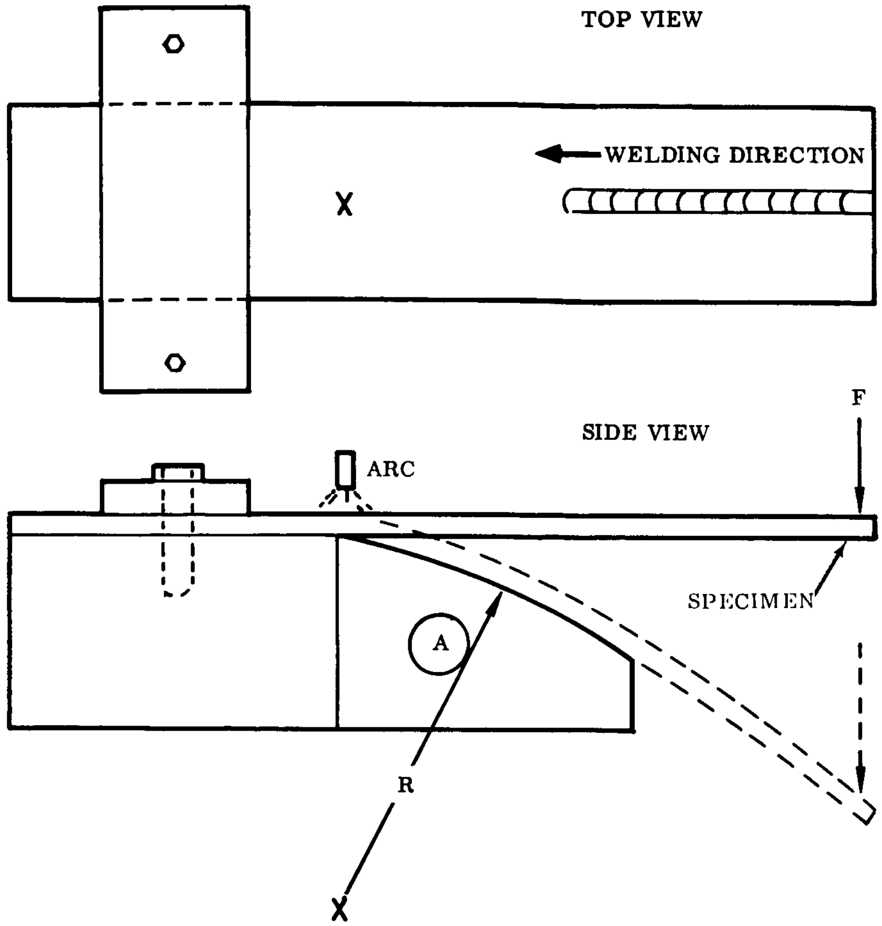


FIGURE 1. OPERATION OF THE VARESTRAINT TEST

1.1 PHASE I - STUDY

1.1.1 Varestraint Test Apparatus

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

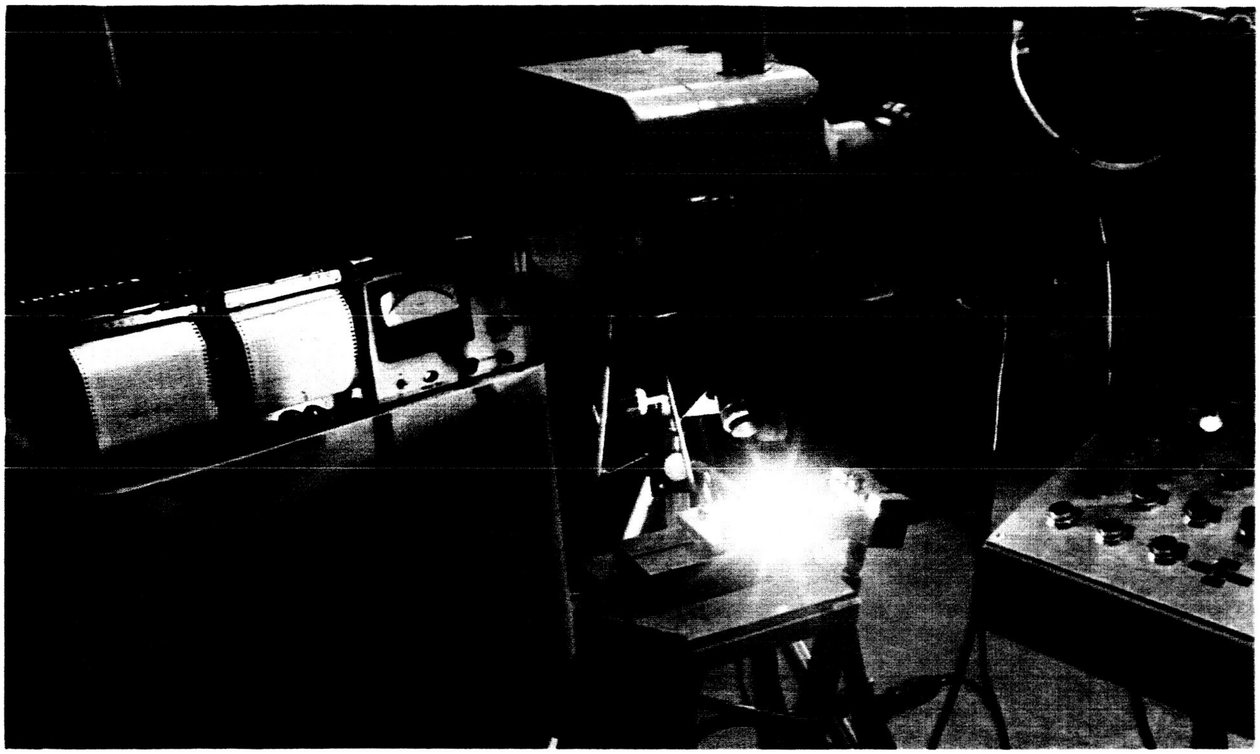


FIGURE 2. OVERALL VIEW OF VARESTRAINT TESTING AND RECORDING EQUIPMENT

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.

Analysis of the extent of cracking attached to welding and/or processing parameters shows the quantitative relationship between restraint and cracking. In addition, by noting the location and extent of microcracks in the heat-affected zone in relation to the weld at the instant of loading, the range of temperatures where micro-cracking occurs can be determined. In this program, the total combined crack length of heat-affected-zone cracks, as determined with a metallurgical microscope on the as-welded surface will provide the quantitative index of base metal cracking sensitivity for a given thermal treatment and a given augmented strain.

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

- Purge gas flows to torch
- Initiation of high-frequency arc start
- Arc is established - automatic voltage control is in effect
- High frequency is turned off

- Voltage and amperage recorders are started
- 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 is de-energized

The Varestraint Testing Apparatus is designed so that only minor adjustments are necessary to weld and bend materials of varying thicknesses.

Welding parameters used on the 0.040-inch 718 material are:

- Electrode - 2 percent thoriated tungsten ground to point
- No. 6 Ceramic gas cup - 3/8 inch diameter
- Helium-Argon gas mixture - 1:1 ratio
- Weld Travel Speed - 8.5 inches/minute
- Voltage - 10
- Amperage - 20
- Radius of Guide Block - 1 inch
- Augmented Strain - 2 percent

1.1.2 Materials

The 718 material to be evaluated in this program consists of 0.040-inch thick and 0.209-inch thick material. Five heats of the 718 alloy with specified restricted chemical composition were ordered. The chemical variations to be studied are within the broad range of various specifications covering the alloy (Ref. 2).

The bulk of the material for this evaluation is being produced by Huntington Alloy Products. In addition, Eastern Stainless Steel is supplying two heats for evaluation. Material is being supplied in the cold-rolled and pickled condition with Solar performing the required high-temperature anneals.

Table I shows the target composition range of the aluminum and titanium content as well as the reported analysis of heats supplied or scheduled to be supplied. Table II shows the reported chemical composition of the heats supplied to date. Since most producers tend to melt to a particular aluminum-titanium ratio, Solar's restrictive requirements on these two elements caused considerable difficulty in acquiring materials for evaluation. Of particular difficulty was the acquisition of a heat with the high-aluminum, low-titanium range; however, Huntington Alloy Products has agreed to supply a small laboratory yield for preliminary evaluation.

TABLE I

718 MATERIALS FOR EVALUATION

Target Composition		Reported Composition and Supplier				
Composition	Percent	Aluminum (%)	Titanium (%)	Heat Number	Gage (in.)	Supplier
Low aluminum Low titanium	0.20 to 0.40 0.65 to 0.80	0.41	0.88	6790	0.040 and 0.209	Huntington
Low aluminum High titanium	0.20 to 0.40 1.00 to 1.20	0.46	1.15	6394	0.040 and 0.209	Huntington
High aluminum High titanium	0.65 to 0.80 1.00 to 1.20	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 aluminum Low titanium	0.65 to 0.80 0.65 to 0.80	Special laboratory yield to be supplied by Huntington Alloy Products				
Average aluminum Average titanium	0.55 to 0.65 0.80 to 0.95	0.60	0.92	6518	0.040 and 0.209	Huntington

TABLE II

REPORTED CHEMICAL COMPOSITION

Heat Number	C	Mn	S	Si	Cr	Ni	Cu	Ti	Al	Cb+Ta	Mo	B	Co	Fe
6300E	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	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	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	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

Primary fabrication information from Huntington Alloy Products shows that the 718 material is air melted, hot forged, then vacuum-arc remelted. Whereas, material supplied by Eastern is vacuum induction melted, followed by vacuum-arc remelting. Complete primary processing of the materials acquired to date is as follows:

<u>Huntington Produced Material</u>

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 9-1/4-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 36 inches by 96 inches
8. Hot roll to approximately 0.050 inch
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

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

TABLE III

ROOM TEMPERATURE MECHANICAL PROPERTIES VERSUS VARIATION IN HEAT TREATING CYCLES

Heat Number	Tensile Strength	Yield Strength	Percent Elongation in 2 Inches
A. As received			
6300	171.5	145.0	11.0
6790	160.6	141.2	15.0
6394	158.5	140.0	18.0
6518	146.4	126.2	19.0
B. As received - Aged 1325 F 4 hours, furnace cooled to 1150 F, hold at 1150 F for 4 hours			
6300	235.6	226.0	5.0
6790	219.4	204.3	10.0
6394	227.1	217.1	7.5
6518	211.0	196.7	9.0
C. 1750 F 5 minutes, 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			
6300	212.5	179.0	16.5
6790	207.5	174.0	18.5
6394	211.0	185.5	18.0
6518	194.5	161.5	25.0
D. 1800 F 5 minutes, 1325 F 4 hours, furnace cool to 1150 F, hold for 4 hours			
6300	211.0	177.0	20.0
6790	193.0	158.5	17.5
6394	196.0	164.5	13.5
6518	190.0	155.5	22.0
E. 1850 F 5 minutes, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours			
6300	208.5	177.0	16.0
6790	202.5	172.5	18.5
6394	207.0	182.0	15.0
6518	190.5	157.0	21.5
F. 1900 F 5 minutes, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours			
6300	208.0	177.0	19.0
6790	204.0	175.0	20.0
6394	205.5	182.0	18.0
6518	188.5	156.0	22.5
G. 1950 F 5 minutes, 1400 F 10 hours, furnace cool to 1200 F, hold at 1200 F so that total aging time is 20 hours			
6300	202.5	162.0	21.0
6790	187.5	144.0	20.0
6394	198.5	162.5	20.0
6518	182.5	138.0	22.5

1.2 TEST RESULTS AND DISCUSSION

1.2.1 Variations in Thermal Treatments

Inconel 718 is being used in Saturn V hardware and will be used for many aerospace applications where joining in the aged condition may be necessary. As a result weld cracking has occurred, particularly in welding heavy sections or thin sections to heavy sections under high restraint. Because the principal hardening phase of the 718 alloy differs from other superalloys, precipitation behavior during heat treatment will also differ. Information concerning the effect of abbreviated aging treatments after variations in annealing treatments on the precipitate morphology and its effect on weldability is not presently available. During the present program, evaluation will be made of the most commonly used thermal treatments as baseline, and tests will be conducted to compare several abbreviated thermal cycles with respect to mechanical properties, microstructure, and weldability. The following thermal treatments will be used to generate baseline weld cracking susceptibility and strength data:

Solution Anneal	Aging Cycle
1750 F	1325 F 8 hours, furnace cool 100 degrees F/hour to 1150 F, 1150 F 8 hours
1800 F	1325 F 4 hours, furnace cool to 1150 F, 1150 F 4 hours
1800 F	1325 F 8 hours, furnace cool to 1150 F, 1150 F 8 hours
1900 F	1325 F 8 hours, furnace cool to 1150 F, 1150 F 8 hours
1950 F	1400 F 10 hours, furnace cool to 1200 F, 1200 F 10 hours

Room temperature mechanical properties of baseline strength data are shown in Table III.

Although Table III shows that aging response varies from heat to heat, it is felt that this difference in properties may be the result of variations in final processing as well as chemistry effects. Although all four heats were reportedly hot rolled to 0.050 inch and then cold rolled to 0.040 inch, these figures are only approximate. Test results indicate that Heat 6300E received more cold work than 6790E; 6790E received more cold work than 6394E; and 6394E received more cold work than 6518E. This variation in cold work can thus partially account for the difference in mechanical properties. In addition, a personal communication (Ref. 3) from Huntington Alloy Products indicates that the titanium/aluminum ratio has a significant effect on the aged properties of the 718 alloy. The greater the titanium/aluminum ratio, the greater the strength. Although the columbium plus tantalum is acknowledged as a factor, it was felt by Huntington that it is of secondary consideration in this case.

Noted below is a summation of the titanium/aluminum ratio on the four heats available for evaluation.

Heat Number	Titanium (%)	Aluminum (%)	Ti/Al Ratio	Cb+Ta (%)	0.2 Percent Yield Strength(1) (ksi)	Tensile Strength (ksi)	Percent Elongation
6394E	1.15	0.46	2.50	5.63	164.5	196.0	13.5
6790E	0.88	0.41	2.15	4.91	158.5	193.0	17.5
6518E	0.82	0.60	1.53	5.09	155.5	190.0	22.0
6300E(2)	1.00	0.70	1.43	5.45	164.5	196.0	13.5

1. Solar's Specification on Heat Treatment - 1800 F, 1325 F 4 hours, furnace cool to 1150 F, hold 4 hours, air cool.
2. Although Heat 6300E shows the lowest titanium/aluminum ratio, it received the highest amount of cold work.

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 addition of aluminum in any precipitation hardened nickel-base alloy is present as part of the gamma prime, the major strengthening phase which for 718 alloy has the general formula Ni_3 (Al, Ti, Cb). The higher the aluminum content, the greater the aluminum in the gamma prime. Since aluminum is a small atom in comparison with titanium and columbium, the resultant lattice strain will be less; therefore, heats with a high aluminum content will generally be lower in strength.

1.2.2 Varestraint Test

Three different types of control heads were tried with limited success. Finally, equipment as shown in Figure 2 was assembled and tested. This equipment consists of a Heliweld Automatic Head, HMH-E. Use of this more refined welding control head has resulted in obtaining excellent consistency and reproducibility on Varestraint tests of four heats of 0.040-inch 718 material.

TABLE IV

VARESTRAINT TEST RESULTS

Heat Treat Cycle	Specimen Number	Total HAZ Crack Length: Heat No. 6790 Low Titanium Low Aluminum (in.)	Heat No. 6518 Average Titanium and Aluminum (in.)	Heat No. 6394 High Titanium Low Aluminum (in.)	Heat No. 6300 High Titanium High Aluminum (in.)	Total HAZ Crack Length Average for Four Heats (in.)
1	1	0.0536	0.0564	0.0516	0.0396	
	2	0.0480	0.0688	0.0580	0.0420	
	3	0.0490	0.0596	0.0596	0.0428	
Average		0.0500	0.0616	0.0564	0.0414	0.0526
2	1	0.0772	0.0608	0.0640	0.0620	
	2	0.0768	0.0580	0.0696	0.0688	
	3	0.0818	0.0536	0.0584	0.0628	
Average		0.0786	0.0574	0.0640	0.0645	0.0661
3	1	0.0672	0.0696	0.0808	0.0816	
	2	0.0716	0.0696	0.0828	0.0792	
	3	0.0672	0.0684	--	0.0816	
Average		0.0686	0.0692	0.0818	0.0808	0.0751
4	1	0.0684	0.0832	0.0692	0.1040	
	2	0.0608	0.0804	0.0744	0.0920	
	3	0.0680	0.1052	0.0688	0.0930	
Average		0.0657	0.0896	0.0708	0.0960	0.0805
5	1	0.1080	0.1296	0.0924	0.0896	
	2	0.1032	0.1044	0.0960	0.0908	
	3	0.1056	0.1516	0.0968	0.0924	
Average		0.1056	0.1285	0.0950	0.0909	0.1050

Heat Treat Cycle (1) 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

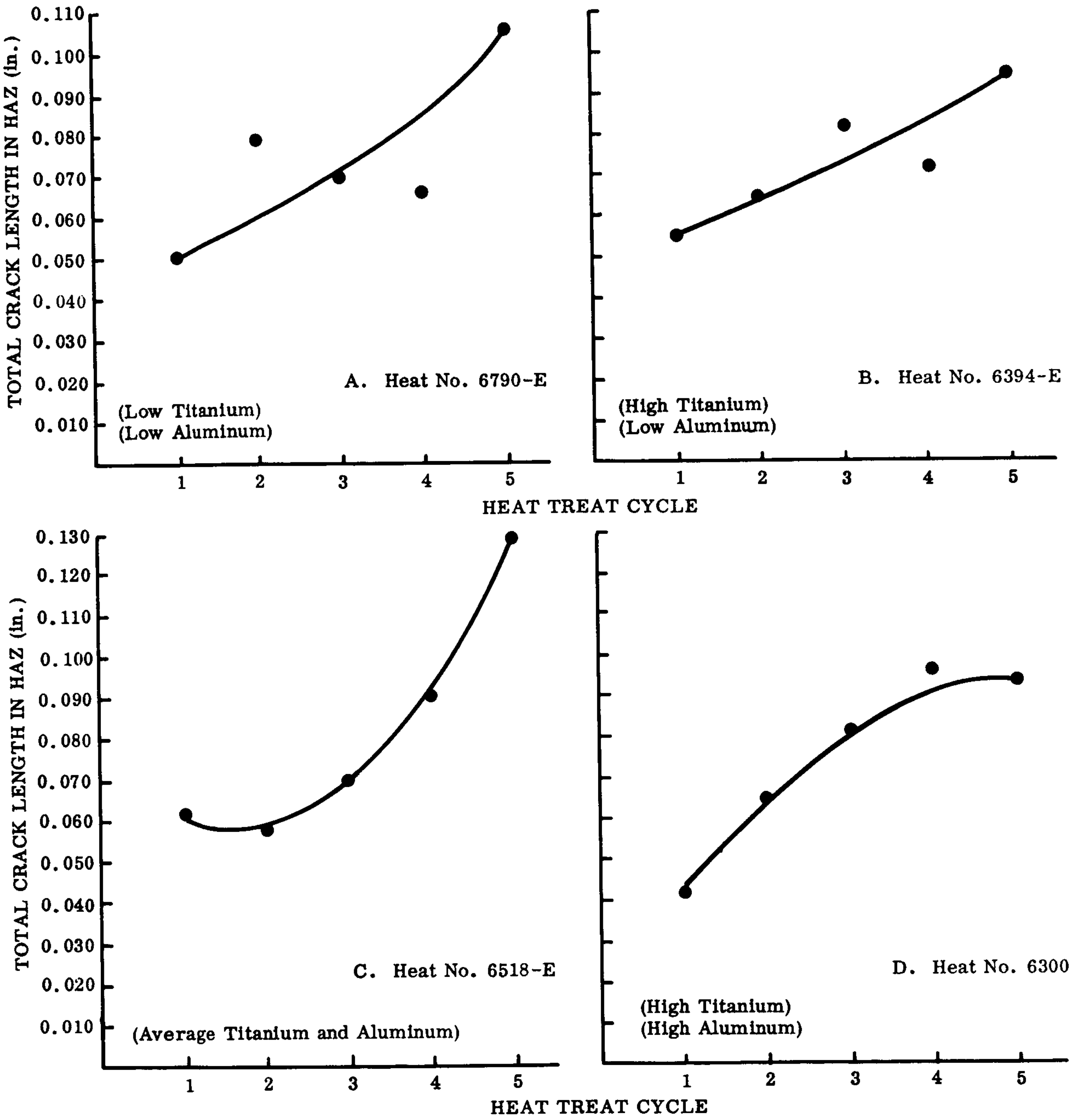
Heat Treat Cycle (2) 1800 F air cool, 1325 F 4 hours, furnace cool to 1150 F, hold at 1150 F for 4 hours

Heat Treat Cycle (3) 1850 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours

Heat Treat Cycle (4) 1900 F air cool, 1325 F 8 hours, furnace cool to 1150 F, hold at 1150 F for 8 hours

Heat Treat Cycle (5) 1950 F air cool, 1400 F 10hours, furnace cool to 1200 F, hold at 1200 F so that total aging time is 20 hours

Preliminary evaluation of test results contained in Table IV and shown in Figure 3, indicate that the annealing temperatures appear to be the most influential factor in promoting cracking sensitivity of the 718 alloy. The four heats studied during this period indicate that there is no particular pattern in the sensitivity to hot cracking from one heat to another in relation to a particular heat treatment. However, all heats become significantly more sensitive to hot cracking as the annealing temperature is increased above 1750 F. The total crack length in the heat-affected zone of



HEAT TREAT CYCLE (1) 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

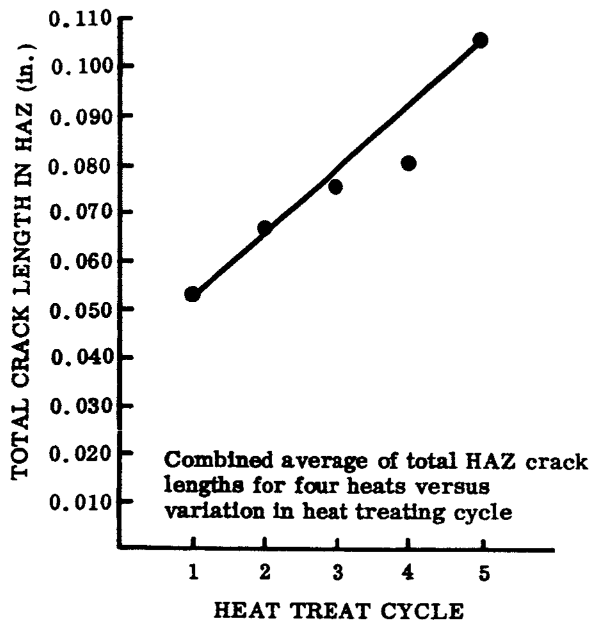
HEAT TREAT CYCLE (2) 1800 F AIR COOL, 1325 F, 4 HOURS, FURNACE COOL TO 1150 F, HOLD AT 1150 F FOR 4 HOURS

HEAT TREAT CYCLE (3) 1850 F AIR COOL, 1325 F, 8 HOURS, FURNACE COOL TO 1150 F, HOLD AT 1150 F FOR 8 HOURS

HEAT TREAT CYCLE (4) 1900 F AIR COOL, 1325 F, 8 HOURS, FURNACE COOL TO 1150 F, HOLD AT 1150 F FOR 8 HOURS

HEAT TREAT CYCLE (5) 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

FIGURE 3. VARESTRAINT TEST TOTAL HAZ CRACK LENGTH VERSUS VARIATION IN HEAT TREATING CYCLE



HEAT TREAT CYCLE (1) 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 (2) 1800 F AIR COOL, 1325 F, 4 HOURS, FURNACE COOL TO 1150 F, HOLD AT 1150 F FOR 4 HOURS

HEAT TREAT CYCLE (3) 1850 F AIR COOL, 1325 F, 8 HOURS, FURNACE COOL TO 1150 F, HOLD AT 1150 F FOR 8 HOURS

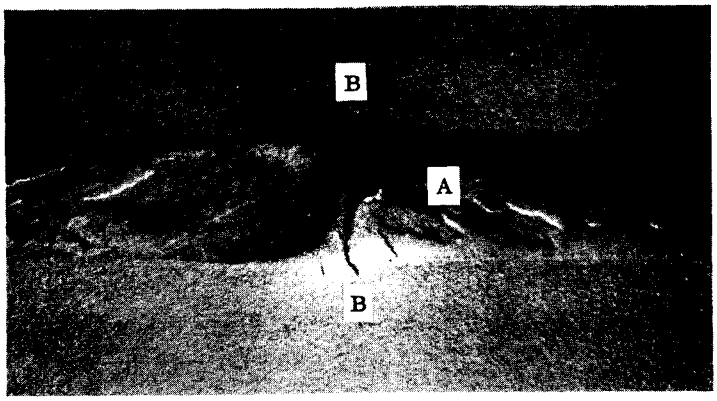
HEAT TREAT CYCLE (4) 1900 F AIR COOL, 1325 F, 8 HOURS, FURNACE COOL TO 1150 F, HOLD AT 1150 F FOR 8 HOURS

HEAT TREAT CYCLE (5) 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

FIGURE 4. VARESTRAINT TEST RESULTS

specimens annealed at 1750 F and double aged averaged just over 0.050 inch. Specimens annealed at 1950 F and double aged showed a combined total crack length of approximately twice the amount of the 1750 F annealed specimens (0.105 inch). Although the aging cycle on the 1750 F specimens is different from specimens annealed at 1950 F, the double aging cycles between heat treat Cycles 1, 2, 3, and 4 are quite similar, yet there is a definite trend of increased total crack length (Fig. 4) as the annealing temperature is increased above 1750 F.

Figures 5 through 8 show the cracking pattern on 0.040-inch test specimens from Heats 6300, 6394, 6518, and 6790, respectively.

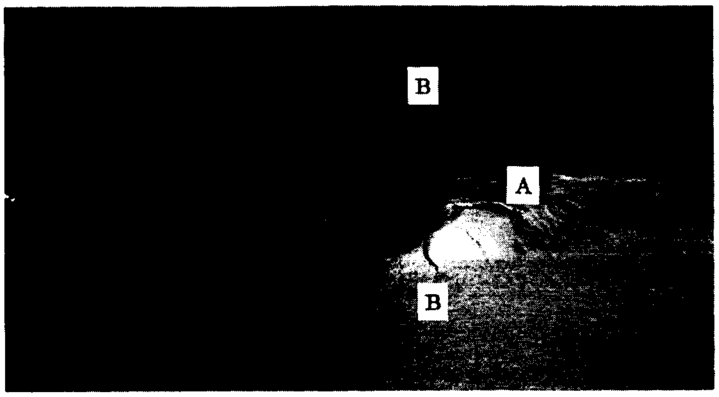


Area A designates region of weld metal cracking. Areas B show HAZ microfissuring

Magnification: Approximately 10X

FIGURE 5.

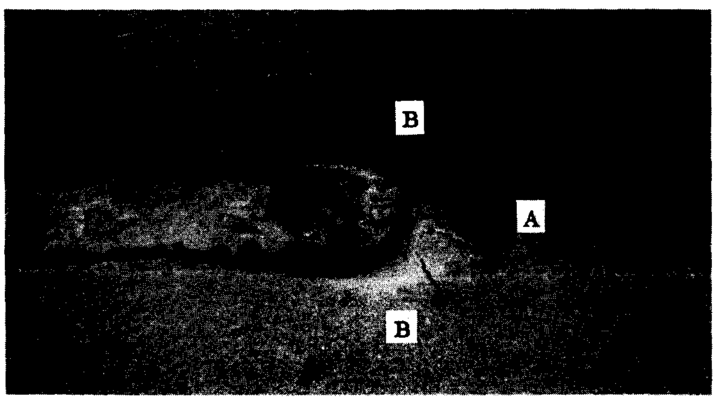
VARESTRAINT 0.040-INCH TEST SPECIMEN; Heat No. 6790



Magnification: Approximately 10X

FIGURE 6.

VARESTRAINT 0.040-INCH TEST SPECIMEN; Heat No. 6518

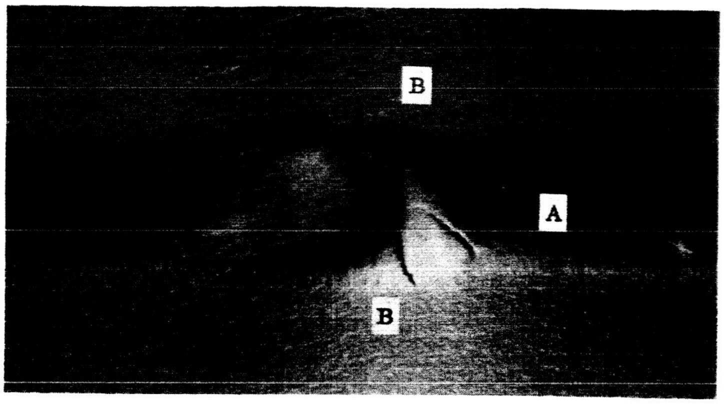


Magnification: Approximately 10X

FIGURE 7.

VARESTRAINT 0.040-INCH TEST SPECIMEN; Heat No. 6394

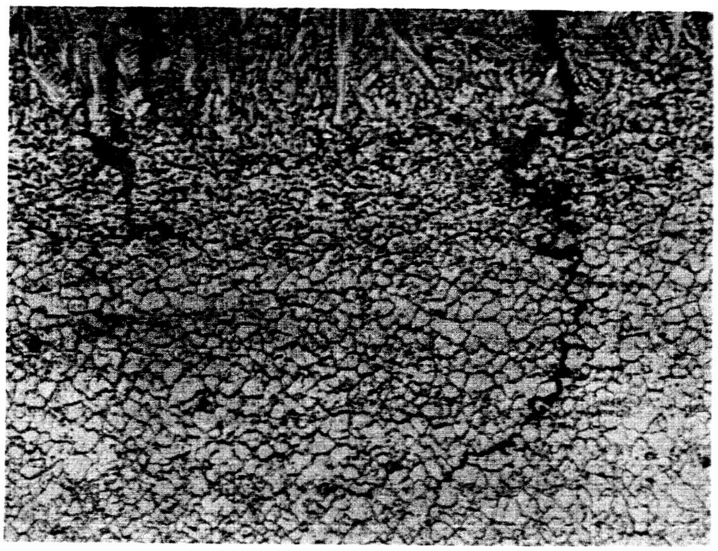
The area designated as A shows the cracking extent in the weld metal. Area B indicates where heat-affected zone cracking occurred. Figure 9 shows a cross-section through area B found in Figure 8. Fissures are definitely intergranular and are restricted to the heat-affected zone.



Magnification: Approximately 10X

FIGURE 8.

VARESTRAINT 0.040-INCH TEST SPECIMEN; Heat No. 6300



Fissures are definitely intergranular and extend into the HAZ

Magnification: 150X

Etchant - - 5% oxalic acid etch

FIGURE 9.

CROSS SECTION THROUGH AREA B OF 0.040-INCH TEST SPECIMEN; Heat No. 6300

SECTION II
WORK FOR FINAL REPORT

Continue studies on the effect of variations in heat treating cycles and the relation of mechanical properties, microstructure, and crack susceptibility to the thermal treatments.

Study the effect of abbreviated aging cycles on highly cold worked 718 material in an effort to eliminate interstage annealing cycles.

Determine the effect of welding high-mass 718 aged-hardened materials to low-mass Type 321 Stainless Steel and aged 718 materials.

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