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BIMONTHLY PROGRESS REPORT NO. VIII

THERMAL-SHOCK INVESTIGATION

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OBJECT

The object of this research is to evaluate optimum design of test specimens and criteria which will permit correlation of thermal-shock data with performance of the material in the form of turbine buckets.

SUMMARY

Data are presented on the themal-shock resistance of 21 specimens of N-155 alloy. The best specimens of this alloy appear to be as resistant or more resistant to cracking by thermal shock than those of Inconel and S-816 alloy previously reported. As would be expected, resistance to cracking by thermal shock decreased as the specimen temperature was increased from 1600°F through 1700°F to 1800°F.

The marked effect of difference in thermal-shock resistance between specimens from two different bars is definitely shown by results on two lots of this material. This effect may have been due in part to minor differences in supposedly identical heat treatments.

INTRODUCTION

Previous research has been concerned primarily with stainless steels, Inconel, and S-816 alloy. This research, conducted primarily during the period August 11, 1952, through November 11, 1952, was concerned with extending results to another material, namely N-155 alloy.

APPARATUS

The test rig employed was substantially the same as that used in tests reported in the last two progress reports, with modifications to the specimen-holding assembly and crack-detection procedure.

The specimen holder (Fig. 1) was altered to hold the specimen horizontally, with the air blast coming from below to the cooled edge of the specimen. The right end of the specimen was held in a combination electrode-support that was free to translate horizontally under the thermal expansion of the specimen during the test cycle. It was constrained, however, to prevent the specimen end from rotating, in order not to interfere with the positioning of the specimen relative to the air nozzle. The air nozzle was rigidly connected to the specimen-holding assembly. A movable gage attached to the specimen holder was used to position the back of the specimen normal to the line of sight of the radiation pyrometer. An end stop on the specimen holder positioned the specimen along its axis at the left end. In this way all specimens were located in substantially the same position.

Crack detection was facilitated by the use of a measuring telescope (Fig. 2). This telescope was mounted rigidly on the frame of the test rig, free only to rotate in a horizontal plane so that the telescope could be used to scan the length of the cooled edge. This setup enabled cracks to be detected almost at their inception, and the crack growth to be followed during the test. Only cracks which were obscured by oxide formation could not be definitely identified until the end of the test, when they were opened by bending the specimen; such cracks were present infrequently. A magnification of five diameters was found to be suitable for this study.

The cracks were not equally visible during all portions of the test cycle, nor was the most suitable portion of the cycle the same for all specimens. In general, however, cracks were most easily discerned immediately after the air blast had started or immediately after the air blast had ceased.

The specimens used contained no central holes, since the radiation pyrometer had been found to be reliable provided the surface of the specimen was adequately oxidized prior to test. All specimens were preoxidized prior to these tests.

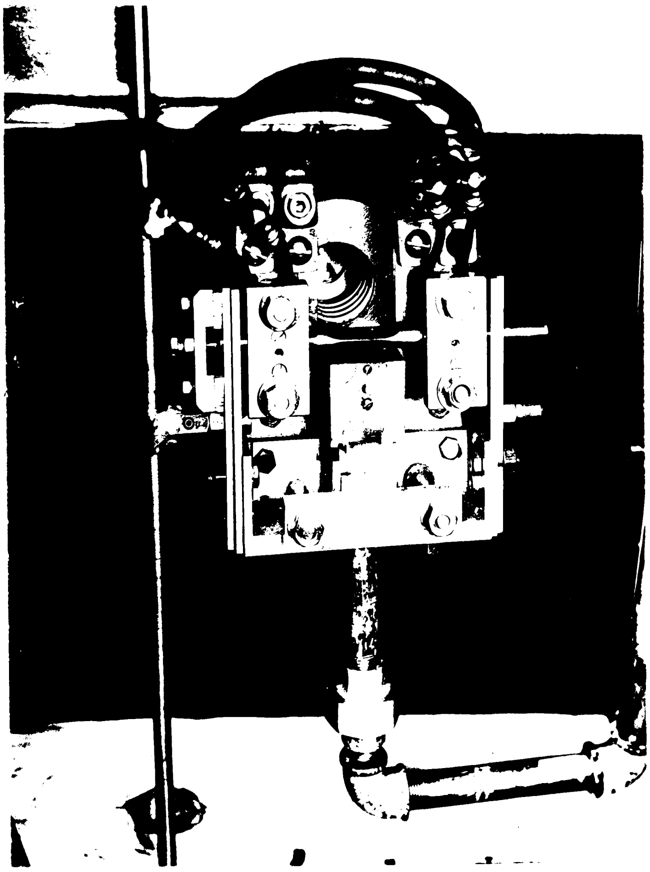


Fig. 1. Front View of Specimen Holder, Specimen, Air Nozzle, and Radiation Pyrometer.

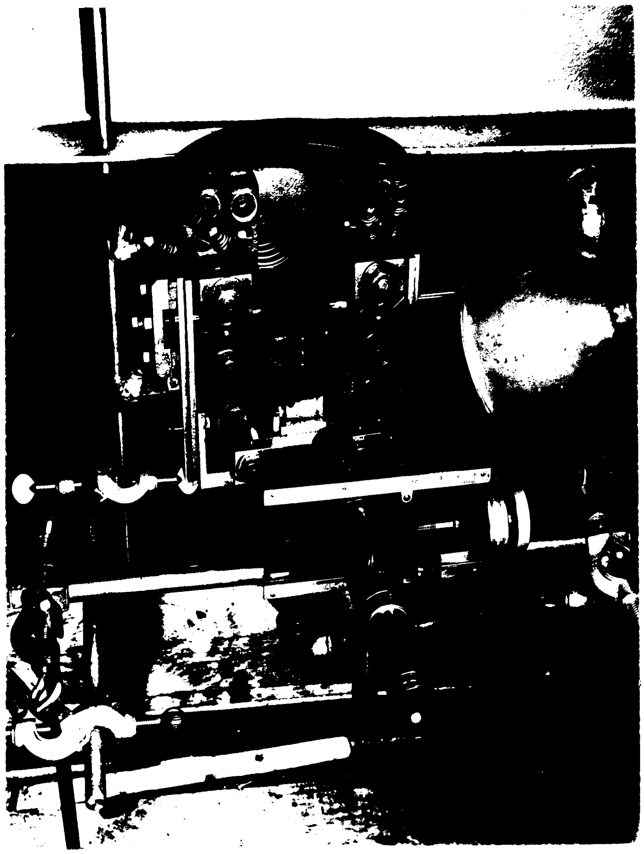


Fig. 2. View of Specimen Holder With Measuring Telescope in Position To View Specimen

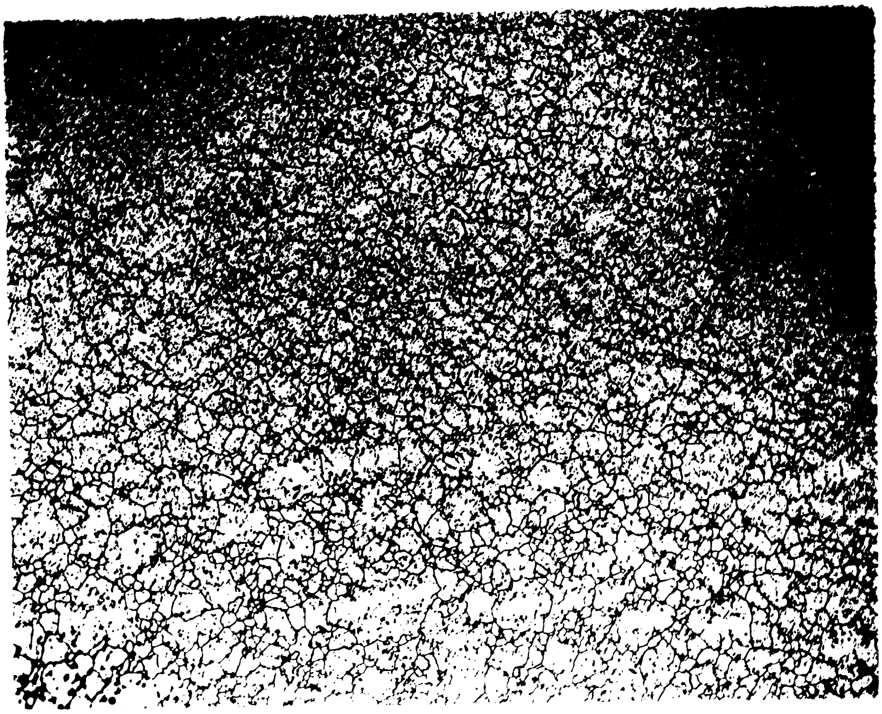
Two lots of specimens, identified by Roman numerals I and II in the sixth column of the log, were heat-treated for 20 minutes at 2200°F, water-quenched, and soaked for 50 hours at 1400°F. These specimens were obtained from different bars of the same heat, and were heat-treated at different times. Although no differences in microstructure were apparent on viewing the cross sections of the bars (Figs. 3 and 4), longitudinal sections (Figs. 5 and 6) revealed substantially greater twinning in lot II. This twinning is best seen in Fig. 6. These two lots of specimens manifested quite different behaviors in the thermal-shock tests.

RESULTS

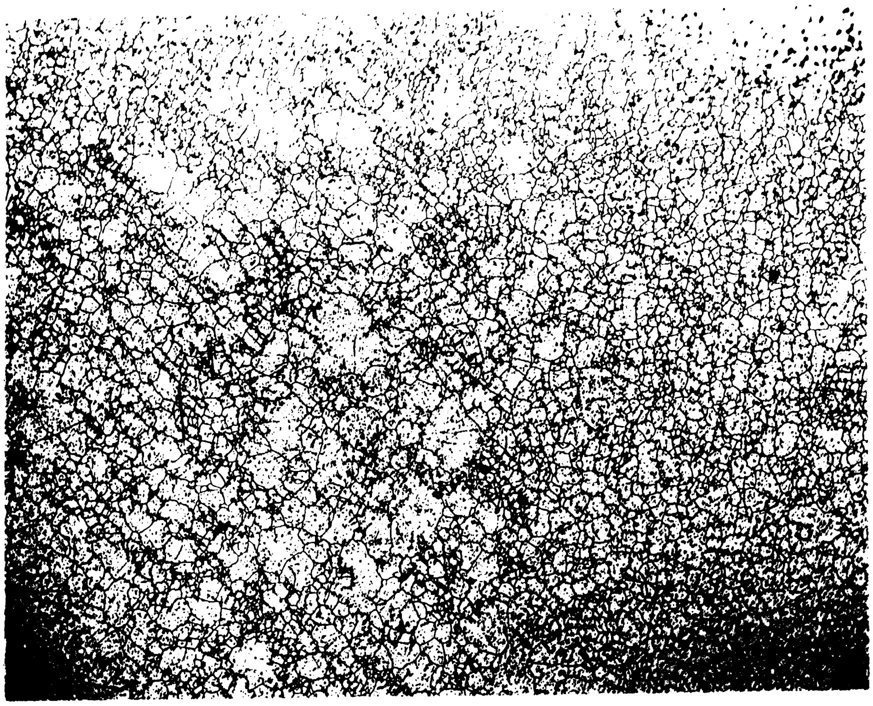
The results from the tests on the two lots are different, although results within each lot are reasonably consistent. A table of results is shown below in order of the number of cycles to failure.

1600°F		1700°F		1800°F	
Cycles	Lot	Cycles	Lot	Cycles	Lot
No crack at 10,124	I	3764	I	2052	I
No crack at 3,886	I	3248	I	1818	I
5,153	II	3211	I	1508	I
3,530	II	3195	I	1228	II
		3105	I	1130	II
		2888	I	1095	II
		2320	II	1042	II
		2229	II	990	II
		1995	II		

The N-155 alloy from Lot I outperformed the S-816 alloy. It is about the same as the best Inconel specimens in resistance to cracking by thermal shock. This behavior is not evident in Lot II, which shows approximately the same behavior as the S-816 alloy previously tested. It is possible that the twinning which is present from large amounts of original cold-working appreciably reduces the thermal-shock resistance of N-155 alloy. It is known that small amounts of cold work (tensile strains up to 10%) had no major effect on specimens of Inconel (Progress Report No. VII). If cold work is the reason for the difference in behavior of the two lots of N-155 alloy, then the alloy is either more sensitive than Inconel to cold work or else a tensile strain of 10% was not sufficient to reduce appreciably the



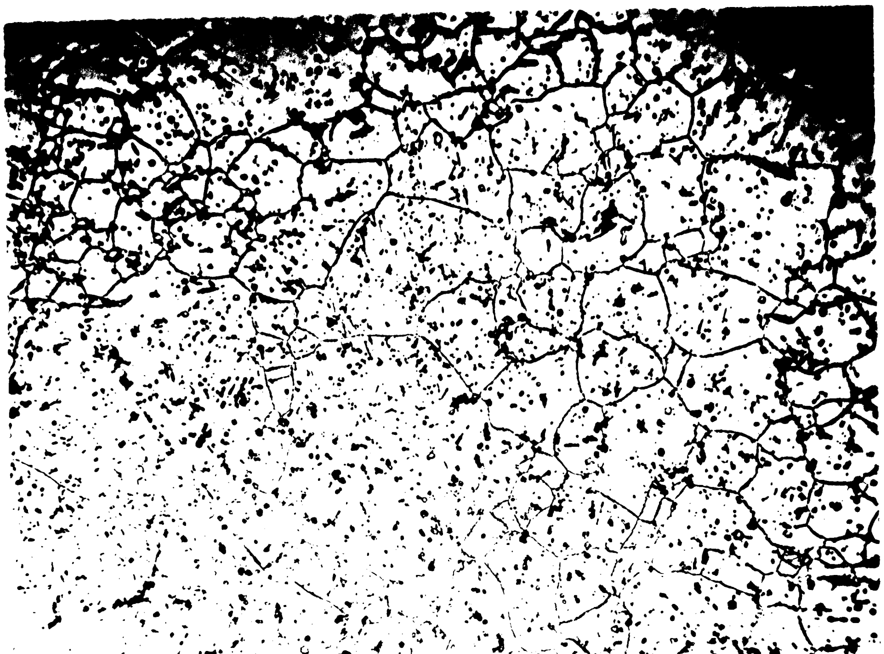
a) Lot I



b) Lot II

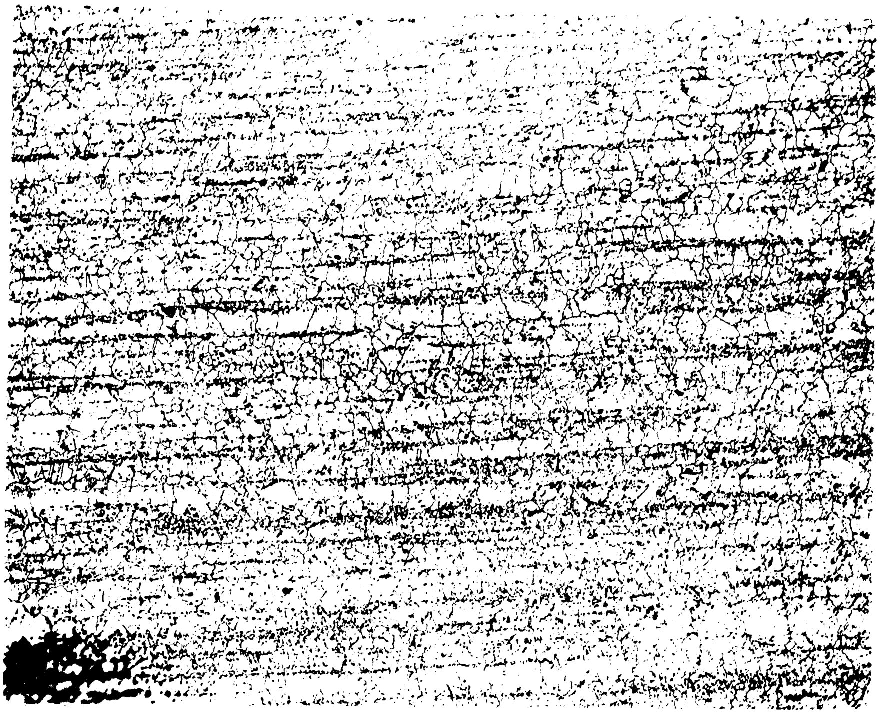
Fig. 3. N-155 Alloy, Cross Section of Bar, x100

a) Lot I

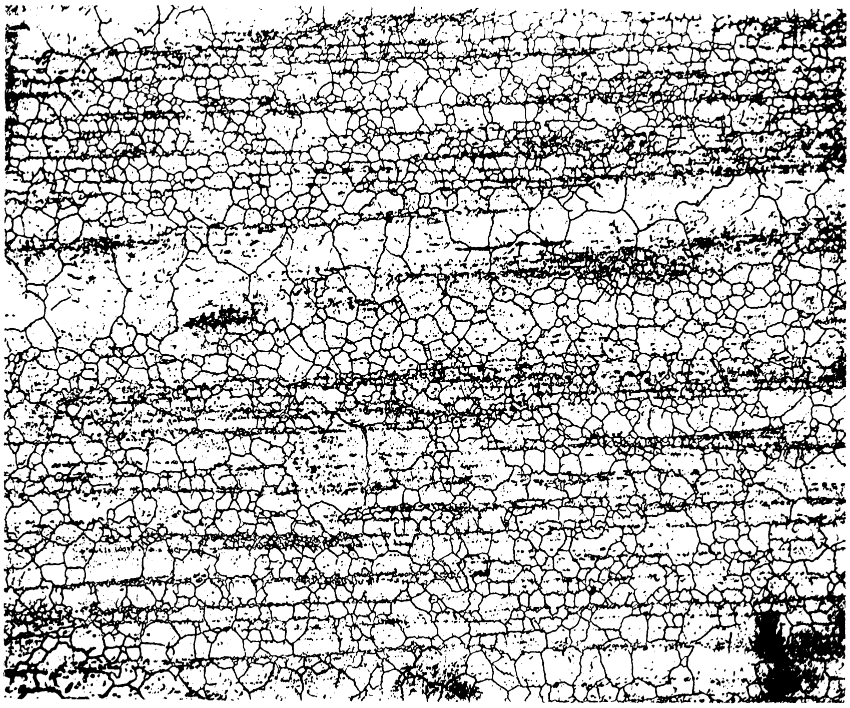


b) Lot II

Fig. 4. N-155 Alloy, Cross Section Of Bar, x500

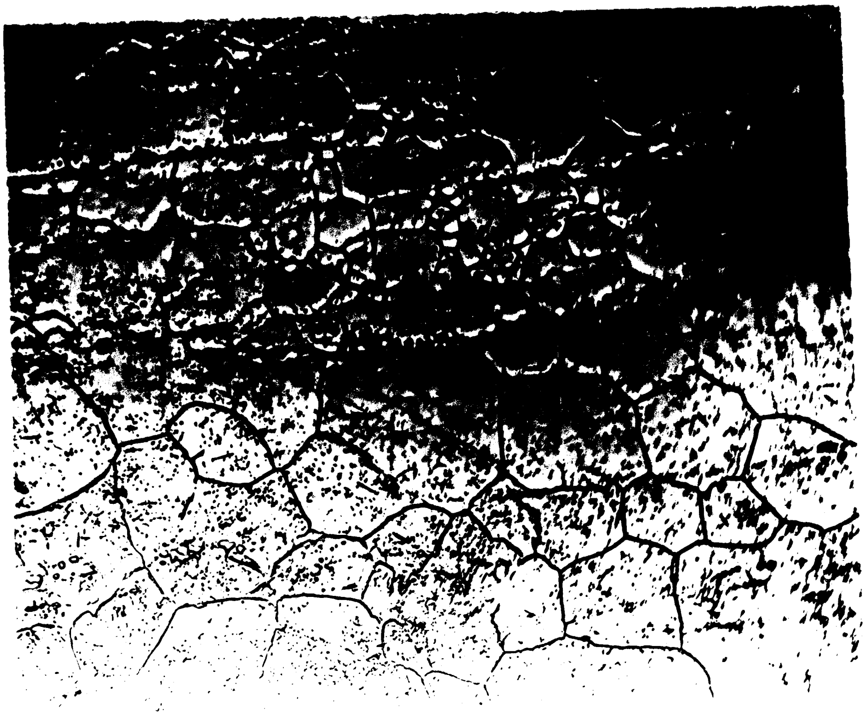


a) Lot I

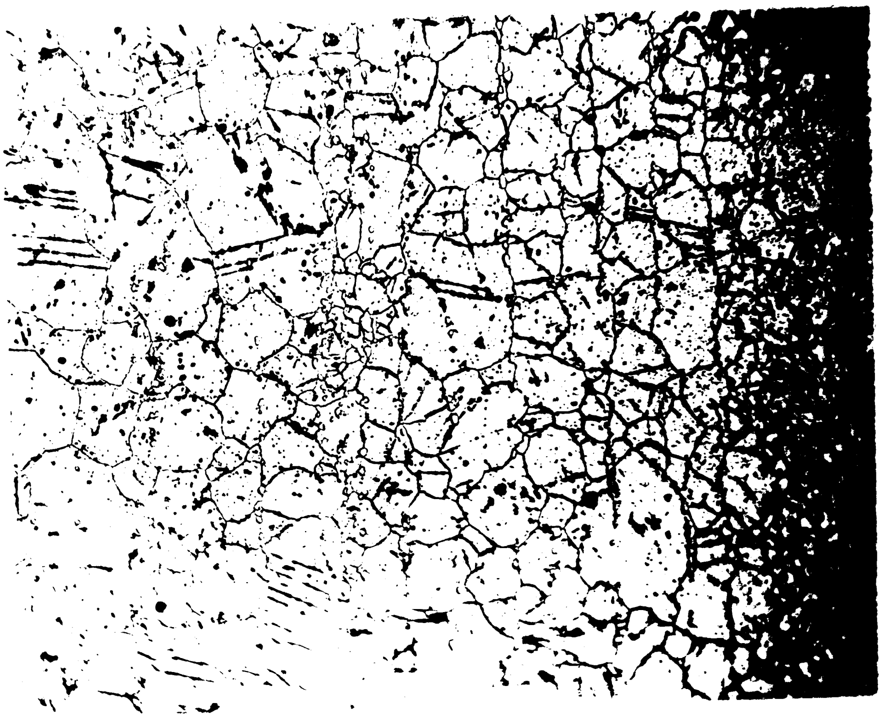


b) Lot II

Fig. 5. N-155 Alloy, Longitudinal Section Of Bar, x100



a) Lot I



b) Lot II

Fig. 6. N-155 Alloy, Longitudinal Section of Bar, x500

the thermal-shock resistance of Inconel, or both. In any case, N-155 appears to be the best or nearly the best alloy, from the point of view of thermal shock, of any of the materials studied to date.

CONCLUSION

Wrought N-155 alloy, heat-treated as described above, shows thermal-shock resistance equal to or better than wrought S-816 alloy. One lot of N-155 alloy, free from twinning, was better in resistance to thermal shock than another lot, which showed large numbers of twins. The best Inconel and the better lot of N-155 alloy were about the same in resistance to cracking by thermal shock.

KEY TO LOG

Column (1)

(1)	Relative position on bar stock
1	Specimen number

Column (2)

	Arrow indicates direction and location of cooling jet; cooling medium is air unless otherwise stated
W	Cooling medium is water
.045	Width of cooled edge, inches
P.F.	Previously subjected to rotating beam fatigue as shown in column (6)
X	Failed during pre-fatigue

Column (3)

M	Thermal shock cycle manually controlled
1500/5	Automatic cycle control; maximum temperature, °F, and length of cooling period, seconds
P1800	Dead load, 1800 lbs
+10/100	Starting with stated maximum temperature, maximum temperature was increased 10°F after each 100 cycles
40.5K	Reversed-bending (rotating-beam) fatigue tests; maximum stress, 40,500 psi
to 1800	Maximum temperature held constant after 1800°F was reached

Column (4)

A	Air cooling for stated number of cycles
W	Water cooling for stated number of cycles
no symbol	Air cooling for stated number of cycles

Column (5)

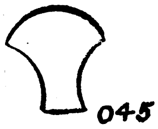
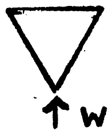
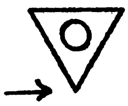
O	No failure visible
F	Fracture
C	Cracks
G	Grooves
FC	Face crack
PC	Possible crack

Column (6)

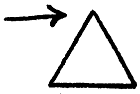
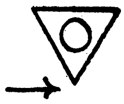
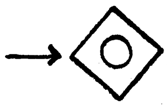
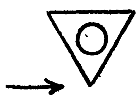
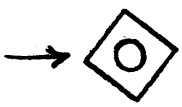
B	Specimen warped due to thermal strains
A 0.14	Area of cross section, square inch
T300/1600	Heat treated before testing 300 hr at 1600°F
G1500	Grooves first appeared at 1500 cycles
OH	Stated maximum temperature was exceeded due to malfunction of control unit
BT	Broke through to thermocouple hole

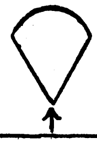
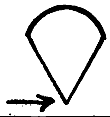
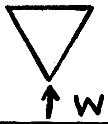
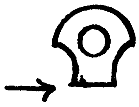
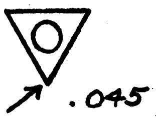
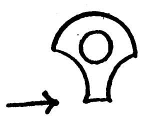
40.5K/ 82000	Previously subjected to 82000 cycles at 40,500 psi
R	Reproducibility test
N	Specimen formed a neck due to tensile strain.
+100/5108	Maximum temperature was increased 100°F at 5108 cycles.
Check II	Second test to determine the effect of alteration of testing procedure.
P	Study of crack propagation
PT1	Previously subjected to tensile strain of 1% at room temperature
LRSI	Long-time test at reduced severity, Test No. I
T{ }I	Heat treated as shown in braces { }. Lot No. I
C20/1700	Heat treated for 20 hours by heating to 1700°F and allowing to cool for 5 seconds by natural convection.

TEST LOG

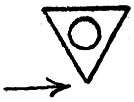
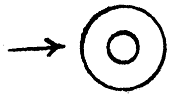
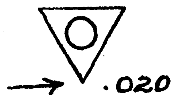
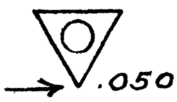
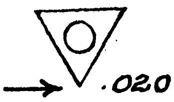
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
Type 304 Stainless Steel					
1		M	——	O	B
2		1600/10	4400 A 300 W	C	B
3		1600/4	1783	C	
4a 4b	Fatigue Specimens	40.5K 40.5K	3300 2600	F F	
5		1700/4 1800/4	1100 675	O C	
6		1600/4 1900/4	6240 1240	O C	G6500
7		1500/4 P600	4130	F	A 0.16

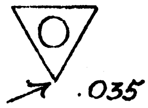
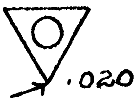
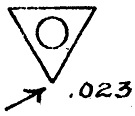
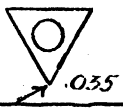
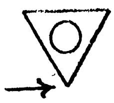
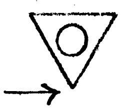
TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
8		1600/5 1800/4	3082 517	O C	T300/1600
9		1500/3	5753	O	
10		1600/4 1700/4 1800/4	1000 1000 80	O O C	
11		1500/5 P1800	1000	F	A 0.132
12		1500/5 P600 P900 P1800	 5000 1200 203	 O O F	A 0.133
13		1600/4	1284	C	G 115
14		1500/4	1000	F	OH
15		1600/5	1900	C	T300/1600
16		1600/5	409	C	

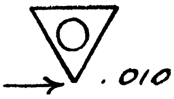
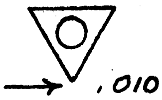
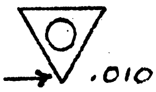
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
17		1500/5 P1800	300	F	A 0.140
18		1800/4	1950	C	G 1500
19		1700/3	530W	C	
20		1500/3	1000	O	BT
Type 347 Stainless Steel					
1		1600/4 +10/100	866	C	
2		1600/4 +10/100	1147	C	
3		1500/4 +10/100	575	C	BT
4a 4b	Fatigue Specimens	54K 54K	5200 10400	F F	 40.5K 82000

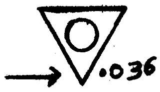
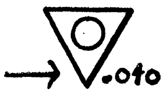
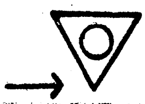
TEST LOG (cont)

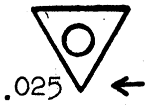
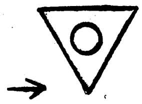
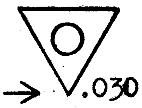
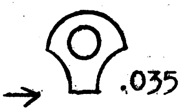
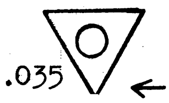
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
5		1500/4 +10/100	1326	C	
6		1500/4 +10/100	1990	C	
7		1600/3.5 +10/100 to 1800	2700	G	
8	(Defective)				
9		1600/4	2863	C	R
10		1600/4	3787	C	Check II
11		1600/4	2580	C	
12		1600/4	3162	C	G 736
13		1600/4	2204	C	G 2072
14		1600/4	2707	C	G 2604

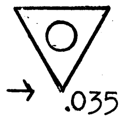
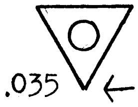
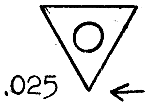
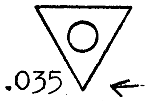
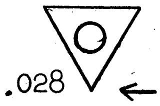
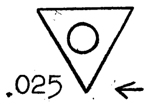
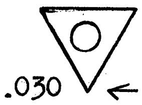
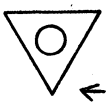
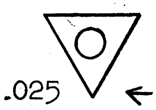
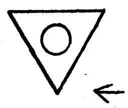
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
15		1600/4	3003	C	G2820 R
16		1600/4	2518	C	R
17		1600/4	4850	O	Check I
18		Fatigue 64K	7200	F	54K 103300
19		1600/4	1825	C	R
20		Fatigue 64K	4300	F	37K/217100 42K/11000 48K/35600 54K/10000 59K/10400
21		1600/4	4430	C	
22	(Defective)				
23		1600/5	2962	C	
24		Fatigue 59K	52900	F	

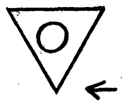
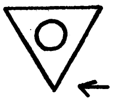
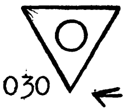
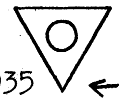
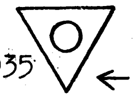
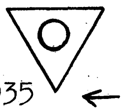
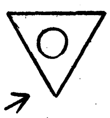
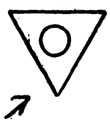
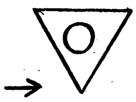
TEST LOG (cont)

Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
25		1600/5 P.F.	1562	C	54K/50000
26		1600/5	1960	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/500
27		X P.F.	—	F	53K/52000 59K/11300
28		1600/5 P.F.	1594	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/500
29		X P.F.	—	C	53K/52000 59K/12000 64K/1000 70K/1000 75K/300
30		1600/5	1973	C	
31		1600/5	2764	C	
32		1600/5	1500	C	

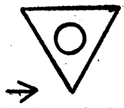
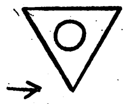
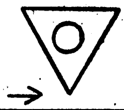
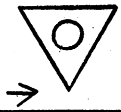
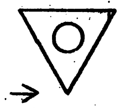
Specimen Number (1)	Cross Section (2)	Cycle (3)	Number of Cycles (4)	Type of Failure (5)	Remarks (6)
33 (4)	 .040	X P.F.	——	F	59K/32600
34 (3)	 .036	P.F.	1811	C	60K/39000
35 (2)	(Used for calibration of Heat-Eye)				
36 (1)	 .040	1600/5 P.F.	1859	C	58K/30000
37 (5)	 .040	1600/5	4635	C	
38					T2/2000
39 (7)		1600/5	2440	G	G 2440 Rigid Support Nozzle No. 3
40 (8)		1600/5	3143	G	Nozzle No. 4
41		1600/5	2710	C	G 2000 Rigid Support Nozzle No. 3

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
42					
43 (11)		1600/5	10708	C	P Rigid Support Nozzle No. 4
44					
45					
H.S. 21 (vitallium) Cast					
1		1500/3.5	1000	C	BT
Inconel					
1		1500/3	1450	C	
2		1500/3 +10/100	2730	C	
3		1500/3 +10/100	428	C	BT
4		1700/5	3167	C	T2/500 T1/3/1400
5		1700/5	1819	C	T2/500 T1/3/1400

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
6	 .035	1600/4	7449	C	
7	 .035	1700/5	4706	C	T2/500 T1/3/1400
8	 .025	1700/5	2090	C	T1/3/1400 PTI
9					
10	 .035	1700/5	3680	C	T1/3/1400 PT10
11	 .028	1700/5	2860	C	T1/3/1400 PT5
12					
13	 .025	1700/5	2500	C	T1/3/1400 PT1
14	 .030	1700/5	2527	C	T1/3/1400 PT5
15		1700/5	2804	C	T1/3/1400 PT10
16	 .025	1700/5	3590	C	T1/3/1400 PTO
17		1700/5	2270	C	T1/3/1400 PTI

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
18		1700/5	2576 3015	PC C	T1/3/1400 PT5
19		1700/5	1830	C	T1/3/1400 PT10
20	 .030	1700/5	2898	C	T1/3/1400 PTO
21					
22	 .035	1700/5	4339 6866	FC? C	T1/3/1400 flex. pipe to nozzle
23	 .035	1700/5	2250	C	T1/3/1400
24					
25	 035	1700/5	3538 4229	FC C	T1/3/1400
S-816 Alloy (wrought)					
1		1500/4 P700 No load	1788 18391	O C	A 0.08 N +100/5108 +100/10000
2		1500/4 P1100 to P700	2657	F	A 0.08 N
3		1700/4	2256	C	

TEST LOG (cont)

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
4		1700/4	2250	C	
5		1600/4	3870	C	
6		1500/4	2630	C	
7		1500/4	13280	C	
8		1600/4	7497	C	

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
N-155 Alloy (Wrought)					
1	.038 ▽ ←	1700/5	3764 3878 4949	FC C 2C	T {1/3/2200 W 50/1400} I
2	.040 ▽ ←	1700/5	3211	C	T {1/3/2200 W 50/1400} I
3	.038 ▽ ←	1700/5	3248	C	T {1/3/2200 W 50/1400} I
4	.034 ▽ ←	1800/5	1508	C	T {1/3/2200 W 50/1400} I
5	.036 ▽ ←	1600/5	3886	O	T {1/3/2200 W 50/1400} I Removed for check; No crack
6	.040 ▽ ←	1700/5	3105	C	T {1/3/2200 W 50/1400} I
7	.042 ▽ ←	1800/5	1818	C	T {1/3,2200 W 50/1400} I
8	.039 ▽ ←	1700/5	3195	C	T {1/3/2200 W 50/1400} I
9	.037 ▽ ←	1700/5	2888	C	T {1/3/2200 W 50/1400} I
10	.041 ▽ ←	1600/5	10124	O	T {1/3/2200 W 50/1400} I
11	.045 ▽ ←	1800/5	2052	C	T {1/3/2200 W 50/1400} I

(1) Specimen Number	(2) Cross Section	(3) Cycle	(4) Number of Cycles	(5) Type of Failure	(6) Remarks
12	.038	1800/5	1228	C	T {1/3/2200 W 50/1400} II
13	.048	1800/5	1095	C	T {1/3/2200 W 50/1400} II
14	.035	1800/5	1042	C	T {1/3/2200 W 50/1400} II
15	.0385	1800/5	990	C	T {1/3/2200 W 50/1400} II
16	.0415	1800/5	1130	C	T {1/3/2200 W 50/1400} II
17	.040	1700/5	2229	C	T {1/3/2200 W 50/1400} II
18	.0365	1700/5	1995	C	T {1/3/2200 W 50/1400} II
19	.0395	1600/5	5153	C	T {1/3/2200 W 50/1400} II
20	.0465	1700/5	2320	C	T {1/3/2200 W 50/1400} II
21	.0433	1600/5	3530	C	T {1/3/2200 W 50/1400} II