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RESEARCH MEMORANDUM

EFFECTS OF A STRAIGHTENING OPERATION ON PERFORMANCE OF INCONEL 550 BUCKETS

By C. A. Gyorgak, J. R. Johnston, and J. W. Weeton

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The effects of a straightening operation on the life of Inconel 550 buckets were determined in a J33-9 engine. Reproducibility of engine life of unstraightened Inconel 550 buckets was also determined.

The stress-rupture life of specimens cut from airfoils of straightened and aged buckets was reduced considerably below the life of specimens from unstraightened buckets. Microstructures present in the straightened and aged buckets contained considerable Widmanstätten structure and slip-line precipitates. Engine life of the straightened and aged buckets did not appear to be severely affected.

A flash solution treatment (12 min at 2150° F) after straightening recovered the stress-rupture life lost by the straightening operation and caused the microstructure to be similar to that of unstraightened buckets. Engine life of straightened, flash-solution-treated and aged buckets was equal to the engine life of unstraightened buckets.

Fully solution-treated and aged groups of buckets, from lots previously run in an identical type of engine evaluation, reproduced the results of the first study.

INTRODUCTION

Inconel 550 is a potential turbine bucket material having a low strategic-element content compared with the extensively used blade alloy S-816. It is a modification of the precipitation-hardening Inconel X in which the aluminum was increased on the average from 0.7 to 1.2 percent.

The effects of forging temperatures and heat treatments on Inconel 550 bucket life were reported in reference 1, as follows:

(1) A high forging temperature followed by high solution-treating temperature proved superior to other treatments.

(2) Operating lives of Inconel 550 buckets were equal to or appreciably better than the lives of S-816 buckets used as a standard for comparison. The life of the best group of buckets ranged from 450 to 857 hours, whereas the S-816 buckets ran from 204 to 599 hours.

It is well recognized that variables such as forging temperature and heat treatments affect the lives of wrought turbine buckets. However, the effects of other fabrication practices on bucket performance are not so well understood. For example, the practice of straightening airfoils by restriking or hot-dropping is controversial, since it is held by some that the practice damages the bucket and by others that it does not. It is understood that such straightening operations are sometimes done after the bucket has been solution-heat-treated but not aged, and in other cases after full heat treatments, including aging. In either case, the metal is deformed plastically and may not have a chance to be stress-relief annealed. In other words, it is hot-cold worked.

This investigation was conducted at the NACA Lewis laboratory to determine the effects of a straightening operation on the bucket performance of Inconel 550. Two additional groups of Inconel 550 buckets from the best groups studied in the first engine investigation of this alloy were also run to determine whether the results formerly obtained could be reproduced.

Bucket performance was determined in a J33-9 engine under cyclic operating conditions. Stress-rupture life of specimens cut from bucket airfoils was determined at 1500° F under stresses of 20,000, 25,000, or 30,000 psi and compared with data obtained from bar stock of the same material.

MATERIALS, APPARATUS, AND PROCEDURE

Turbine Buckets

The chemical analysis of the buckets used in this investigation is as follows:

Alloy	C	Mn	Fe	Si	S	Cu	Cr	Al	Ti	Cb + Ta	Ni
Inconel 550	0.05	0.73	6.59	0.28	0.007	0.03	14.97	1.16	2.5	1.03	[a]72.653

[a]By difference.

Forging temperatures and heat treatments used in fabrication of the buckets are listed in table I, along with the number of buckets of each condition tested. All buckets used in this investigation were inspected by radiographic and zyglo inspection methods and found to be sound.

The straightened buckets (group 1) were not inserted in the test wheel until 438 hours at rated speed had been accumulated on the engine. This was done as a precautionary measure to protect another alloy being run in the same engine test, because it was feared that the straightened buckets might fail near the base of the airfoil. Such failures in past investigations of this type have resulted in severe damage to the remaining buckets in the engine. Normally, bucket failures occur in the middle third of the airfoil, and fractured fragments pass from the engine without doing serious damage to the other buckets.

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Engine Operation

The buckets selected for engine evaluation were operated in a J33-9 engine under cyclic conditions. Cycles were of 20-minute duration and consisted of 15 minutes at rated speed of 11,500 rpm and approximately 5 minutes at idle speed of 4000 rpm.

CQ-1 back

Engine operation was interrupted to obtain data on bucket elongation, to check buckets for cracks, to replace failed buckets, to overhaul the engine when necessary, and to shut down at the end of each day. The engine testing phase of the investigation was terminated after 878 hours (rated speed).

Stress and temperature distribution in turbine buckets during engine operation. - Since the buckets used for this study were from the same lots as those of reference 1, the centrifugal stresses and temperature distribution for these buckets would be the same as those of reference 1 (see fig. 1).

Bucket temperatures were measured during engine operation with two thermocoupled S-816 buckets. Temperatures were recorded by an electronic potentiometer.

Bucket-elongation measurements. - Two buckets of each group were scribed at 1/2-inch intervals, as shown in figure 2. Elongation measurements were made at approximately 8-hour intervals for the first 25 hours of test time and at approximately 20-hour intervals for the remainder of the test life. The elongation of each scribed segment was measured with an optical extensometer having a sensitivity of 0.001 inch. Accuracy of the elongation measurement is, however, influenced by the degree of bucket distortion and warpage.

Macro- and microexamination of buckets. - Three buckets from one of the groups (group 2) and six buckets from each of the other groups were macroetched in an 80 percent HCL - 20 percent H_2O_2 solution to reveal grain size and flow lines. These buckets were also used for macro- and microstudies and stress-rupture tests.

The buckets selected for engine operation were inspected for cracks at intervals throughout the engine operating phase of the investigation. A bucket was said to have failed either when actual fracture occurred or when cracks in the airfoil made it apparent that failure was imminent. Failed buckets were examined at low magnifications to determine as nearly as possible the manner by which the failures originated. The failures were classified as stress-rupture, fatigue, stress-rupture followed by fatigue, and damage as defined in reference 1.

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Stress-Rupture Tests

Stress-rupture tests were conducted to determine the stress-rupture life at 1500° F of the different groups of buckets. Stress-rupture specimens were machined from the airfoil as shown in figure 3. Two to five specimens of each group were tested at stress levels of 20,000, 25,000, and 30,000 psi.

RESULTS

Engine Performance

Engine life of the different groups of buckets is listed in table II and shown in figure 4. The straightened buckets (group 1), which were placed in the engine after 438 hours had been accumulated on the other groups of buckets, had a first failure after 248 hours. No other failure occurred in this group of buckets for the remainder of the investigation. The total accumulated time on these straightened buckets was 439 hours.

The buckets that were straightened and re-solution-treated prior to aging (group 2 buckets) had an excellent engine life. The first two failures of this group were damage-induced failures occurring at 428 and 586 hours. One unfailed bucket was removed from the engine at 618 hours to permit balancing of the turbine wheel. The first true failure occurred at 765 hours, and the other failure (last bucket of group 2) occurred at 872 hours at rated speed.

The engine life of the best-performing group of reference 1 (group 3 herein) ranged from 493 hours to the termination of the test at 878 hours. One bucket in this group did not fail.

The performance of group 4 buckets herein (second-best-performing group of ref. 1) ranged from 361 to 645 hours, when the last bucket of this group was removed to permit balancing of the turbine wheel. A damage-induced failure occurred in this group at 222 hours of rated-speed operation.

The performance of the S-816 control buckets ranged from 50 to 357 hours at rated speed. The last failure was by damage.

Bucket elongation during engine operation. - The buckets exhibited very low elongations during engine operation. The maximum elongation measured was of the order of 0.30 percent. This was similar to that observed for the Inconel 550 buckets reported in reference 1. The significance of elongation measurements is discussed in detail in that reference.

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Macro- and microexaminations. - Photographs of macroetched buckets are shown in figure 5. Grain sizes within each group were relatively uniform, and the grain sizes of the different groups were somewhat similar. The largest grain size was noted in buckets of groups 1 and 2. Both fine and coarse grains were found in most of the groups of buckets, but no germinated ("elephant") grains were observed.

Microstructures representative of the different bucket groups, prior to operation in the engine, are shown in figure 6. The Inconel 550 buckets that were straightened (restruck) after solution treatment, prior to aging (group 1), show considerable evidence of working (fig. 6(a)). This is revealed by precipitation in slip lines and by Widmanstätten structures that formed during subsequent aging. Re-solution-treatment after the straightening operation has eliminated most of this evidence of cold work (fig. 6(b)); and the structure appears similar to that of groups 3 and 4, which have not been given the straightening treatment (figs. 6(c) and (d)).

The results of the stress-rupture tests of specimens cut from bucket airfoils are given in table III and figure 7. The stress-rupture properties of the specimens cut from the straightened buckets (group 1) were the poorest obtained. The stress-rupture lives of the specimens from the group of buckets given the flash-solution-treatment after the straightening operation (group 2) equal or exceed the stress-rupture lives of specimens cut from the group 3 buckets that performed best in reference 1 (see group 3 herein). The life of the buckets from group 4 herein (the second-best group of ref. 1) duplicated the results obtained in reference 1.

Bucket-Failure Mechanism

In the preceding investigation of Inconel 550, it was found that stress-rupture failures should occur in a zone extending from $1\frac{1}{2}$ to $2\frac{1}{2}$ inches above the base platform (critical zone). Several failures occurring outside this region were shown to be influenced by mechanisms other than stress-rupture, even though the appearance of these failures indicated only stress-rupture characteristics.

The apparent failure mechanisms for the buckets of the present investigation are listed in table II along with the location of the failure origins. On the basis of appearance and/or location of the failure origins, 64 percent of the Inconel 550 bucket failures (excluding damage failures) were influenced by fatigue. On the basis of appearance of the fractured edges alone, 36 percent of the failures were influenced by fatigue.

In the preceding study (ref. 1) and in almost all engine studies made at this laboratory, it has been found that bucket life is less than or equal to life of stress-rupture specimens cut from bucket airfoils for comparable stresses and temperatures. In the present investigation this was true for groups 2, 3, and 4 but not for the straightened buckets of group 1. The group 1 bucket life was considerably longer than the life predictable from stress-rupture properties. This may be seen in figure 7, where bucket life for the different groups is plotted (as in ref. 1) at the stress levels occurring at the failure origins.

Attempts have been made to explain this anomaly by various means. Metallographic studies revealed that the microstructures of the stress-rupture bars cut from central portions of buckets differed from structures at or near the leading and trailing edges. In general, more slip-line precipitation, finer grains, and less Widmanstätten structure occurred at or near the edges than occurred in the interior portions of the airfoils. The strength of the material in the leading- and trailing-edge regions may have been greater than that of the central portion tested in stress-rupture. However, it was not feasible to determine the stress-rupture strength of the leading- and trailing-edge material, because it is most difficult to obtain satisfactory test specimens from these areas.

DISCUSSION OF RESULTS

Only one failure occurred in the bucket group that was straightened after solution treatment (group 1). This failure occurred in 248 hours and possibly was the result of damage from the straightening operation. However, this life of 248 hours is somewhat better than the mean life of the S-816 buckets used as standards for comparison. All other buckets of group 1 had run for 439 hours when the engine test was discontinued. (It should be remembered that these buckets were inserted in the engine after the other groups of buckets had run 438 hours.)

If it is assumed that the single early failure of the straightened-bucket group was a direct result of the straightening, then it must be concluded that the flash solution treatment following straightening recovered properties of the buckets (group 2). On the other hand, if it is assumed that the 248-hour failure of group 1 is a result of normal scatter of bucket life or that it was an unusually poor bucket, then the apparent effect of the flash solution treatment on bucket life appears less significant.

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Although the results do not conclusively prove that the straightening operation used in this investigation was harmful, they do show that the straightening did not catastrophically reduce bucket performance.

It can be noted in figures 7, 6(a), and 6(b), respectively, that the interposed flash solution treatment affected both the stress-rupture life and the precipitation mechanisms of the restruck buckets. The effects of various precipitation phenomena on the physical properties of high-temperature alloys are not definitely known, but a past investigation (ref. 2) showed that the stress-rupture life of a cobalt-base alloy was structure-sensitive. It was found that a Widmanstätten structure was associated with low stress-rupture life and that salt-and-pepper precipitation (general precipitation) was beneficial.

In the present investigation, the stress-rupture life of straightened buckets (group 1), which contained Widmanstätten structure and slip-line precipitates, was approximately 1/4 of the stress-rupture life at 20,000 psi of the unstraightened buckets (group 3). The stress-rupture life of the straightened and flash-solution-treated buckets of group 2 (which was devoid of Widmanstätten structure and relatively free of slip-line precipitation) was equal to that of the group 3 buckets. These significant facts strongly indicate that a flash solution treatment after straightening would be desirable.

The results also show that reproducibility of performance was obtained for the two groups of Inconel 550 (groups 3 and 4) which were common to both this investigation and the previous one (see fig. 4).

SUMMARY OF RESULTS

This investigation was conducted to determine the effects of a straightening operation on the bucket life and the reproducibility of life of Inconel 550 buckets in a J33-9 engine. The following results were obtained:

1. The straightening operation reduced the stress-rupture properties of the airfoil material and produced a microstructure containing fairly large quantities of Widmanstätten structures and slip-line precipitation.

2. A flash solution treatment after restriking recovered stress-rupture properties of the alloy and restored a more normal solution-treated microstructure. Buckets given this treatment ran as well as unstraightened buckets.

3. The straightening operation given buckets of this investigation did not catastrophically damage the buckets. In fact, it was not conclusively evident that the straightening operation reduced the bucket life.

4. Fully solution-treated and aged groups of buckets from lots previously run in an identical type of engine evaluation reproduced the results of the first study.

CONCLUDING REMARKS

Although the engine performance of the buckets of this investigation was not proved to be reduced by the straightening operation, enough evidence of property damage and microstructural changes was obtained to suggest (1) bucket life may be reduced under engine conditions where stress-rupture is the primary failure mechanism, and (2) bucket life may be reduced under engine conditions where fatigue, thermal shock, and so forth, are influenced by microstructural changes resulting from the straightening operation. 3795

Under certain conditions, as was the case of this investigation, it may be possible to compensate for damage to properties by a re-solution-treatment. It would seem advisable to avoid straightening wherever possible; however, when it cannot be avoided, careful consideration should be given to the possible detrimental effects.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 6, 1955

REFERENCES

1. Gyorgak, C. A., Johnston, J. R., and Weeton, J. W.: Performance of Inconel 550 Turbine Blades in a Turbojet Engine and Effects of Different Forging Temperatures and Heat Treatments. NACA RM E55F08, 1955.

2. Clauss, F. V., and Weeton, J. W.: Relation of Microstructure to High-Temperature Properties of a Wrought Cobalt-Base Alloy, Stellite 21 (AMS 5385). NACA TN 3108, 1954.

TABLE I. - FORGING TEMPERATURES AND HEAT TREATMENTS USED IN PRODUCING INCONEL 550 TURBINE BUCKETS EVALUATED IN INVESTIGATION

Material	Group	Number of buckets	Forging temperature, °F	Solution treatment		First aging treatment		Second aging treatment		Remarks
				Temperature, °F	Time, hr	Temperature, °F	Time, hr	Temperature, °F	Time, hr	
Inconel 550	1	5	2150	2150	1	1600	4	1350	4	Straightened after solution treatment
	2	5	2150	2150	1	1600	4	1350	4	Straightened after solution treatment; flash-solutioned at 2150° F for 12 minutes after straightening
	3	7	2150	2150	1	1600	4	1350	4	Best-performing group (1) of ref. 1
	4	7	1950	2100	4	1550	24	1300	20	Intermediate-performing group (5) of ref. 1
S-816	--	17	Standard for comparison							

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TABLE II. - BUCKET FAILURE MECHANISMS[a] AND LOCATION OF FAILURE ORIGINS

Group	Rated-speed time to failure, hr	Characteristic type of failure	Location of failure origin above base, in.
1	247.5	SR	$1\frac{7}{8}$ MC
	439.3	Test stopped	
	439.3	Test stopped	
	439.3	Test stopped	
	439.3	Test stopped	
2	428.3	Damage	-------
	586.5	Damage	-------
	764.8	SR → F	$3\frac{1}{8}$ LE
	871.5	SR → F	$2\frac{3}{4}$ LE
	618.0	Removed to balance wheel	
3	493.0	F crack	$3\frac{1}{4}$ LE
	537.6	SR	$2\frac{1}{2}$ LE
	604.4	SR → F	3 LE
	662.8	Damage	-------
	697.5	SR	$2\frac{7}{8}$ LE
	749.5	Damage	-------
	877.8	Test stopped	
4	221.8	Damage	-------
	360.6	SR	$2\frac{15}{16}$ LE
	436.2	Damage	-------
	512.4	SR	$2\frac{1}{2}$ MC
	574.8	SR	$2\frac{5}{8}$ LE
	618.5	SR	$2\frac{1}{2}$ MC
	645.0	Removed to balance wheel	
S-816	49.8	SR	$2\frac{1}{2}$ TE
	52.7	F	$3\frac{3}{16}$ TE
	75.1	F	$1\frac{7}{8}$ TE
	84.5	F	$3\frac{3}{16}$ LE
	85.3	F	$1\frac{3}{4}$ TE
	132.8	SR → F	$2\frac{7}{16}$ LE
	151.3	SR → F	3 LE
	162.2	SR → F	$3\frac{1}{8}$ LE
	190.8	SR → F	3 LE
	208.8	SR → F	$2\frac{3}{4}$ LE
	221.8	Damage	
	253.0	Damage	
	258.6	F	$2\frac{3}{16}$ TE
	264.5	SR → F	$2\frac{1}{2}$ LE
	298.6	Damage	
	340.5	SR → F	$2\frac{15}{16}$ LE
	356.8	Damage	

[a]Failure mechanism was classified by appearance of fracture.
F - Fatigue
LE - Leading edge
MC - Midchord
TE - Trailing edge
SR - Stress-rupture
SR→F - Stress rupture followed by fatigue

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TABLE III. - STRESS-RUPTURE LIFE AT 1500° F OF INCONEL 550 BAR STOCK AND SPECIMENS TAKEN FROM BUCKETS

Group number	Specimens taken from	Stress, psi					
		30,000		25,000		20,000	
		Life, hr	Elongation in 1-in.-gage length, percent	Life, hr	Elongation in 1-in.-gage length, percent	Life, hr	Elongation in 1-in.-gage length, percent
	Bar stock	130.5	6.6	[a]320.0	---	739.4	3.3
1	Bucket airfoils	50.9	3.1	103.0	1.6	82.8 178.1	3.1 3.1
2	Bucket airfoils	110.3	1.6	327.1	6.2	813.4	1.6
3	Bucket airfoils	3.0	1.6	343.0	3.1	629.8 659.5 806.7	3.1 9.4 (b)
4	Bucket airfoils	68.2	0	108.3	3.1	463.8 469.5 642.7	3.1 0 3.1

[a]Interpolated value.

[b]Not determined. Fragment missing from gage length.

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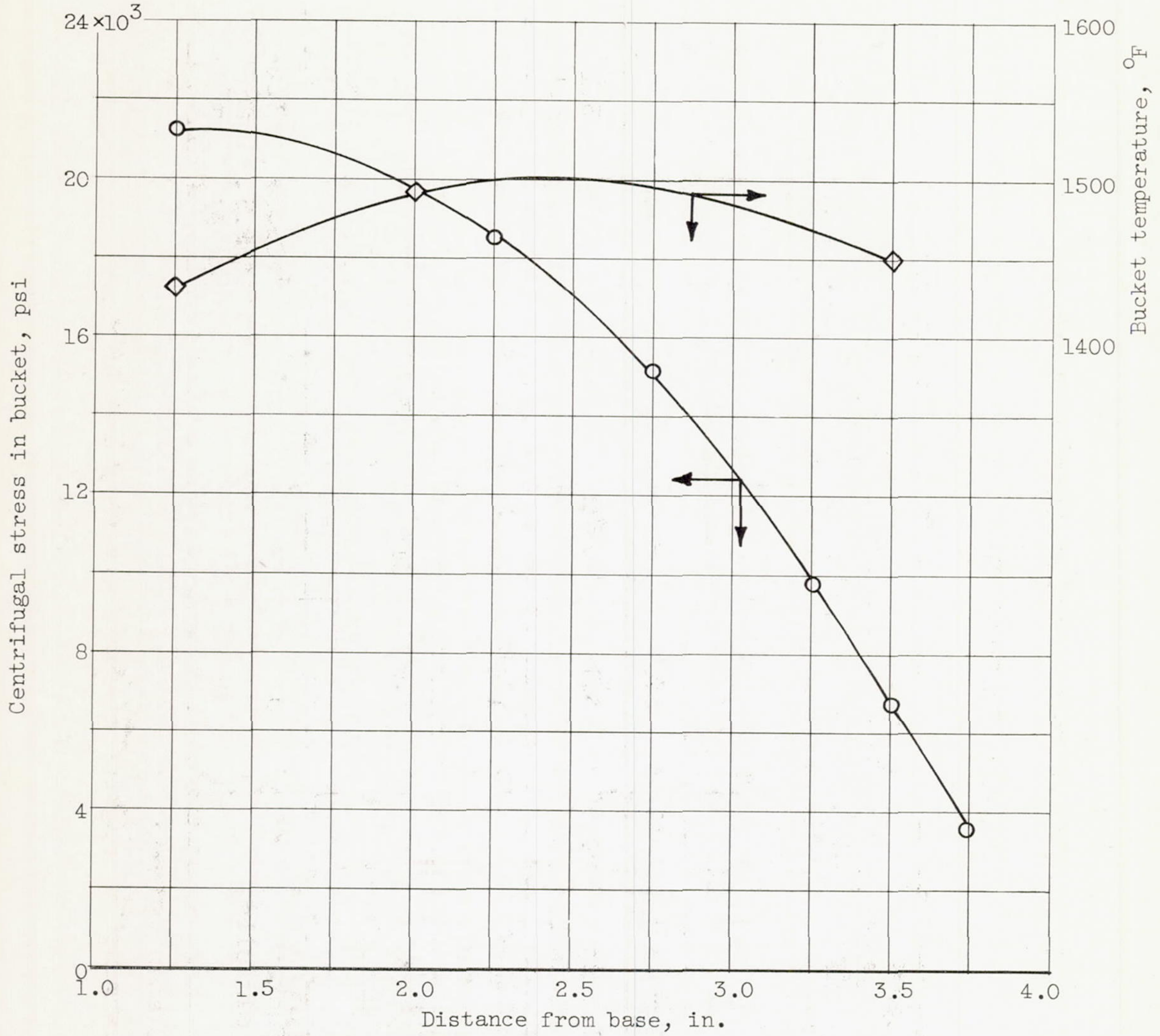

Figure 1. - Stress and temperature distribution in Inconel 550 J33-9 turbine bucket at rated speed.

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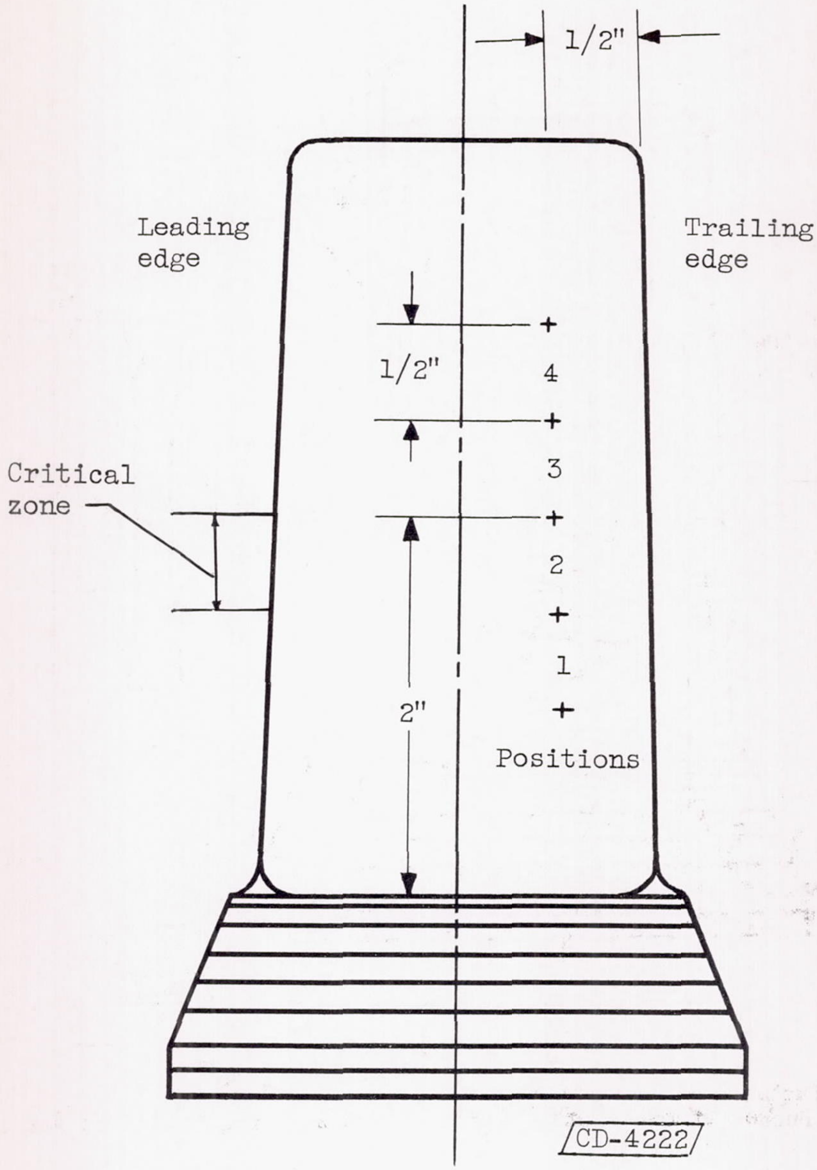

Figure 2. - Location of scribe marks on convex side of turbine bucket for use in measuring elongation.

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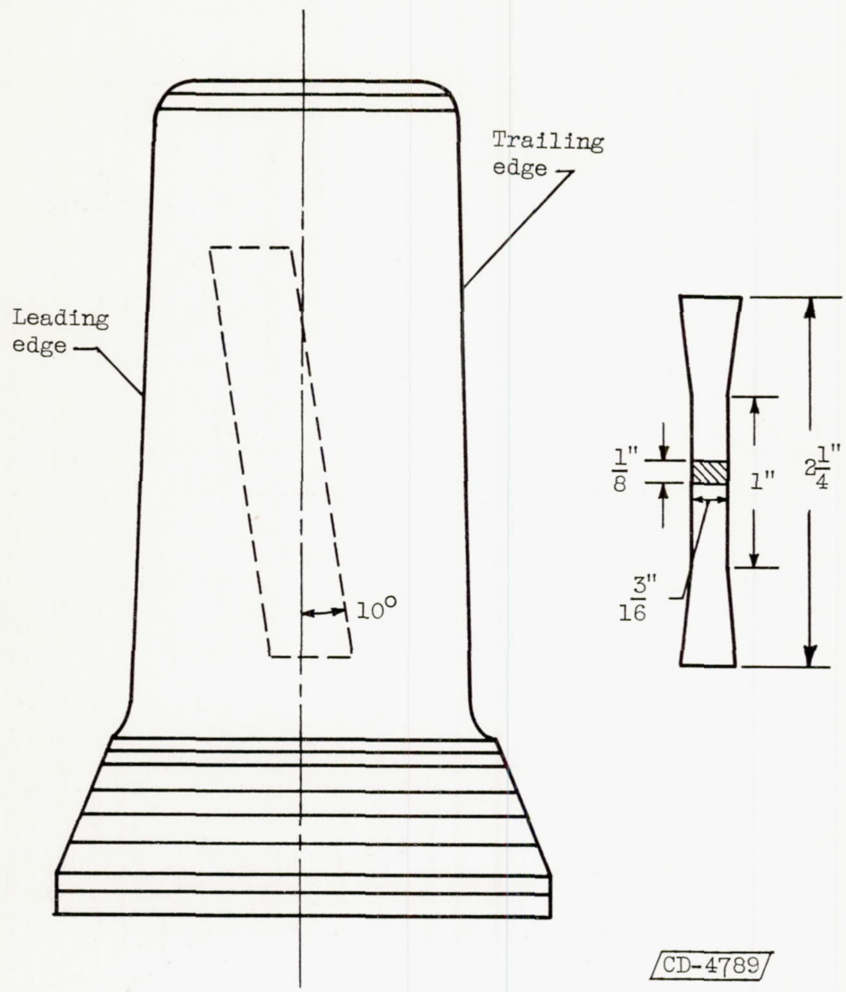

Figure 3. - Bucket stress-rupture specimen and zone from which it was machined.

Group	Forging temper-ature, °F	Solution treatment		First aging treatment		Second aging treatment		Buckets in wheel
		Temper-ature, °F	Time, hr	Temper-ature, °F	Time, hr	Temper-ature, °F	Time, hr	
1	2150	2150 Straighten	1	1600	4	1350	4	5
2	2150	2150 Straighten 2150	1 0.2	1600	4	1350	4	5
3	2150	2150	1	1600	4	1350	4	7
4	1950	2100	4	1550	24	1300	20	7
S-816	Standard Air Force stock							17
Group 1 of ref. 1 (group 3 herein)								
Group 5 of ref. 1 (group 4 herein)								

[a]Bucket group placed in wheel after 438 hours of rated-speed time was accumulated on engine.
[b]Unfailed bucket removed after 645 hours of rated speed to facilitate balancing of test wheel.

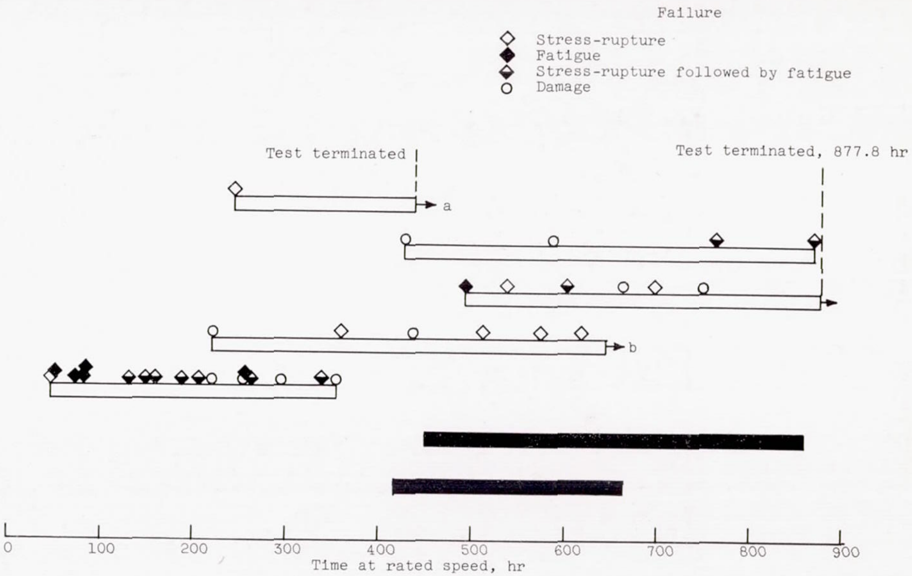

Figure 4. - Effect of straightening on bucket life of Inconel 550 in J33-9 engine at bucket temperature of 1500° F.

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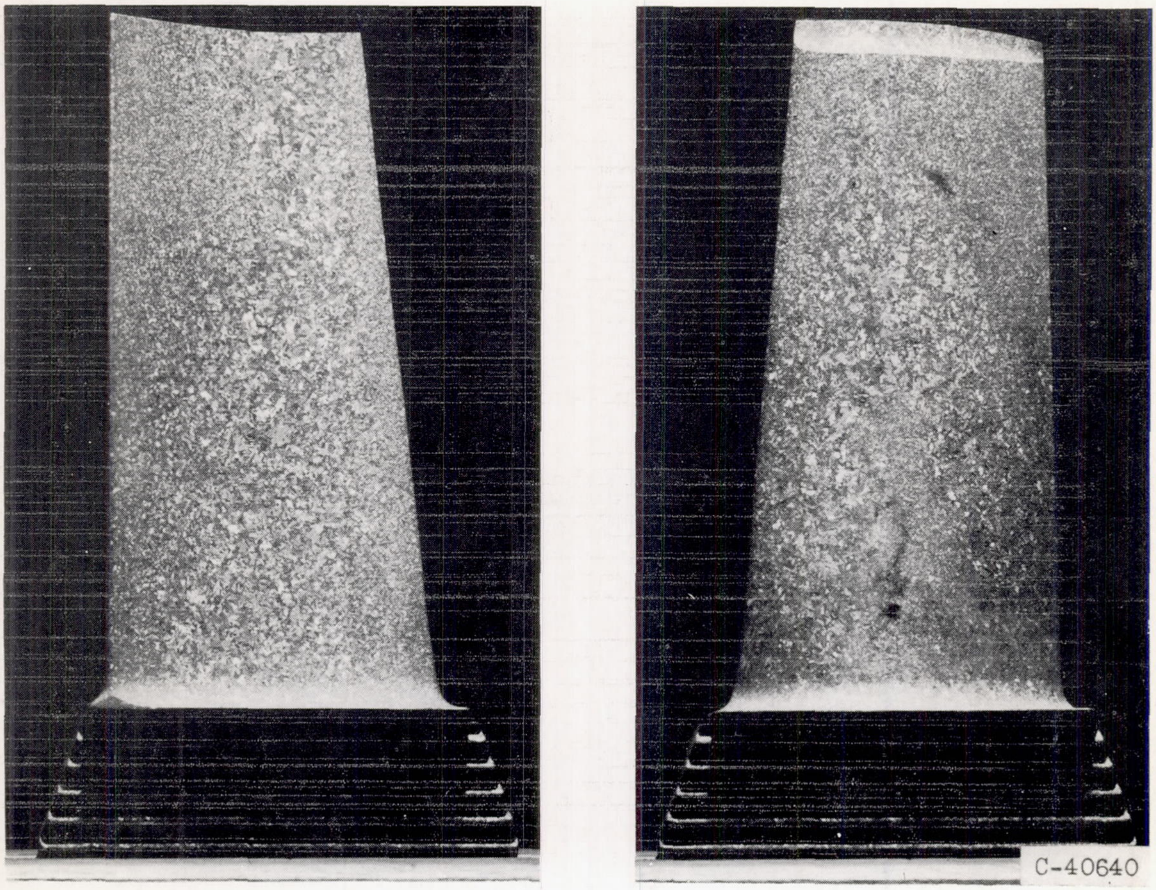
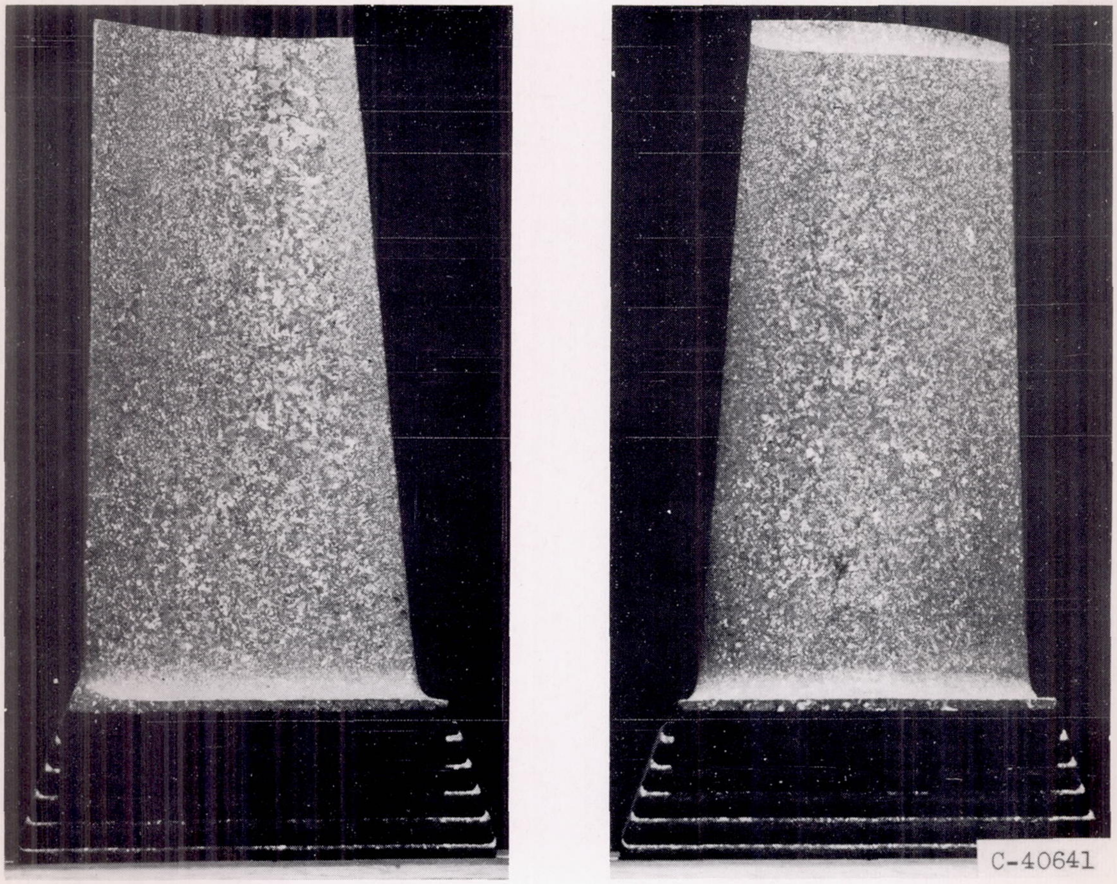


Front, concave

Back, convex

(a) Group 1.

Figure 5. - Macrograin size of Inconel 550 buckets. Etchant, 80 parts concentrated HCl, 20 parts H_2O_2, immersion.



Front Back

(b) Group 2.

Figure 5. - Continued. Macrograin size of Inconel 550 buckets. Etchant, 80 parts concentrated HCl, 20 parts H_2O_2, immersion.

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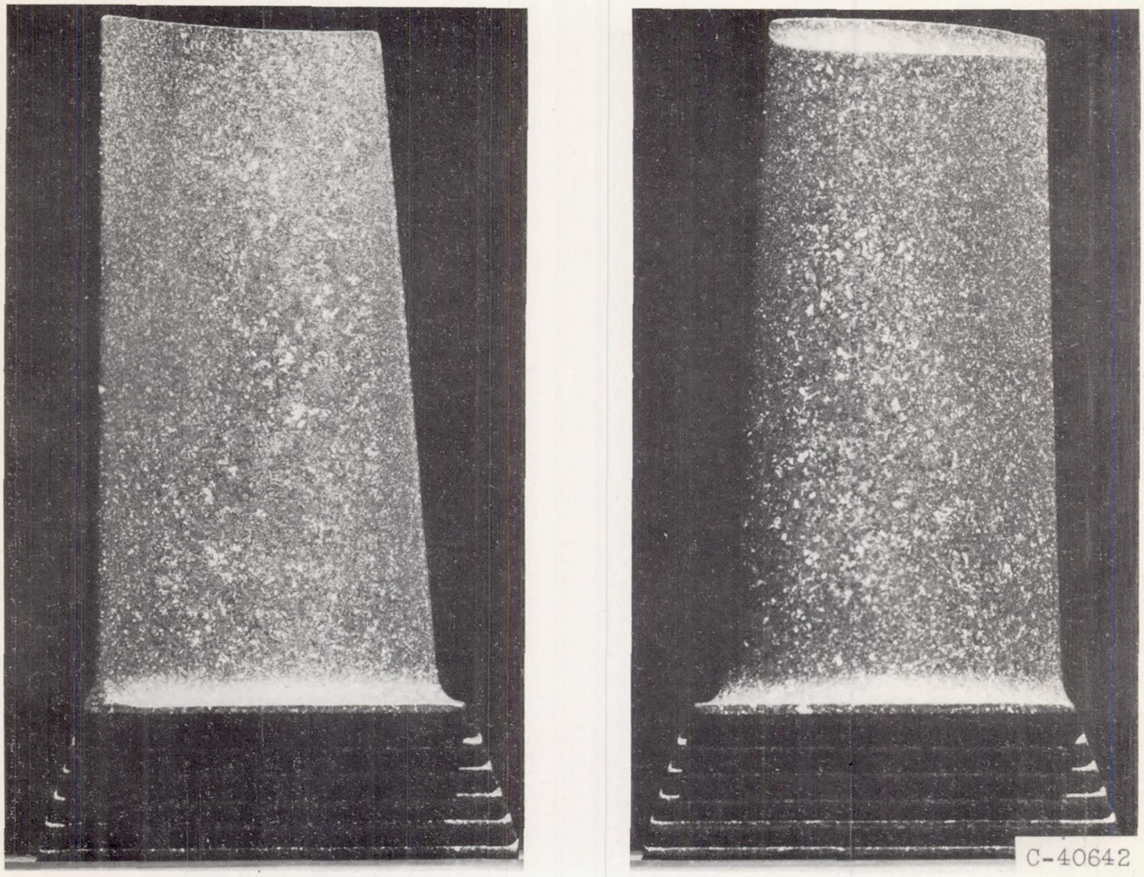

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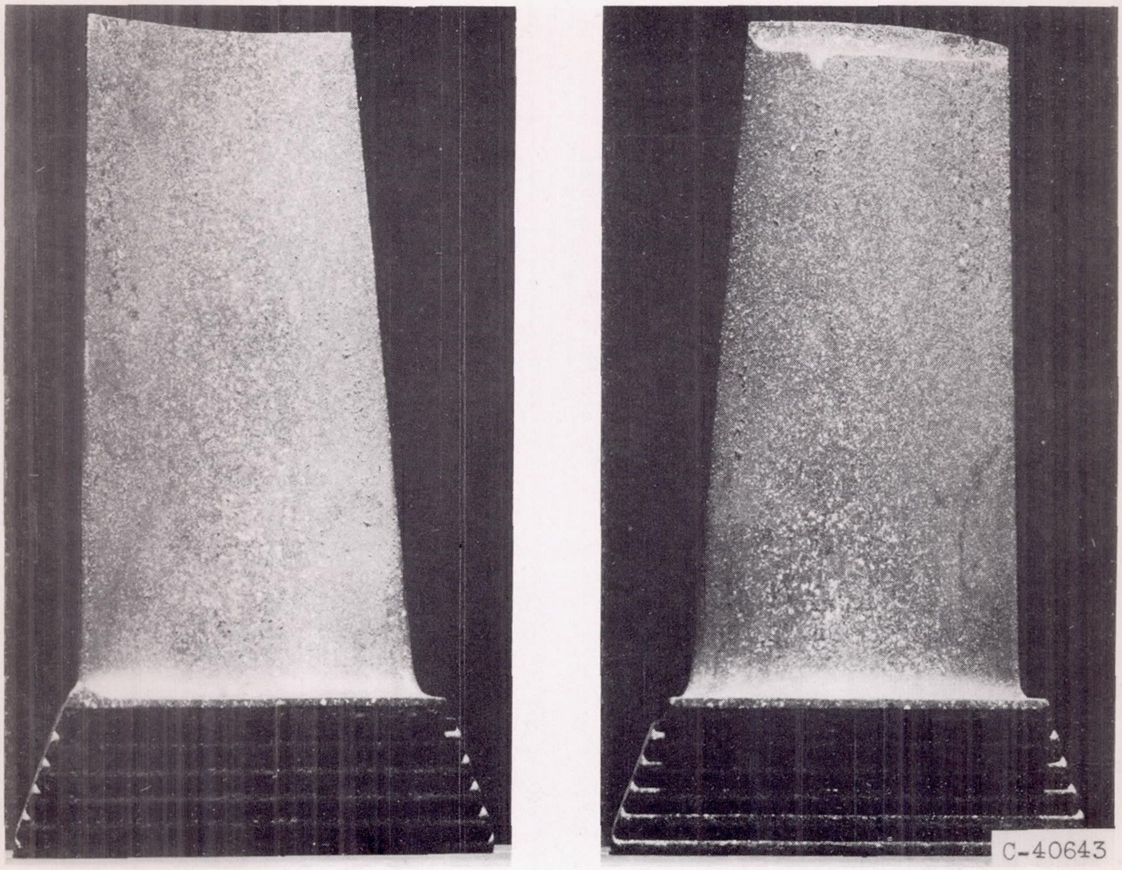
(c) Group 3.

Figure 5. - Continued. Macrograin size of Inconel 550 buckets. Etchant, 80 parts concentrated HCl, 20 parts H_2O_2, immersion.



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(d) Group 4.

Figure 5. - Concluded. Macrograin size of Inconel 550 buckets. Etchant, 80 parts concentrated HCl, 20 parts H_2O_2, immersion.

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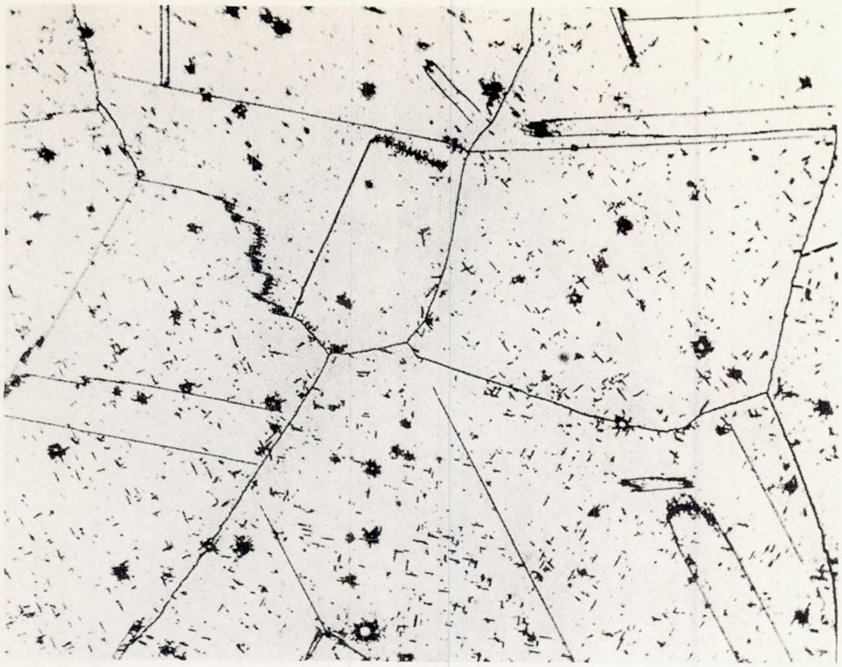
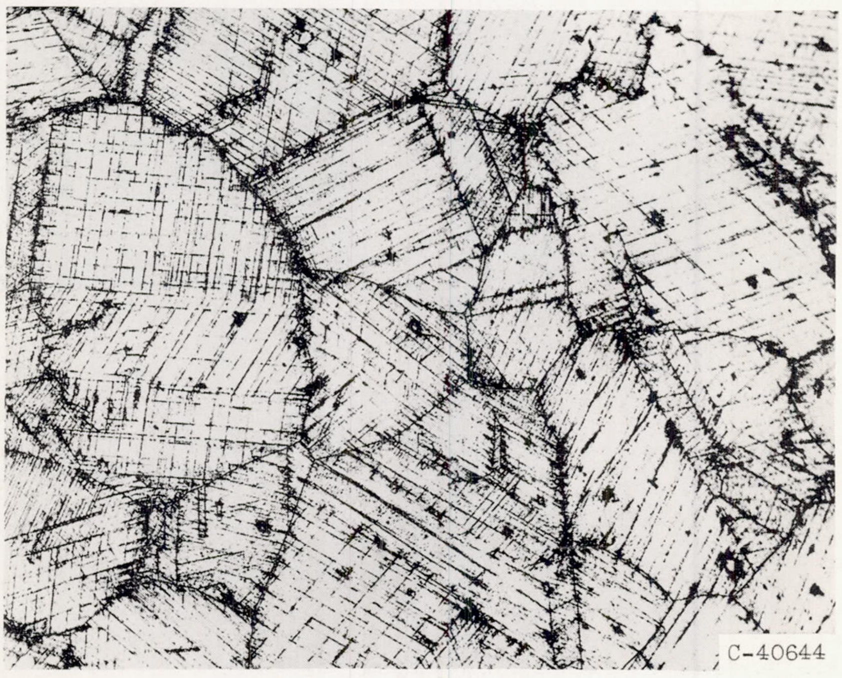


Microstructure typical of major portion of bucket cross section



Microstructure present in trailing edge of bucket cross section

(a) Group 1 (straightened after solution treatment).

Figure 6. - Typical microstructures of as-heat-treated Inconel 550 bucket. Etchant, 5-cc HF, 20-cc glycerine, 20-cc water, electrolytic. X250.

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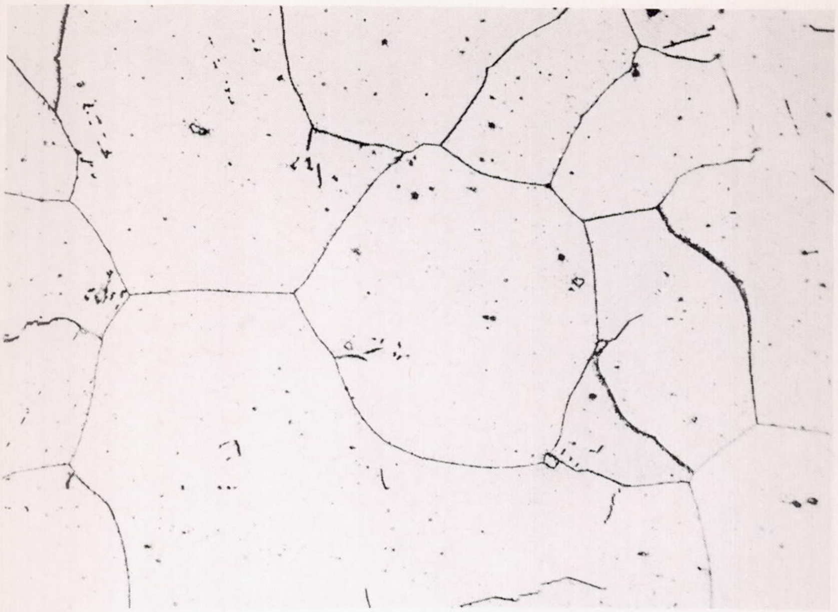

Microstructure typical of major portion of bucket cross section

Microstructure present in small area of bucket leading edge

(b) Group 2 (straightened and flash-solution-treated).

Figure 6. - Continued. Typical microstructures of as-heat-treated Inconel 550 bucket. Etchant, 5-cc HF, 20-cc glycerine, 20-cc water, electrolytic. X250.

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(c) Group 3 (best-performing group from ref. 1, rerun in this investigation. Light etch).

Figure 6. - Continued. Typical microstructures of as-heat-treated Inconel 550 bucket. Etchant, 5-cc HF, 20-cc glycerine, 20-cc water, electrolytic. X250.

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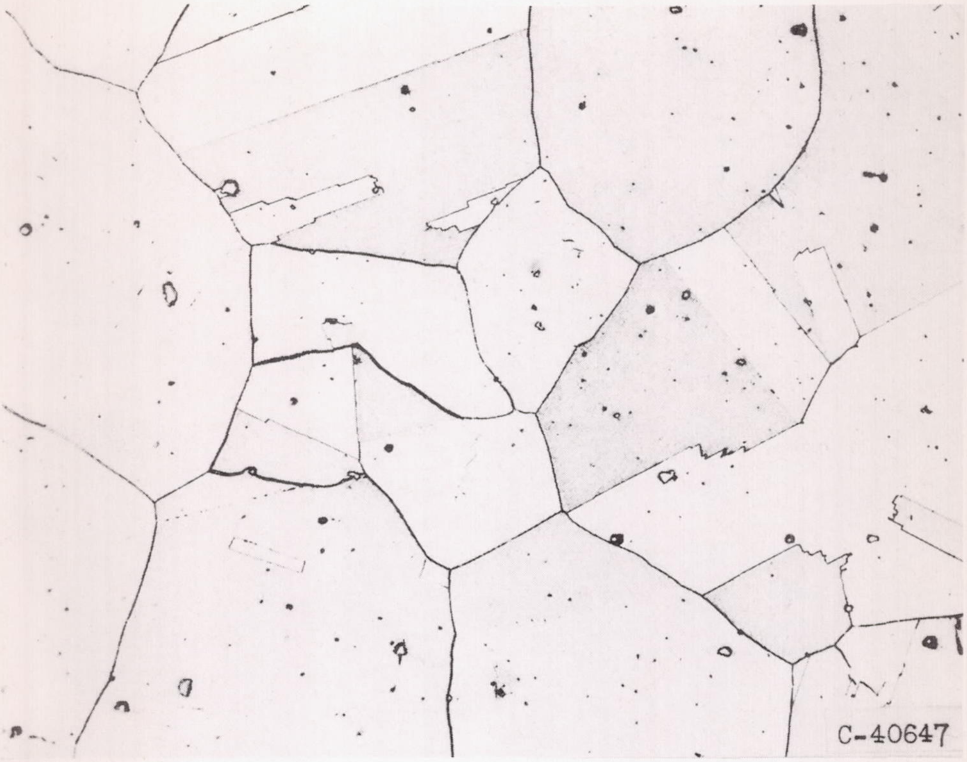

(d) Group 4 (fair-performing group from ref. 1., rerun in this investigation. Light etch).

Figure 6. - Concluded. Typical microstructures of as-heat-treated Inconel 550 bucket. Etchant, 5-cc HF, 20-cc glycerine, 20-cc water, electrolytic. X250.

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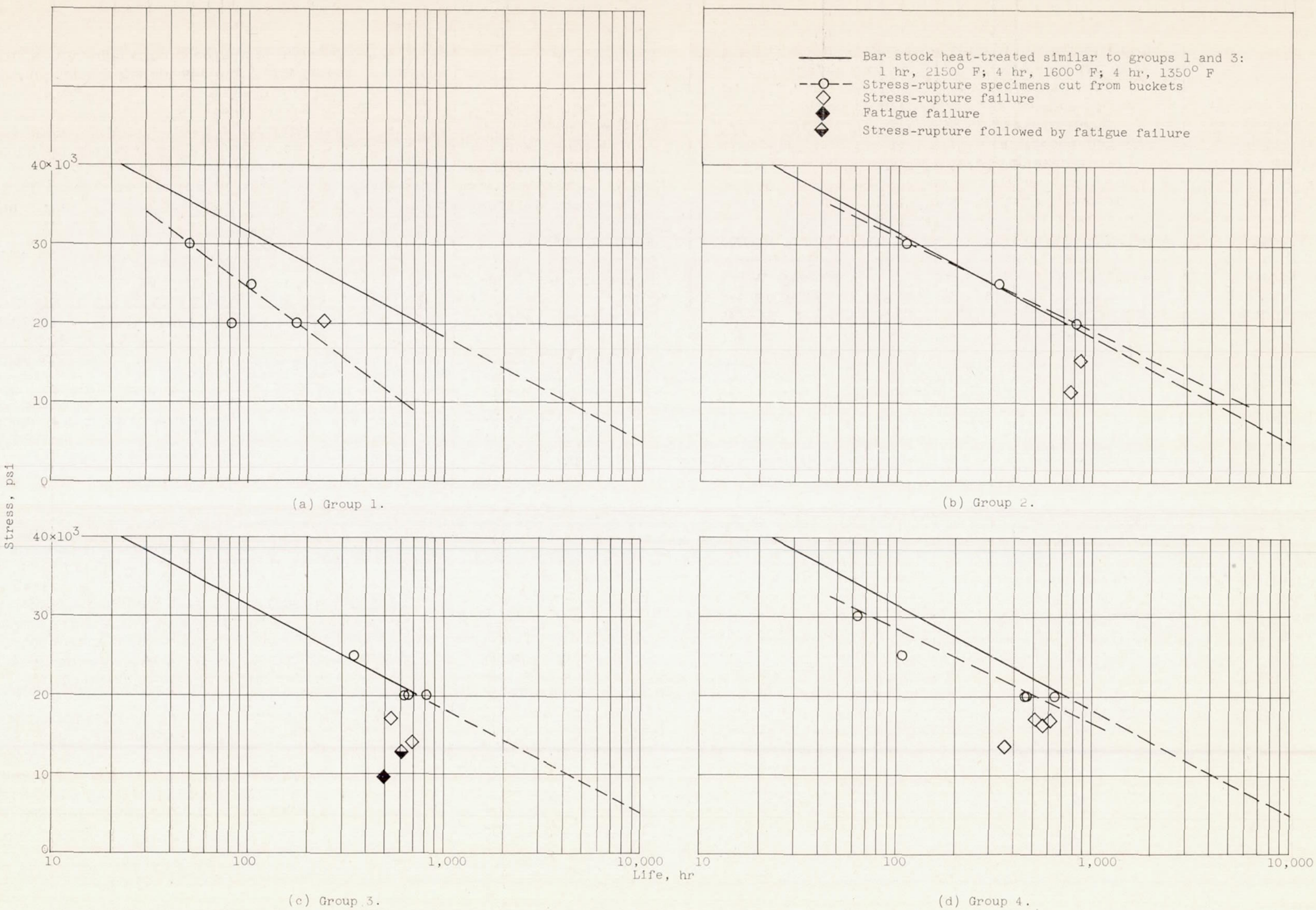

Figure 7. - Comparison of bucket life and stress-rupture life of bar stock and specimens cut from buckets at 1500° F test temperature. (Bucket life is plotted at stress level obtaining at origin of failure.)

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