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RESEARCH MEMORANDUM

CYCLIC ENGINE OPERATION OF CAST VITALLIUM TURBINE BLADES AT AN EXHAUST-CONE GAS TEMPERATURE OF 1440 ± 20° F

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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CYCLIC ENGINE OPERATION OF CAST VITALLIUM TURBINE BLADES AT AN EXHAUST-CONE GAS TEMPERATURE OF 1440 $\pm$ 20° F

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SUMMARY

An investigation was conducted to determine the effects of increased gas temperature on the performance of cast Vitallium blades in a turbojet engine. The blades were mounted in a Timken 16-25-6 rotor and subjected to accelerated operation consisting of 20-minute cycles, approximately 5 minutes at idle and 15 minutes at rated speed. The maximum estimated blade temperature during the evaluation was 1600° F.

After $7\frac{1}{2}$ cycles (2 hr, 30 min) of operation, one blade fractured as the result of a fatigue failure and two blades had large transcystalline cracks, which did not appear to result from fatigue. A large number of blades had intercrystalline cracks. The mechanism leading to intercrystalline failure was analyzed on the basis of the results of the metallurgical examination.

No correlation could be made between blade failure and elongation as compared with grain size and hardness.

Cast Vitallium turbine blades are evidently unsuitable for turbojet-engine use at a rotor speed and gas temperature that result in a stress of 21,000 pounds per square inch in the center of the airfoil section of the blade and a maximum blade temperature of approximately 1600° F. Under these conditions, the Timken 16-25-6 rotor manifested no evidence of elongation or failure in the $2\frac{1}{2}$-hour duration of operation.

INTRODUCTION

The efficiency of a gas turbine is dependent to a large extent on the gas temperature used. One of the principal factors limiting the gas temperature is the allowable operating temperature of the turbine blades. On the basis of improving gas-turbine performance, a determination of the maximum allowable operating temperature of the turbine blades is therefore desirable.

As part of the over-all program to evaluate heat-resisting alloys for use in jet engines, an investigation was conducted at the NACA Lewis laboratory to determine the performance of cast Vitallium blades mounted in a Timken 16-25-6 rotor at a gas temperature of 200° F above the cyclic temperature employed in earlier evaluations (reference 1). The data obtained serve to establish a basis for comparing other heat-resisting alloys at increased operating temperatures.

APPARATUS AND PROCEDURE

The blades used were of the current production type and were radiographically sound. The nominal chemical composition by percent was:

C	Cr	Mo
0.20 - 0.35	25.0 - 30.0	4.50 - 6.50

Ni	Fe	Mn	Co
1.50 - 3.50	2.0 maximum	1.0 maximum	balance

The investigation was conducted on a turbojet engine having a nominal thrust of 4000 pounds and incorporating a dual-entry centrifugal compressor, 14 combustion chambers, and a single-stage turbine. The apparatus, the fuel, and the engine instrumentation are described in reference 1. The operating conditions are shown in the following table:

Duration (min)	Duration (sec)	Rotor speed (rpm)	Gas temperature at exhaust-cone outlet (°F)
5	0	4000±50	1110 maximum
0	15	Acceleration to 11,500	1650±50
15	0	11,500±50	1440±20
0	15	Deceleration to 4000	1460 maximum

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The gas temperature at the exhaust-cone outlet was increased over the 1240° F used in previous cyclic evaluations (reference 1) by raising the back pressure in the turbine by means of a variable-area nozzle. This procedure caused an increase in gas temperature without changing the speed of the rotor.

A determination of the amount of elongation in turbine blades is of importance in correlating performance in the engine with existing design data. In order to determine the amount of blade elongation, five blades were scribed, as shown in figure 1(a), and measurements made between these marks. This number of blades, which were spaced at random in the rotor, was selected to give a representative sample of the entire turbine rotor. The gage marks were scribed near the trailing edge of the blades to allow measurement without removing the turbine rotor from the engine. The measurements were made by means of an optical extensometer reading to ±0.005 inch. In order to determine the amount of turbine-wheel elongation, scribe marks were placed at 1/2-inch intervals along two diameters at right angles to each other on the exhaust side of the rotor.

A metallurgical investigation of broken and unbroken blades was made to determine the mechanism of blade failure. This information permits an appraisal of the relative importance of various physical properties in turbine-blade design. The following examination procedures were used:

Visual examination. - The broken and unbroken blades were examined without magnification or under a low-power microscope to determine the surface condition of blades and of fracture areas in the blades.

Radiographic and fluorescent-oil examination. - All blades were radiographed and given a fluorescent-oil inspection after removal from the turbine wheel to determine the number of cracked blades and the location of the cracks. The turbine rotor was also given a fluorescent-oil inspection to determine if there was any evidence of failure.

Macroexamination. - All broken and scribed blades were electrolytically etched in 10-percent aqueous hydrochloric acid to reveal the macrostructure. The grain size of the blades was determined using the standard A.S.T.M. procedure except that the measurements were made at a magnification of 1 instead of the usual 100 diameters. Examination of the etched blades revealed the nature of crack propagation, that is, transcrystalline or intercrystalline.

Hardness surveys. - Hardness measurements were made on a hardness tester of the indentation type, using a major and a minor load applied by a loaded lever system. The load of 150 kilograms was applied to a spheroconical indenter (Rockwell C). The hardnesses of all the broken blades and the five scribed blades were determined from base to tip along the center and from the leading to trailing edge at the base, the middle, and the tip of the airfoil section. The zones of the hardness surveys are shown in figure 1(b).

Microexamination. - Areas of blade failure and distortion were microscopically examined to determine the mechanisms by which the blade failures occurred. Microscopic examinations were also made to determine the amount of aging occurring during engine operation. All samples were electrolytically etched in a solution of 10-percent nitric acid - 10-percent ethylene glycol in ethyl alcohol.

RESULTS

Experimental Investigation

After $7\frac{1}{2}$ cycles (2 hr, 30 min) of operation, one blade fractured and the upper portion was carried out the exhaust cone of the engine. Engine operation was terminated at this point because the condition of the remaining blades indicated that they were close to failure.

The condition of the four blades that were considered broken because they showed large cracks through the thickness of the airfoil section is presented in table I. The turbine rotor at the conclusion of the run is shown in figure 2; the fractured and cracked blades are shown in figures 3 and 4, respectively.

Final elongation measurements were made and plotted with the measurements made at the end of the first 5 cycles (1 hr, 40 min) as percentage elongation in each 1/2-inch-gage length, as shown in figure 5. Total blade elongations were determined and are presented in table II. The over-all blade elongations after $7\frac{1}{2}$ cycles range from 1.50 to 2.71 percent. From the elongation distributions, it can be seen that the largest portion of the blade elongation (2.37 to 6.04 percent) occurs in the section $1\frac{3}{8}$ to $2\frac{7}{8}$ inches from the top of the blade root. A comparison of the elongation in this section with the total elongation is also presented in table II. This comparison indicates that approximately 60 to 84 percent of the total blade elongation occurs in this zone.

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No measurable elongation occurred between the scribe marks on the rotor after $2\frac{1}{2}$ hours of operation.

Metallurgical Investigation

Visual examination. The blade surfaces were coated with a dark gray oxide and showed surface irregularities, which appeared to have been caused by a relative shifting of grains. Small cracks were visible in many of the blades away from the leading and trailing edges. The failure surface of the fractured blade (fig. 6) exhibited three distinct zones. The zone at the trailing edge was covered with a dark gray oxide and had the smooth surface typical of fatigue fracture, that is, concentric markings through the metal about a nucleus indicating that this failure originated by a fatigue mechanism. The zone at the leading edge, covered with a blue oxide, had a coarse crystalline appearance, characteristic of stress-rupture-test failures of cast Vitallium. The central zone is one of transition between the other two zones. The fracture surface of the large internal crack in another blade was similar to the leading-edge zone in the fractured blade except that it was covered with a dark gray oxide. Large cracks in the trailing edges of two blades were coated with a dark gray oxide and were similar in texture to the transition zone of the fractured blade. No evidence of a fatigue-type failure appeared in these cracks.

Radiographic and fluorescent-oil examinations. Small cracks were found in 31 of the 54 blades by the radiographic and fluorescent-oil examinations. They occurred at midchord of the blades at a distance of $1\frac{1}{4}$ to 3 inches from the top of the blade root. No cracks were found in the leading or trailing edges. No evidence of cracking was apparent in the turbine rotor.

Macroexamination. Examination of the macroetched blades under a low-power microscope showed that the cracks in the fractured blade and in the two blades with large cracks in their trailing edges were transcrystalline. The large internal crack and all small internal cracks were found to be intercrystalline. The results of the grain-size measurements are presented in table III.

Hardness surveys. The hardness distributions throughout the broken, cracked, and the five unbroken and scribed blades are given in table IV. A typical spanwise hardness distribution along the center of a blade is shown in figure 7. All Rockwell C hardness values reported are averages of two to four readings. The variation in these readings at any position was from 1 to 3 points. No appreciable chordwise variation in hardness was observed.

Microexamination. The microstructures of distorted grains and areas of intercrystalline cracking are shown in figures 8 and 9, respectively. These photomicrographs reveal the presence of what appears to be small grains within the large primary grains of the structure. Examination of an unused cast Vitallium blade disclosed no evidence of these secondary grains except for a few scattered traces in the very thin trailing edge (fig. 10). The microstructure in the zone of the fatigue nucleus in the fractured blade is shown in figure 11. Note that a very fine secondary-grain boundary occurs in the grain at the tip of the fracture. Microexamination of the failure zones in the two blades having transcrystalline cracks in their trailing edges revealed no evidence of secondary grains. A comparision of the amount of aging that occurs along the blade during operation, as shown in figure 12, revealed that the amount of aging at the base and the tip of the airfoil section was the same with a greater amount of aging occurring in the center zone of the section.

DISCUSSION OF RESULTS

The centrifugal stress distribution in cast Vitallium blades at a turbine speed of 11,500 rpm is shown in figure 13. The maximum temperature of the blades of this investigation can be approximated on the basis of previous temperature surveys at low gas temperatures. By the extension of the curve of maximum blade temperature plotted against average gas temperature at the exhaust-cone outlet (fig. 14), the approximate maximum blade temperature was 1600° F during this evaluation at an average exhaust-cone-outlet temperature of 1440° F. The conditions of engine operation therefore resulted in a stress of about 21,000 pounds per square inch at the midsection of the airfoil section of the blade (fig. 13) and a maximum blade temperature of approximately 1600° F.

By extrapolation of the data presented in reference 4, the rupture life of Vitallium at a temperature of 1600° F and a stress of 21,000 pounds per square inch is between 1 and 2 hours. These data are for aged Vitallium. The data, however, indicate that the $2\frac{1}{2}$-hour life of the blades in this evaluation is approximately what would be expected on the basis of stress-rupture data for the alloy.

Previous cyclic-engine evaluations and the results of engine operation in service at lower operating temperatures have shown that the largest number of failures of cast Vitallium blades have been caused by fatigue. The results of this investigation indicate that fatigue is a cause of blade failure at a higher temperature of operation as well.

The results of the grain-size measurements failed to produce any relation between blade failure or elongation and grain size, probably because of the wide variation of grain size and orientation within the individual blades. These variations are very likely due to differences in casting variables during blade fabrication. An example of the grain-size variation within a blade is shown in figure 15.

The results of the hardness surveys yielded no correlation between blade failure or elongation and hardness. The hardness variation along the blades (fig. 7) is an indication of the combined effects of stress and temperature distribution in strain and age-hardening the blades during operation.

The results of the metallurgical examination indicate that the grain distortion of the blades is due to orientation differences between grains. These differences result in different magnitudes of grain slip, depending on the variation of the orientation from the preferred slip orientation (fig. 8). The blade-surface distortion is the same as the "orange-peel" or "alligator-skin" surface found in coarse-grained low-carbon steels after deep-drawing (reference 5). The orange-peel effect in steels is also due to orientation differences in coarse-grained areas. After the grains have elongated to the point where they become strain-hardened, they resist further elongation. Further stress then induces failure in the grain boundaries.

The presence of the secondary-grain boundary in the fatigue-fractured blade (fig. 11) suggests the possibility that the secondary grains and their boundaries, when present in the original unused blades (fig. 10) or formed during operation, might serve as the stress raisers that nucleate a fatigue failure. The intercrystalline cracks might also serve as fatigue nuclei. The presence of secondary grains and intercrystalline cracks suggests that, although cast Vitallium blades have a certain rupture life, they are only suitable for use to a point in the rupture life where the stress raisers within the alloy make it susceptible to fatigue failure.

Results of the microexamination of the two blades having large transcrystalline cracks in their trailing edge indicate that they apparently failed by some different mechanism.

SUMMARY OF RESULTS

The results of the investigation of cast Vitallium blades mounted in a Timken 16-25-6 rotor at a gas temperature of 1440° ±20° F at the exhaust-cone outlet may be summarized as follows:

1. The life of the cast Vitallium blades mounted in a Timken 16-25-6 rotor in the cyclic-engine determination at a stress of 21,000 pounds per square inch at the center of the airfoil section and a maximum blade temperature of approximately 1600° F was $7\frac{1}{2}$ cycles (2 hr, 30 min). There was no evidence of failure or radial elongation of the rotor at the end of this time.

2. At the end of $7\frac{1}{2}$ cycles, one blade fractured by a fatigue mechanism. Two blades had large transcrystalline cracks, which did not appear to have been caused by fatigue. One blade had a large internal crack and 31 of the 54 blades had small cracks, all of which were intercrystalline. All blades showed evidence of grain distortion, which resulted in an "orange-peel" effect on the blade surface.

3. The over-all blade elongations after $7\frac{1}{2}$ cycles ranged from 1.50 to 2.71 percent. The elongation in a zone $1\frac{3}{8}$ to $2\frac{7}{8}$ inches from the top of the blade root ranged from 2.37 to 6.04 percent. Approximately 60 to 84 percent of the total blade elongation occurred in this zone.

4. No correlation could be found between blade failure and hardness or between elongation and hardness. All blades were harder at the center than at the tip or the base of the airfoil section.

5. A wide spread in grain size within and between the blades was observed. No correlation could be made between blade failure and grain size or between elongation and grain size.

CONCLUSIONS

The following conclusions can be drawn from the investigation of cast Vitallium blades. Cast Vitallium turbine blades are unsuitable for turbojet-engine use at a rotor speed and a gas temperature that result in a stress of 21,000 pounds per square inch in the center of the airfoil section of the blade and a maximum blade temperature of approximately 1600° F. Under these conditions, the Timken 16-25-6 rotor manifested no evidence of elongation or failure in the $2\frac{1}{2}$-hour duration of operation.

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2. Kemp, Richard H., and Morgan, William C.: Analytical Investigation of Distribution of Centrifugal Stresses and Their Relation to Limiting Operating Temperatures in Gas-Turbine Blades. NACA RM E7L05, 1948.

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TABLE I - CONDITION OF BLADES CONSIDERED BROKEN AFTER $7\frac{1}{2}$ CYCLES

(2 HR, 30 MIN) OF OPERATION

Blade	Condition	Chord position of failure	Distance from root (in.)	Length of crack (in.)
6	Fractured	Entire blade	$1\frac{1}{2}$	-----
39	Cracked	Trailing edge	$2\frac{7}{16}$	0.72
42	Cracked	Trailing edge	$1\frac{9}{16}$	.60
48	Cracked	1/4 inch from trailing edge	$2\frac{1}{4}$	.58

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TABLE II - SUMMARY OF ELONGATION MEASUREMENTS ON SCRIBED BLADES

Blade	Total elongation of airfoil section (in.)		[a]Total elongation in zones 3 to 5 (in.)	Total elongation in airfoil section (percent)		[a]Elongation in zones 3 to 5 (percent)	[a]Fraction of total airfoil section elongation in zones 3 to 5 (percent)
	5 cycles	$7\frac{1}{2}$ cycles	$7\frac{1}{2}$ cycles	5 cycles	$7\frac{1}{2}$ cycles	$7\frac{1}{2}$ cycles	$7\frac{1}{2}$ cycles
15	0.0875	0.1083	0.0906	2.19	2.71	6.04	83.6
18	.0592	.0760	.0582	1.48	1.90	3.88	76.6
45	.0579	.0747	.0550	1.45	1.89	3.67	73.6
47	.0748	.0893	.0708	1.87	2.23	4.72	79.4
54	.0479	.0598	.0356	1.20	1.50	2.37	59.5

[a]$1\frac{3}{8}$ to $2\frac{7}{8}$ in. from top of blade root.

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TABLE III - GRAIN-SIZE MEASUREMENTS

Blade	Average grain size (grains/sq in.)	Range of grain size (grains/sq in.)
15	10	4 - 32
18	5	$\frac{1}{3}$ - 32
45	34	4 - 128
47	8	$1\frac{1}{2}$ - 32
54	9	$1\frac{1}{2}$ - 32
6[a]	5	1 - 16
39[b]	10	4 - 32
42[b]	30	16 - 128
48[b]	10	4 - 32

[a]From root to fracture.

[b]Badly cracked blades.

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TABLE IV - HARDNESS SURVEY

Blade	Condition	[a]Hardness, Rockwell C			
		Root base	Root top	Airfoil center	Blade tip
15	Unbroken	30.0	33.0	40.5	33.5
18	Unbroken	29.5	32.0	39.5	32.0
45	Unbroken	30.0	32.0	39.0	31.0
47	Unbroken	30.0	33.5	39.5	32.5
54	Unbroken	29.5	32.5	39.5	31.0
6	Broken	30.0	33.0	38.0[b]	----
39	Cracked	30.0	33.5	39.0	33.0
42	Cracked	30.0	33.0	40.0	32.5
48	Cracked	29.5	34.0	40.0	34.5

[a]Average hardness values.

[b]$1\frac{1}{2}$ in. from top of root.

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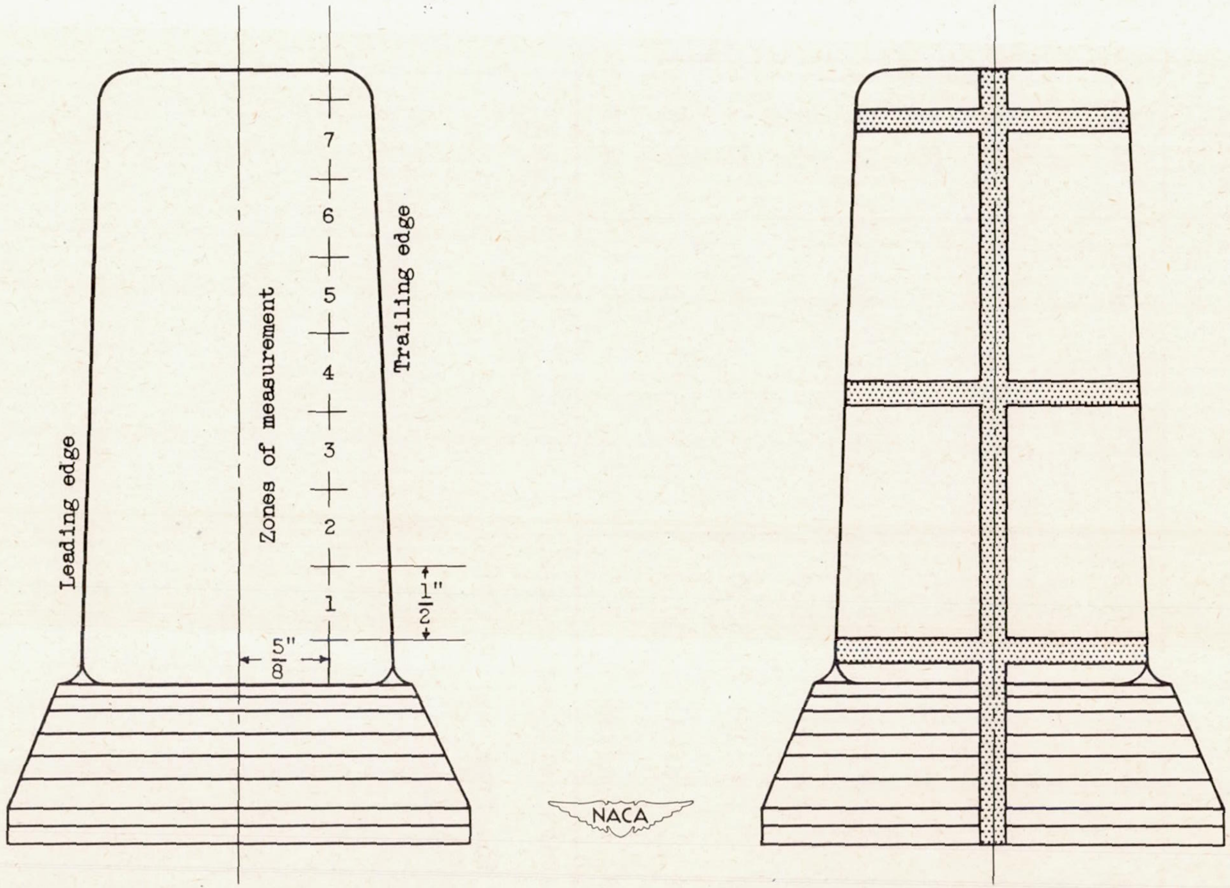

(a) Scribe marks on convex side of turbine blade for use in measuring elongation.

(b) Zones of blade (shaded areas) where Rockwell C hardness measurements were made.

Figure 1. - Location of scribe marks and zones of hardness survey.

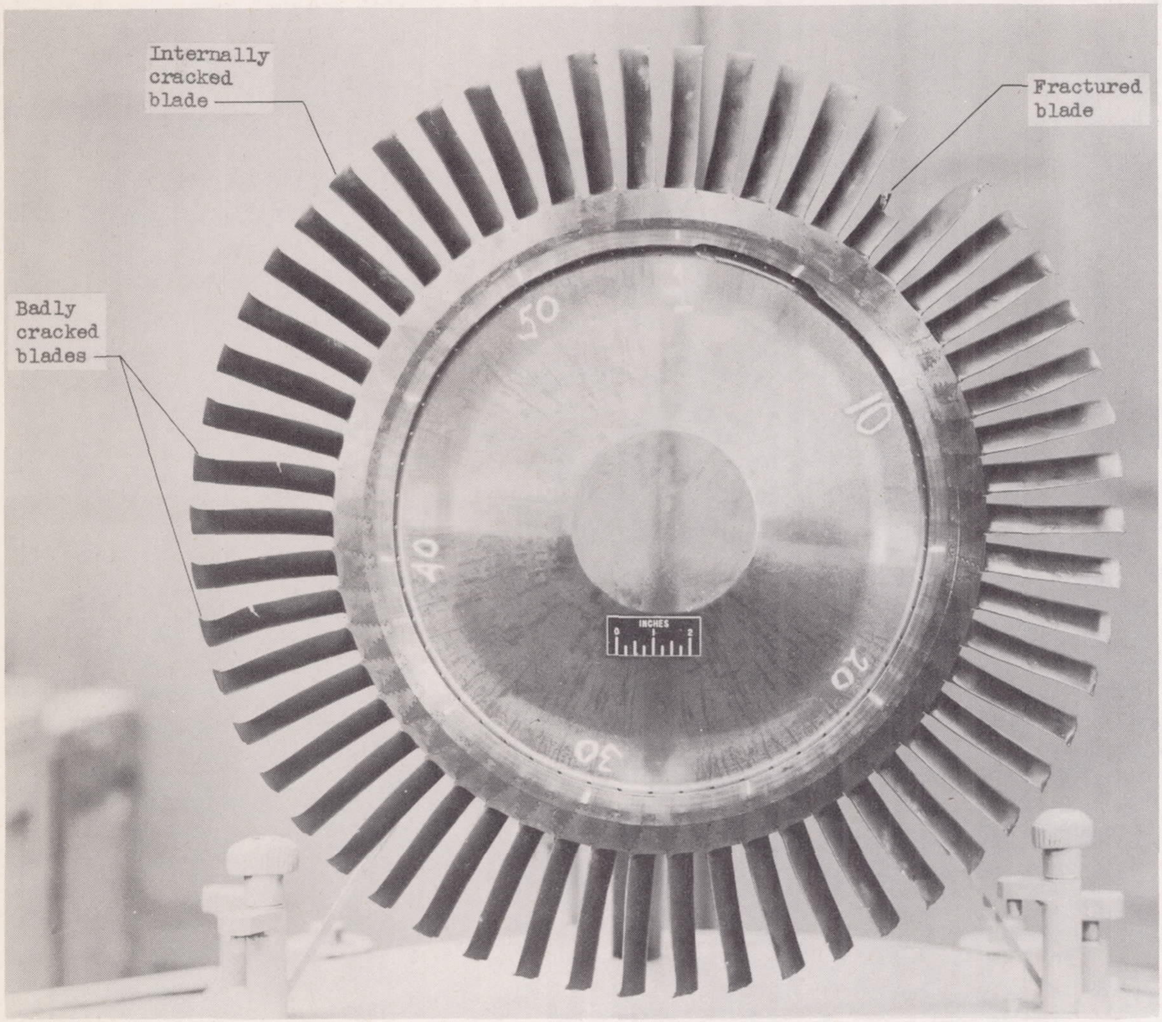

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Figure 2. - Turbine rotor after $7\frac{1}{2}$ cycles (2 hr, 30 min) of operation.

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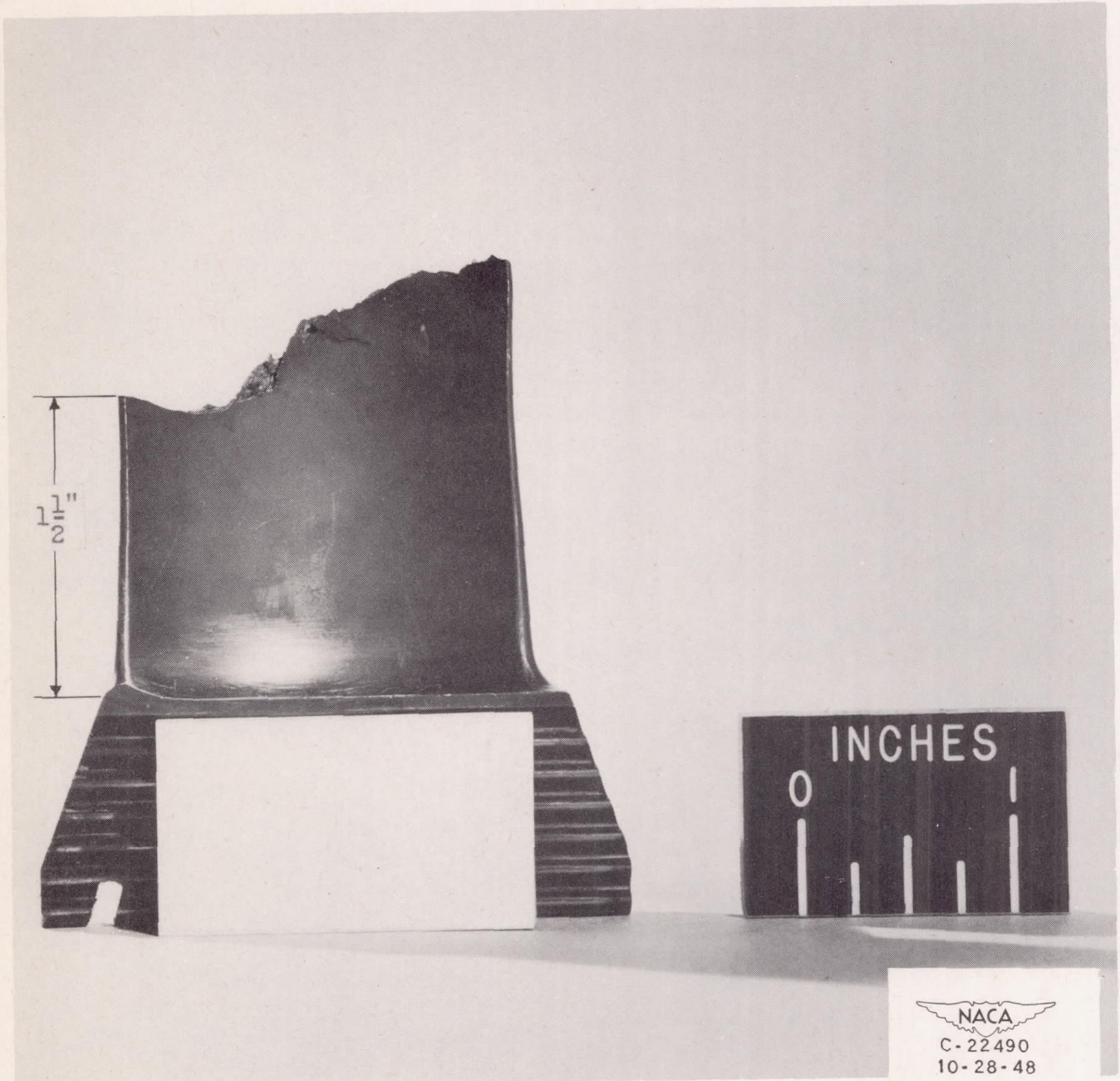

Figure 3. - Failure path across fractured blade.

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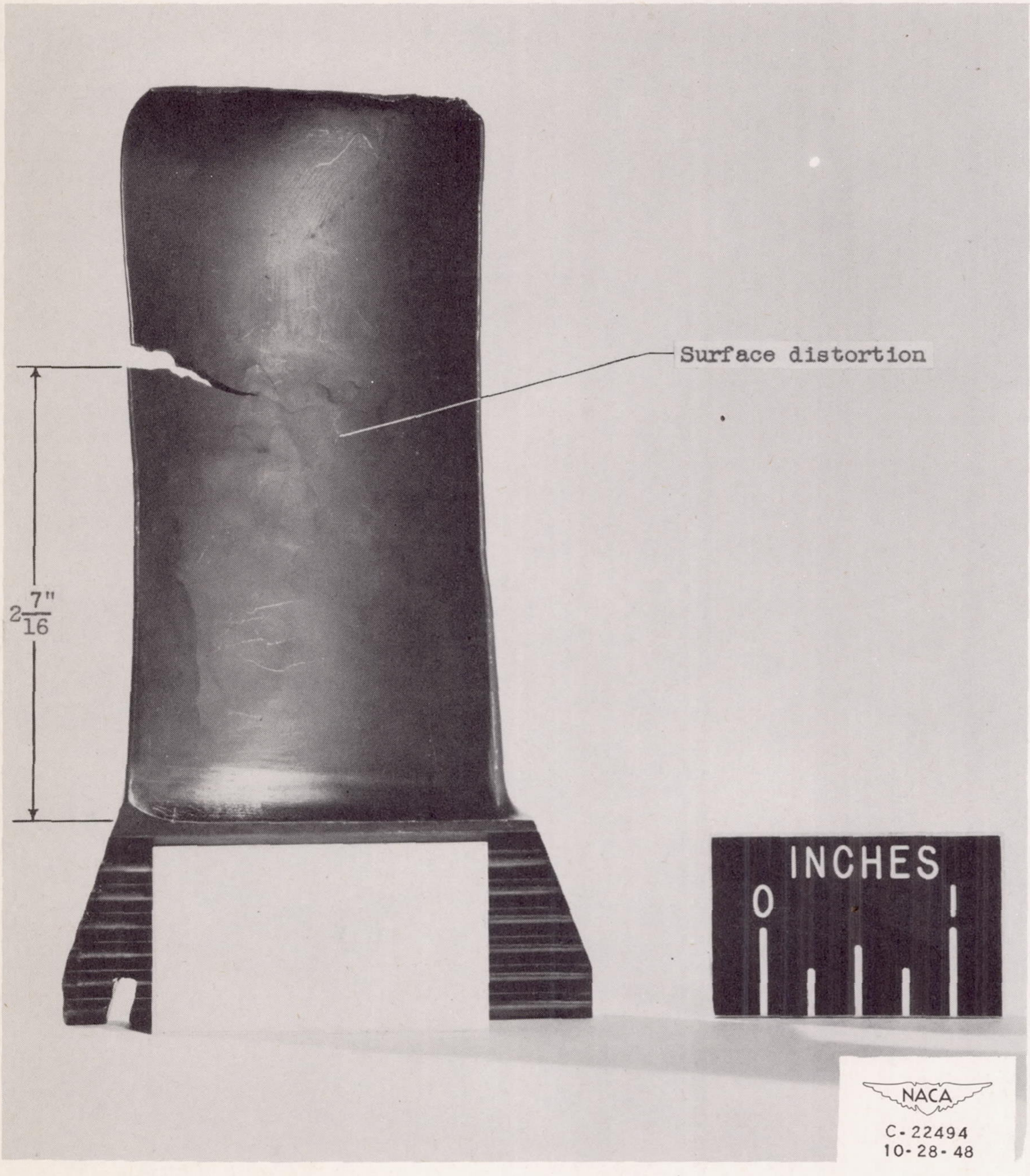

Figure 4. - Blade with large crack in trailing edge. Note surface distortion.

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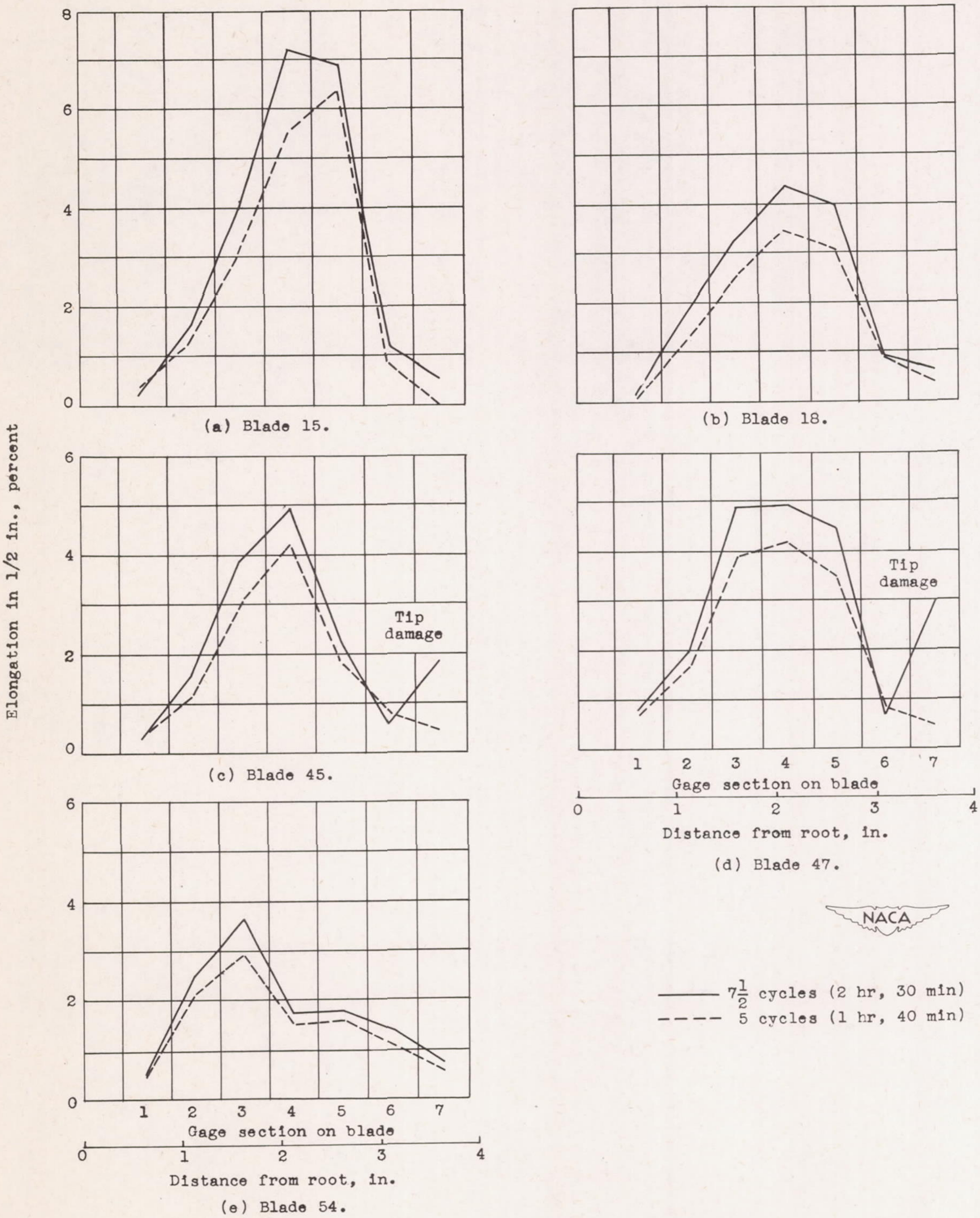

Figure 5.- Variation in elongation along airfoil section of blade plotted at midpoint of gage section.

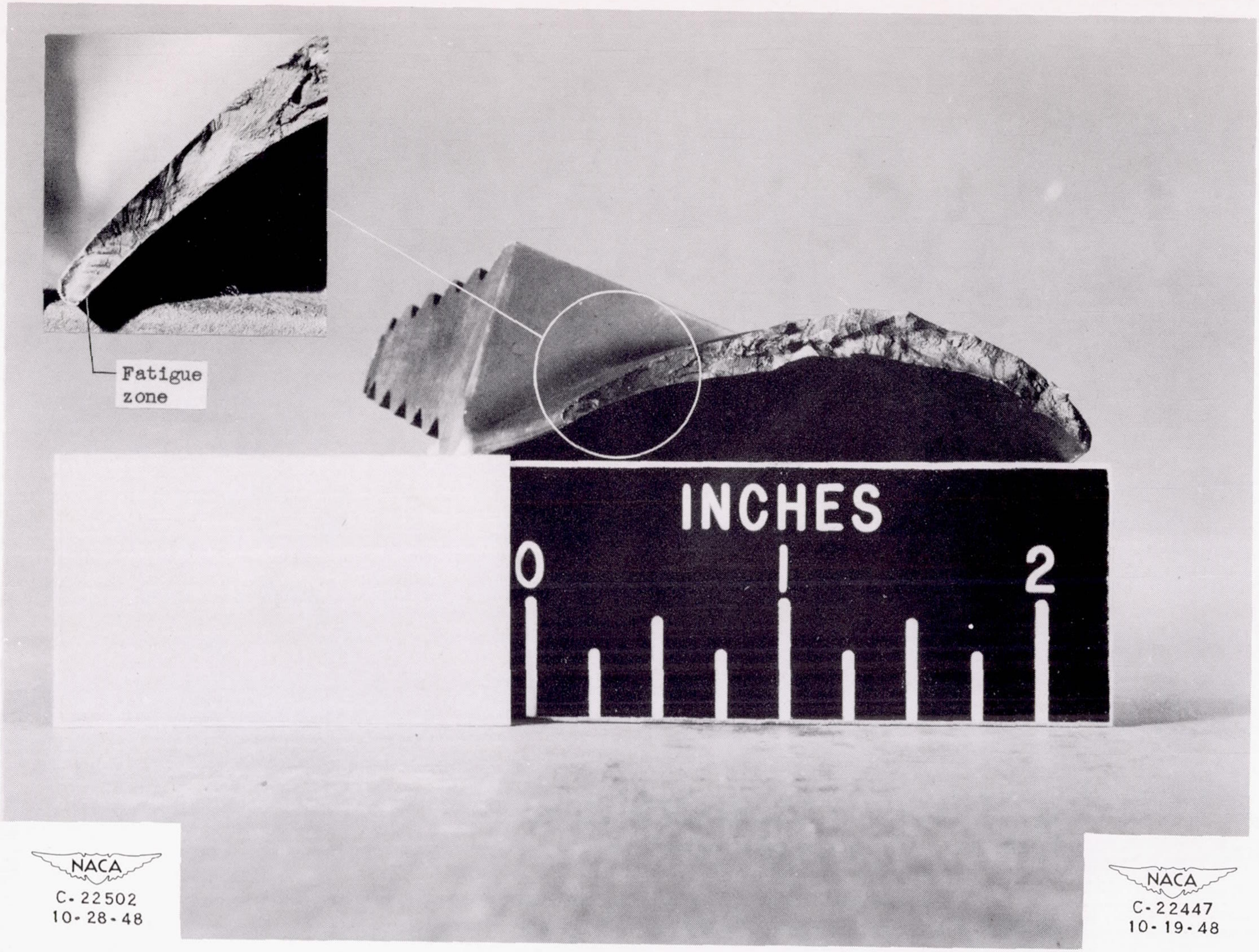

Figure 6. - Fracture surface of fractured blade, X2. Insert shows trailing-edge section, X4. Note fatigue-type fracture starting at edge of blade.

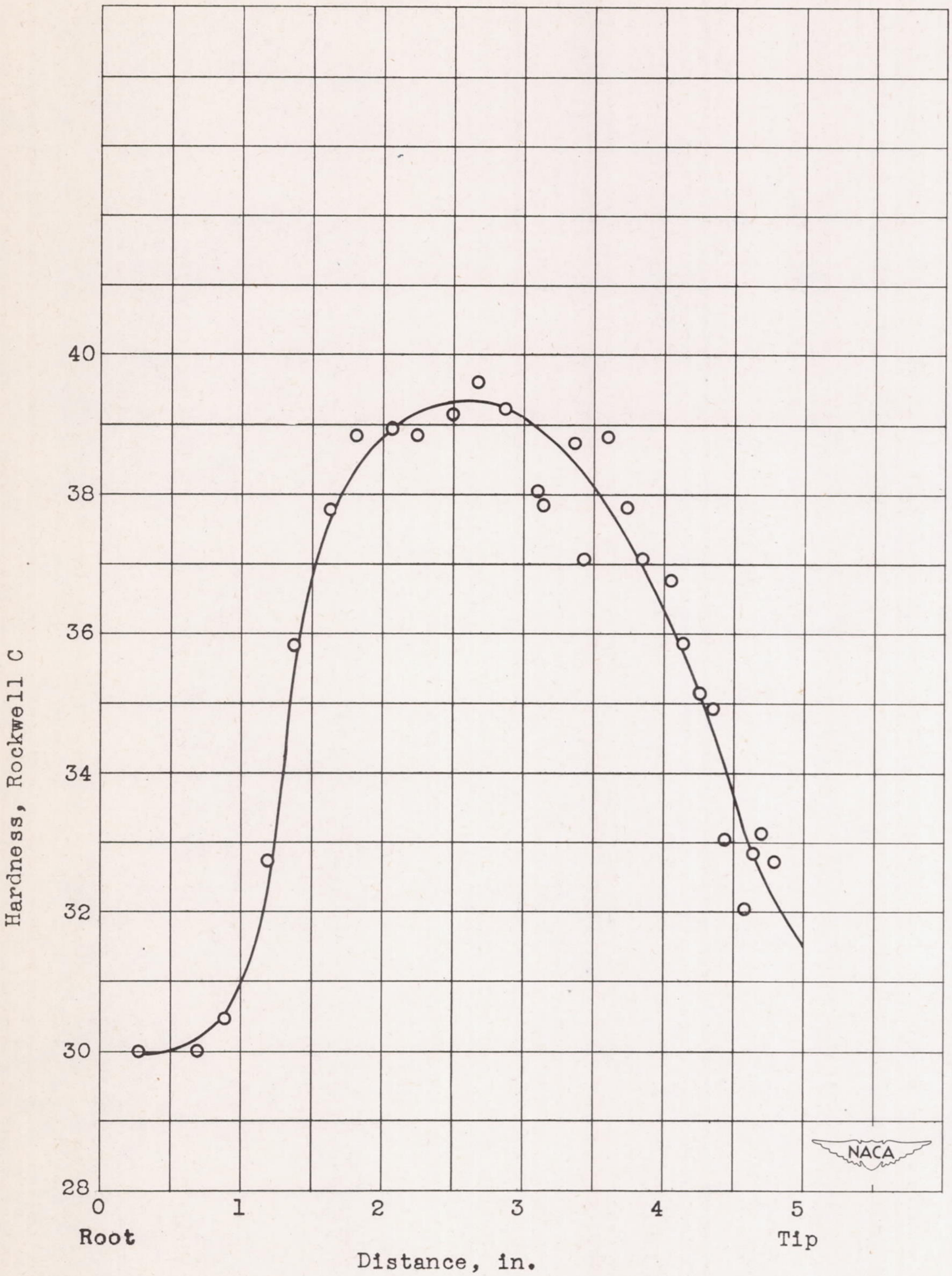

Figure 7. - Typical hardness distribution along center of blade. (Data points are average hardness values.)

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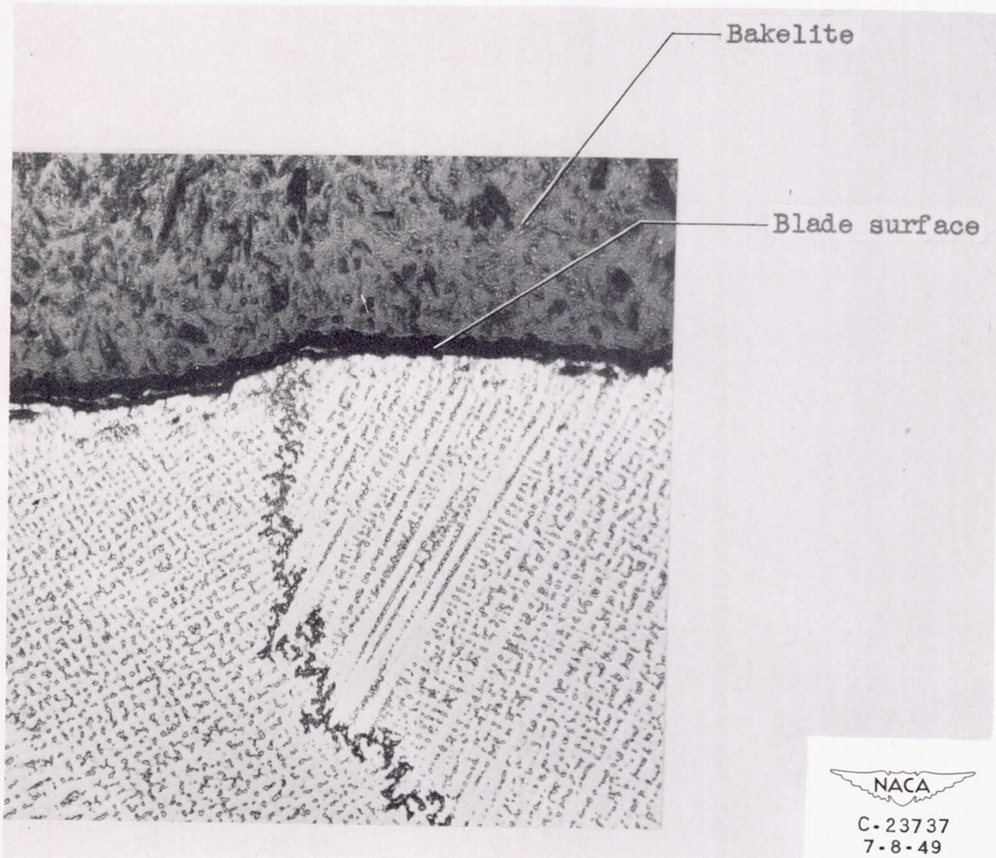

Figure 8. - Distorted grains. Structure at blade surface indicates grain movement, X25.

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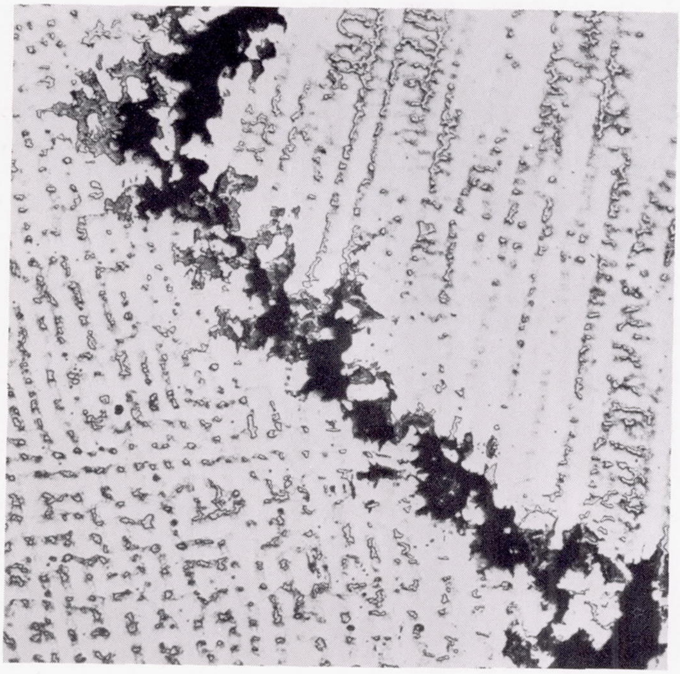
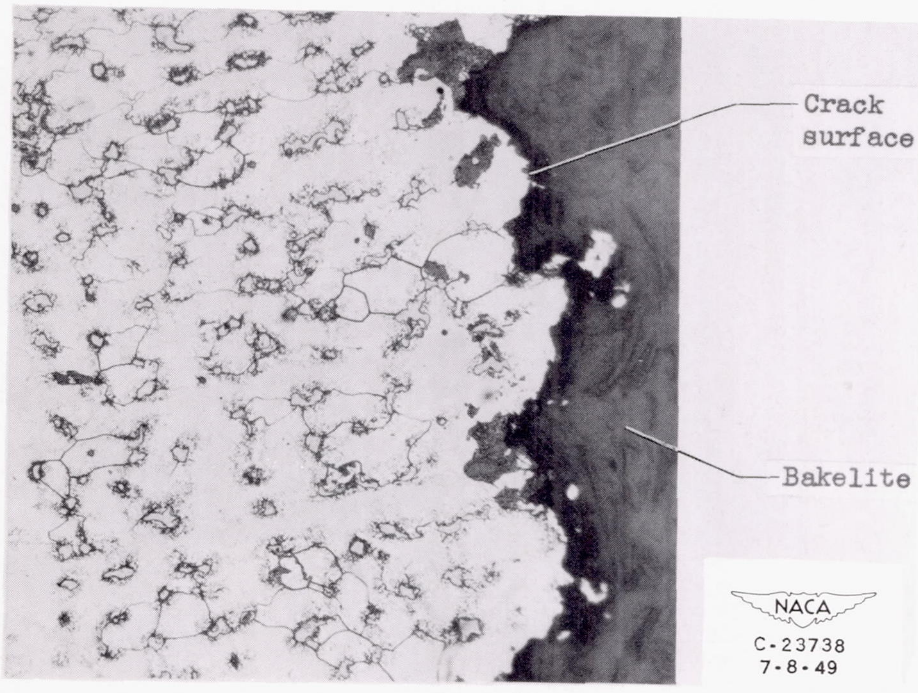


(a) Large intercrystalline crack in blade 48, X50.



(b) Area alongside crack containing secondary grains, X250.

Figure 9. - Intercrystalline cracks.

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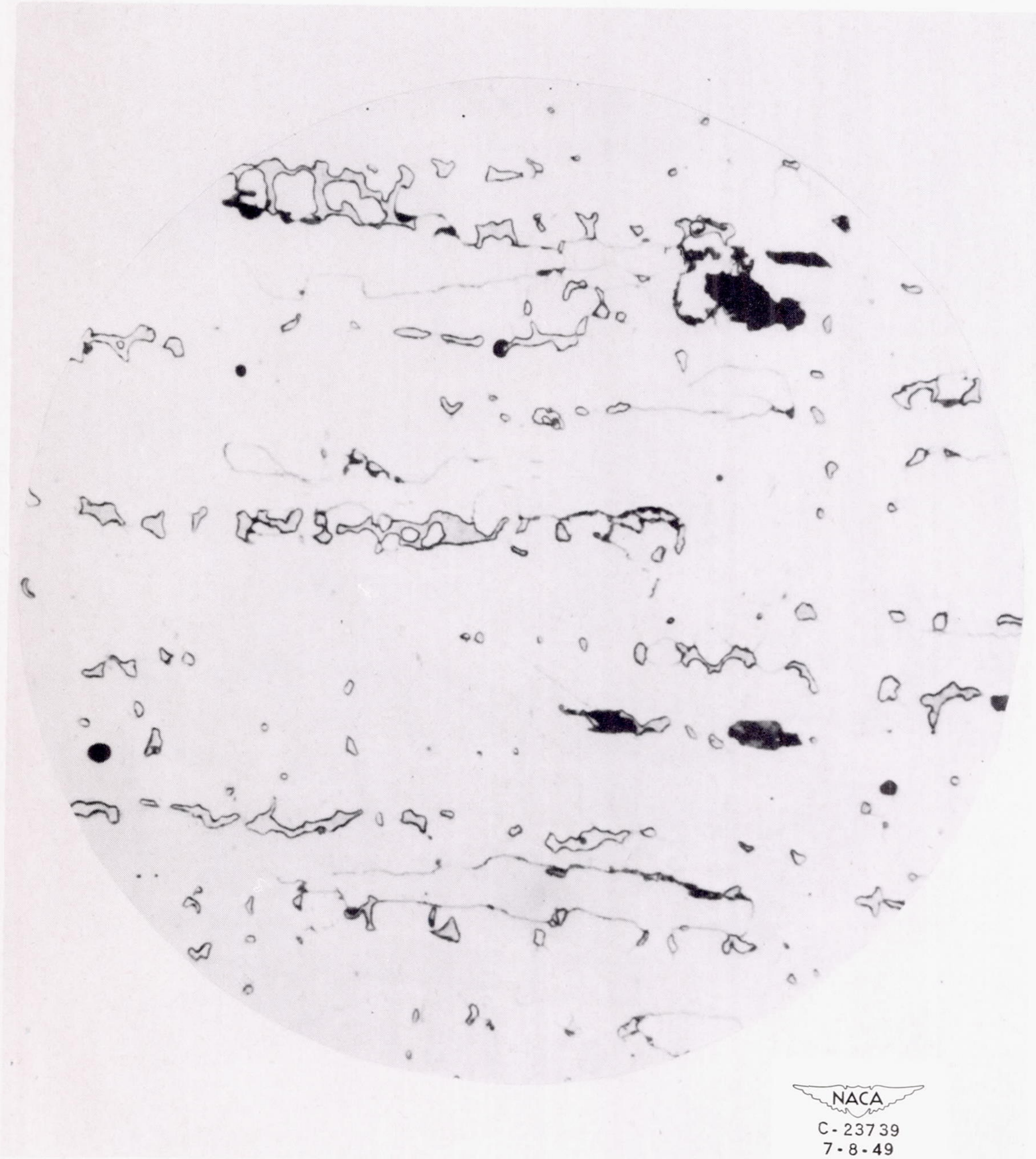

Figure 10. - Microstructure near trailing edge of unused Vitallium blade showing traces of secondary grains, X500.

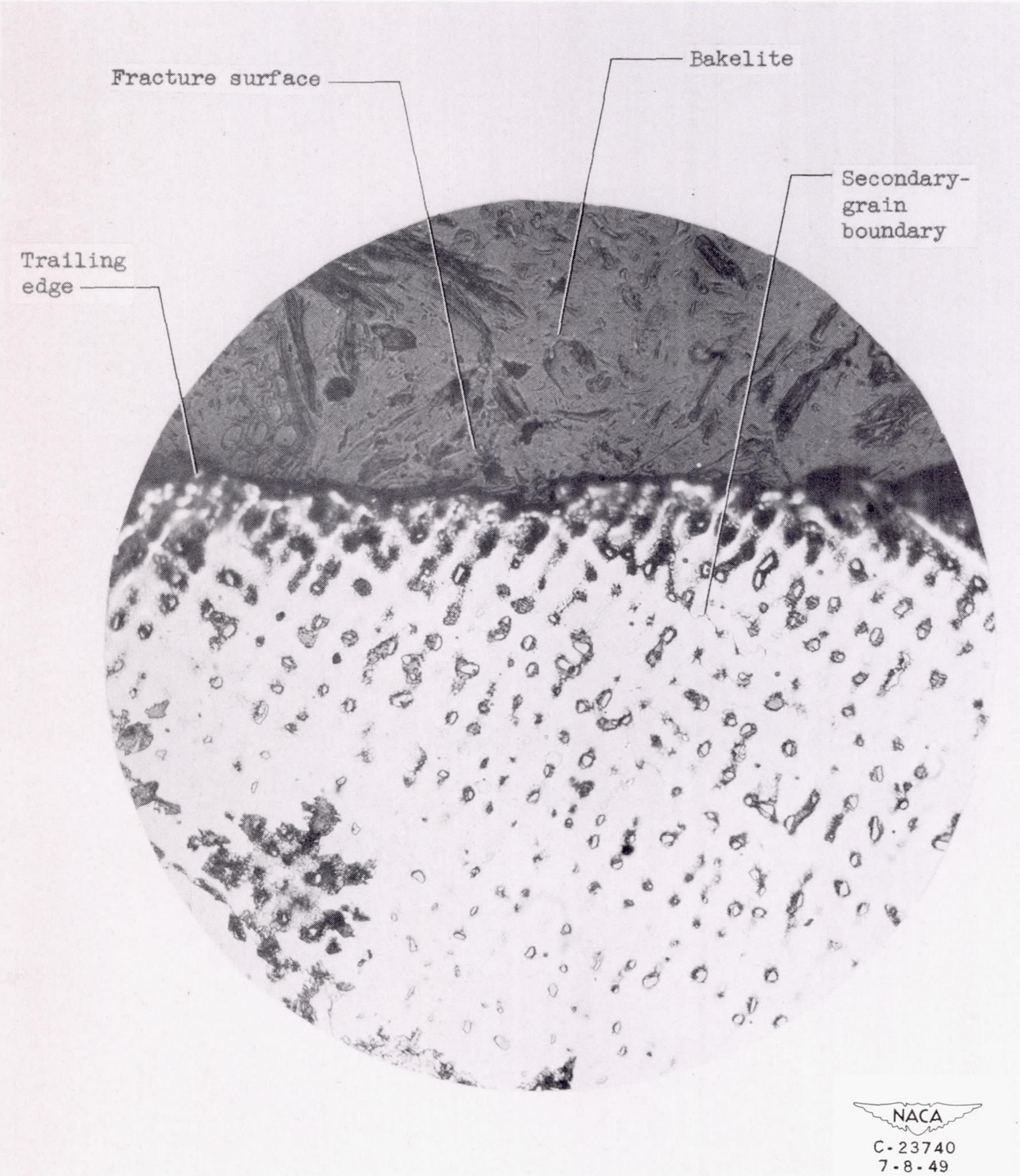

Figure 11. - Microstructure in zone of fatigue nucleus of blade 6. Note secondary grain boundary, X250.

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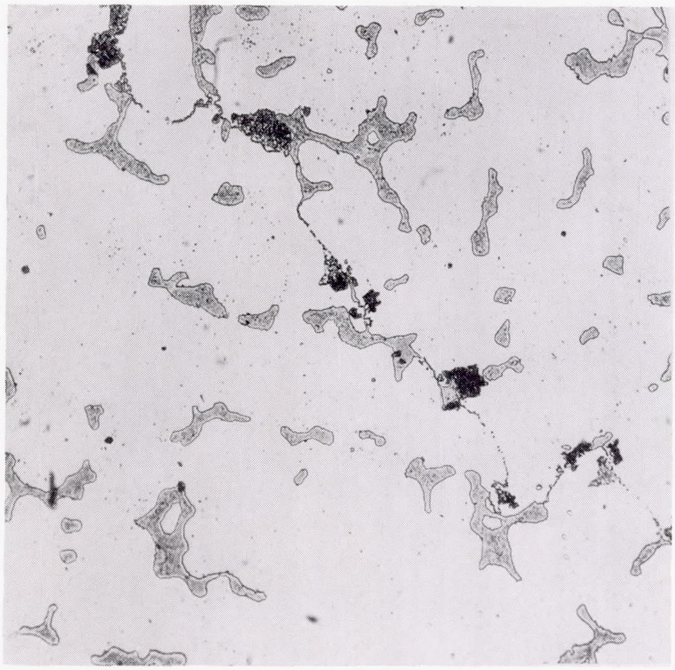
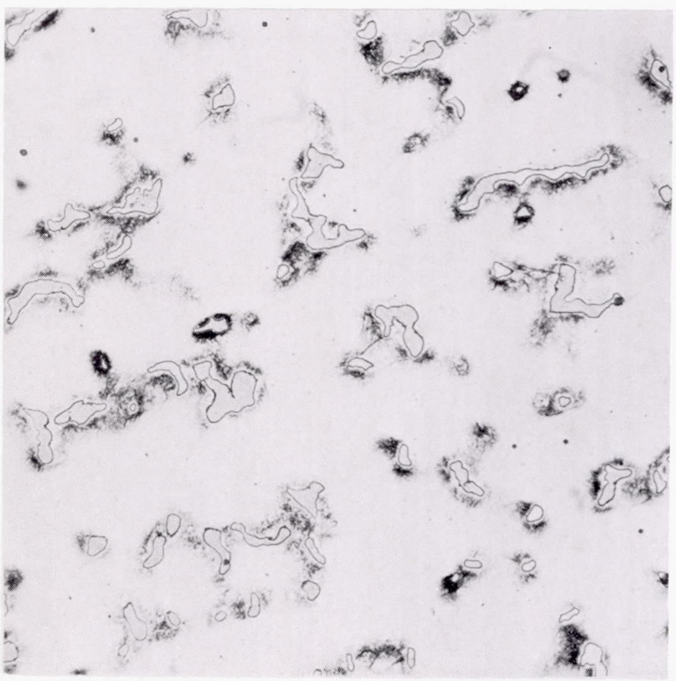


(a) Vitallium before operation. Rockwell C hardness, 30.



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(b) Base of airfoil section. Blade 48; Rockwell C hardness, 34.

Figure 12. - Amount of aging occurring during blade operation, X250.

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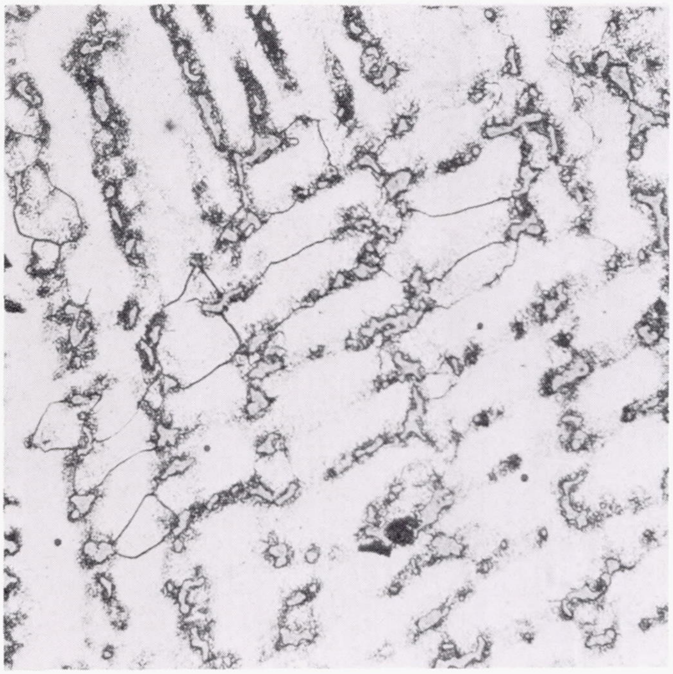

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(c) Center of airfoil section. Blade 48; Rockwell C hardness, 40.

Figure 12. - Concluded. Amount of aging occurring during blade operation, X250.

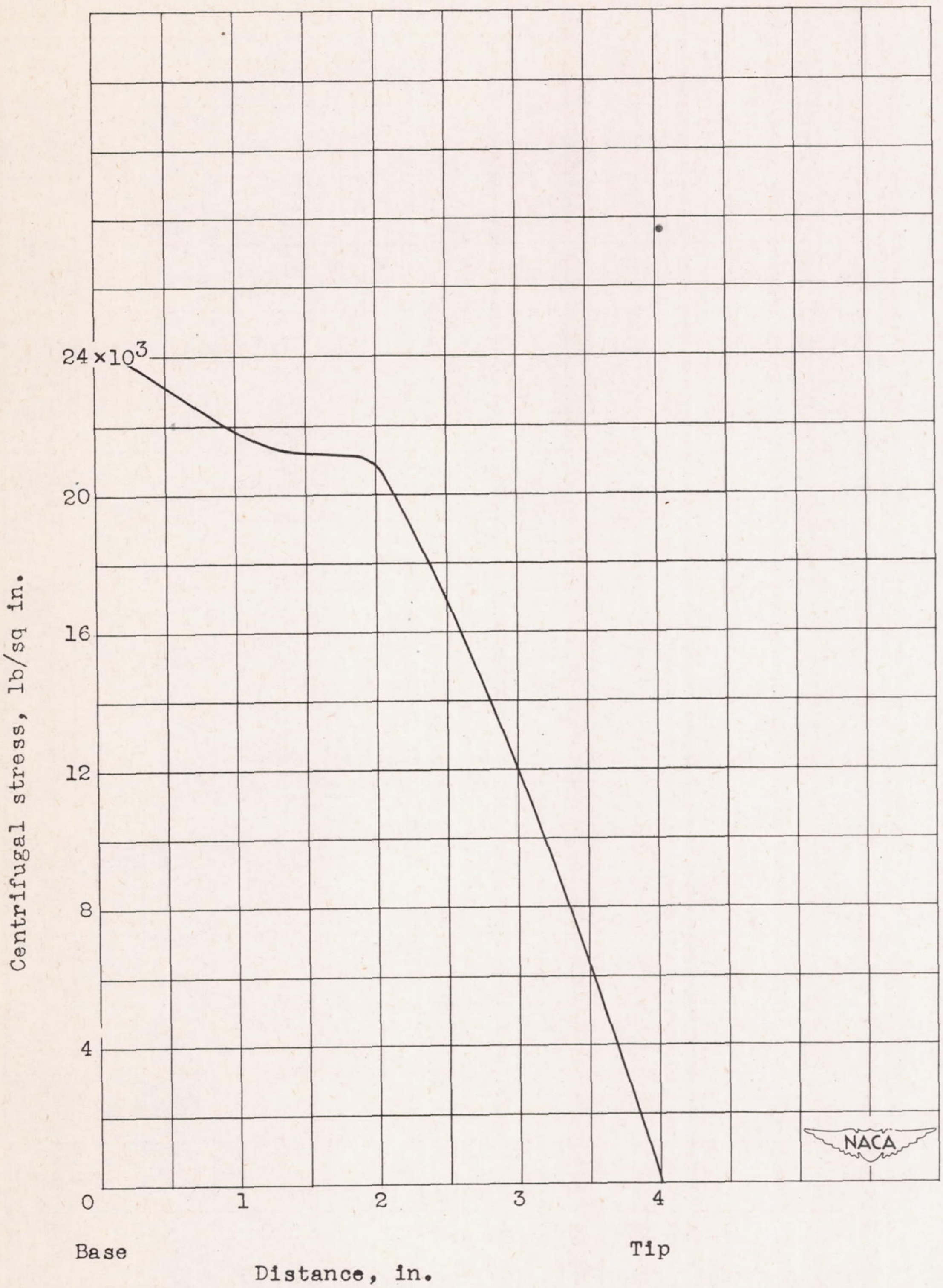

Figure 13. - Variation in centrifugal stress in cast Vitallium turbine blade. Turbine speed, 11,500 rpm; radius of turbine rotor, 8.99 inches. (Data obtained from fig. 6 of reference 2.)

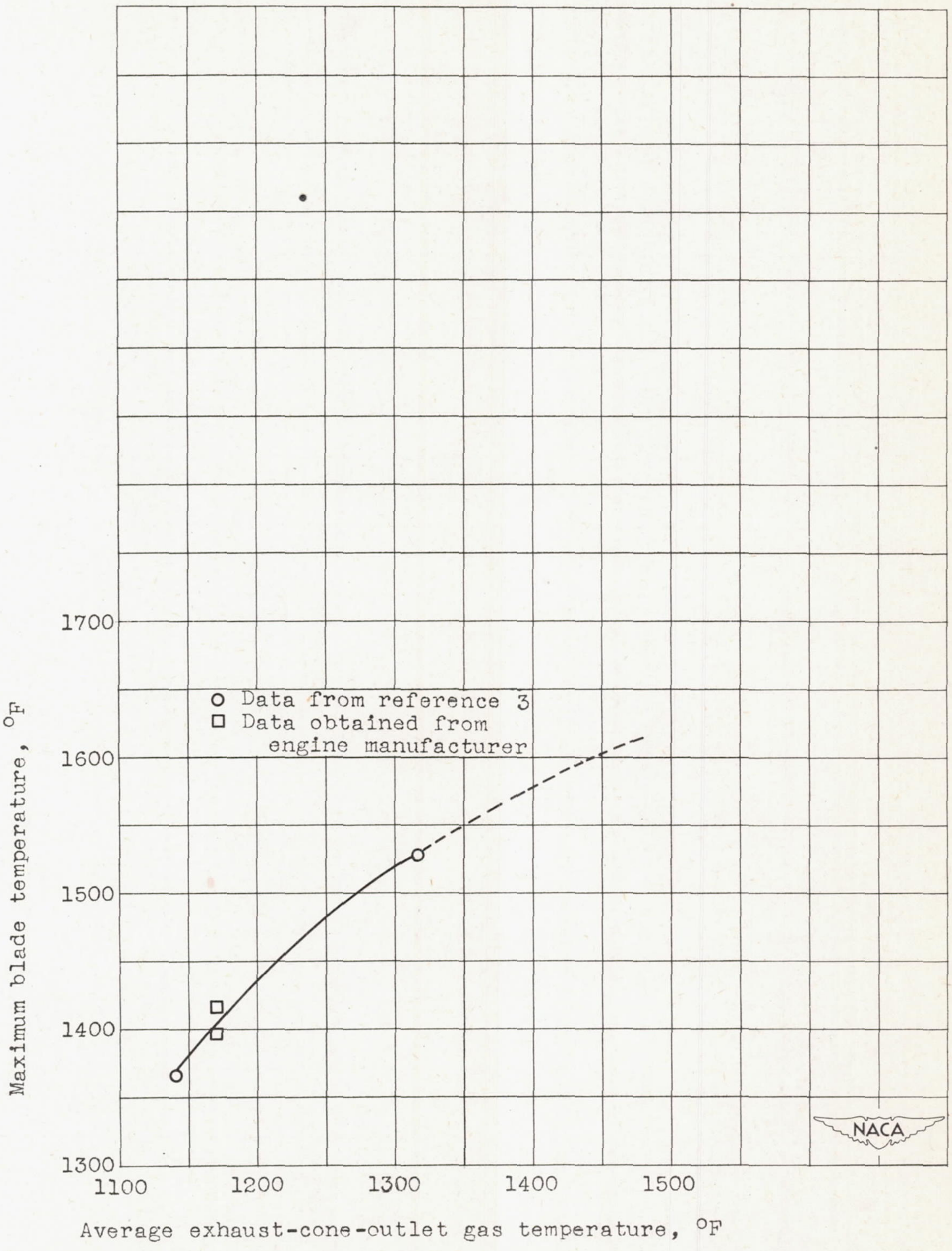

Figure 14. - Variation of maximum blade temperature with average exhaust-cone-outlet gas temperature.

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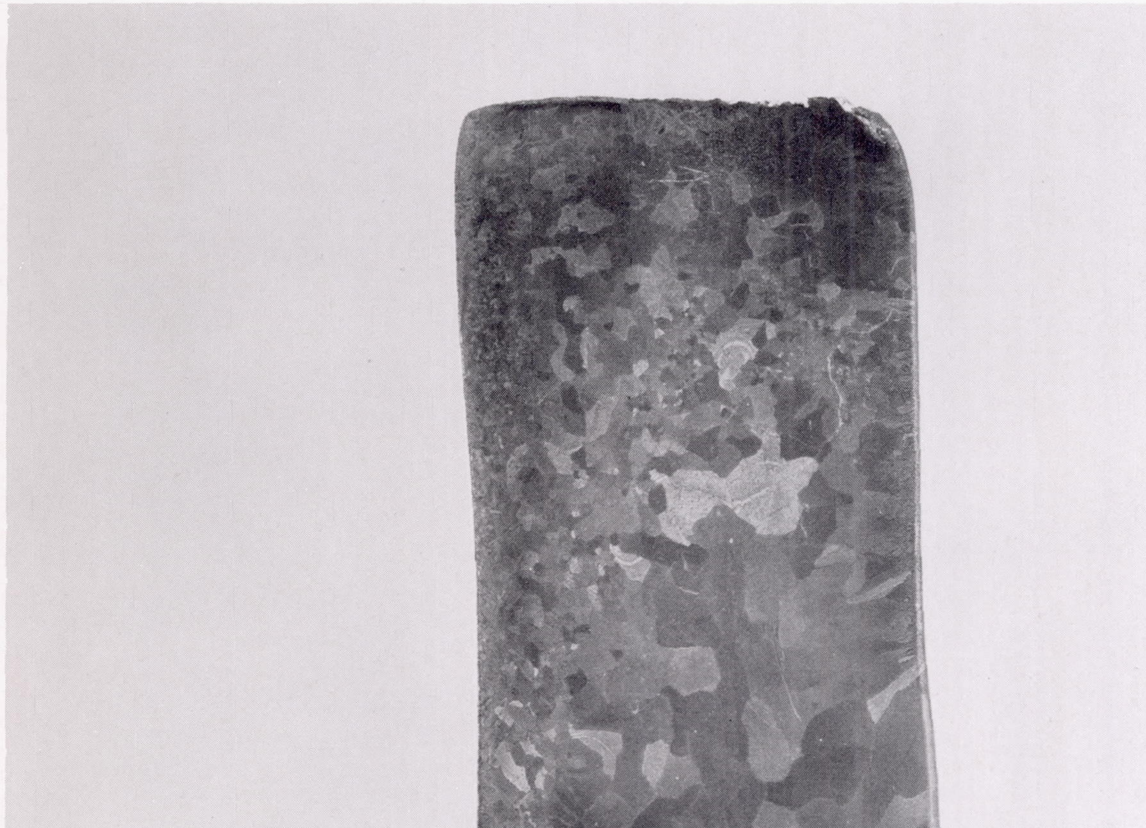

Figure 15. - Grain structure within blade with grain-size range from 4 to 128 grains per square inch. Electrolytically etched in 10-percent hydrochloric acid.