RM E54E05

NACA RM E54E05

NACA

RESEARCH MEMORANDUM

ENGINE PERFORMANCE OF ALLOY 73J TURBINE BLADES CAST TO PREDETERMINED GRAIN SIZES

By James R. Johnston, Charles A. Gyorgak and John W. Weeton

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
WASHINGTON

July 2, 1954
Declassified May 16, 1958

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

ENGINE PERFORMANCE OF ALLOY 73J TURBINE BLADES

CAST TO PREDETERMINED GRAIN SIZES

By James R. Johnston, Charles A. Gyorgak
and John W. Weeton

SUMMARY

An investigation was conducted to determine the suitability of alloy 73J as a turbojet turbine-blade alloy, and the effect of grain size on engine operating life. Blades of alloy 73J were run in a full-scale J33-9 turbojet engine under cyclic conditions. The engine was cycled every 20 minutes, operating 5 minutes at idle and 15 minutes at rated speed. At rated speed, stresses in the critical zone of the blades were 21,000 psi, and the temperature was controlled at 1500° F.

The 73J turbine blades investigated gave excellent performance, which indicates that further study of this material for turbine blades is warranted. The failure times of the best group of blades ranged from 612 to 1023 hours; and of the worst group, from 484 to 785 hours. The best performance was obtained with the medium-grained group, the intermediate performance with the coarse-grained group, and the poorest performance with the fine-grained group.

INTRODUCTION

The forged cobalt-base alloy, S-816, with its high strategic alloy index, is currently the most widely used blade alloy in the United States. Cast X-40 (AMS 5382) is being used as a blade alloy, but to a limited extent. In the past, Stellite 21 (AMS 5385) has been used. A factor which has limited the acceptance of cast alloys is the wide scatter of blade performance observed in engine tests of these alloys. In a given group of blades, abnormally early failures have been known to occur and cause considerable damage. These early failures may have been caused by porosity, microshrinkage, chemical segregations, and heterogeneity of grain size. Two methods have been used in attempting to strengthen cast alloys. The first of these methods is heat treatment. For example, heat treatment of small cast Stellite 21 gas-turbine blades has increased the operating life by as much as 100 percent (ref. 1). The second method is the improvement of casting properties by the production of bodies having uniform grain sizes. Uniform grain sizes in castings have been produced by exercising better control over the metal and mold temperatures at time of pouring (ref. 2). The effects of grain size on the operating life of Stellite 21 (AMS 5385) alloy blades were investigated in references 3 and 4. The results showed that coarse-grained blades have longer life than fine-grained blades and that blades having uniform grain size exhibit less scatter in performance than blades having heterogeneous grain sizes.

Several alloys have been developed (ref. 5) which exhibit excellent stress-rupture properties at 1350° to 1800° F. One of these alloys, 73J, was selected for this investigation because of its reported high strength and because it may be produced in uniform grain sizes by varying the pouring temperature (ref. 2). This alloy, which is age hardenable, was reported to exhibit a stress-rupture life ranging from 114 to 430 hours at 1500° F and 30,000 psi. In reference 6, additional studies of the alloy are presented and microconstituents of the alloy, which could enter into the aging reaction, were identified by X-ray diffraction methods. Such microconstituents as TaC, Cr_7C_3, M_6C, (where M is a combination of carbide formers), and $Cr_{23}C_6$ were detected. The matrix was identified as a face-centered cubic solid solution. It was postulated that an aging phenomenon, which may occur in this type of alloy in addition to the conventional aging, results from the decomposition of the high-carbon carbide Cr_7C_3 to the lower-carbon carbide $Cr_{23}C_6$.

The purposes of this investigation are to determine whether 73J alloy is suitable for use in turbojet turbine blades and to determine, if possible, the effect of grain size upon the engine operating life. It should be noted that the variables of grain size and pouring temperature are not separable, and that varying the pouring temperature alone may be as significant as varying the grain size.

Fine-, medium-, and coarse-grained 73J blades in an aged condition were run in a full-scale Air Force J33-9 turbojet engine. The blade temperature and stress induced during engine operation were controlled at 1500° F and 21,000 psi, respectively. Stress-rupture tests were made of specimens cut from the airfoil section of blades. Microstructures and macrostructures were studied to determine grain size and microconstituents present in the blades.

MATERIALS, APPARATUS, AND PROCEDURE

The blades used in this investigation had the following percentage composition:

C	Mn	Co	Ni	Cr	Mo	Ta	Fe	Si
0.73	1.05	65.76	2.31	20.30	6.30	1.73	0.82	0.43

The supplier of the blades attempted to control the grain size and to minimize variables on metal handling and chemical analysis by producing a single master heat of alloy. Tantalum was added to individual subheats to prevent loss of this element (ref. 2). The blades were centrifugally cast into silica-base molds preheated to 1500° F. A low pouring temperature of approximately 2550° F was used to produce fine-grain sizes; an intermediate temperature of approximately 2700° F was used to produce medium-grain sizes; and a high temperature of approximately 2950° F was used to produce coarse-grain sizes (ref. 2). All blades were aged for 24 hours at 1350° F.

Dimensional checking of the blades showed them to be oversize. The differences in cross-sectional area from the desired blade design are shown in figure 1. These differences in area at any cross section in the blade would tend to reduce the stress at that section, but the resultant greater volume of material beyond this cross section would tend to increase the load that the area must carry. The net result is that the centrifugal stress, calculated by the method described in reference 7, was slightly higher than that of a standard-shaped blade (fig. 2). The increase in cross-sectional area, however, may tend to stiffen the blade and reduce vibratory stresses.

Engine Operation

Forty-six cast 73J alloy blades were mounted in a 16-25-6 Timken alloy rotor and operated in a J33-9 Air Force turbojet engine, together with five S-816 blades used as a standard for comparison. Of the 73J blades, 16 were fine-grained, 15 medium-grained, and 15 coarse-grained. The test engine was operated under continually repeated cycles of 20 minutes duration, 15 minutes of which were at rated speed of 11,500 rpm followed by a 5-minute idle at 4000 rpm. During the rated-speed cycle, the blade midspan temperature was 1500° F, and the nominal centrifugal stress was 21,000 psi. Instrumentation of the engine to obtain blade temperature data is described in reference 8. Thermocouples were placed in two blades located diametrically opposite each other in the rotor. The thermocouple leads were taken through the rotor shaft to a slip-ring assembly mounted on the front of the engine. Temperatures were recorded on a Brown recording instrument.

After 534 hours of rated-speed operation, the engine caught fire. An aluminum casting on the front assembly was melted and the blades were sprayed with the molten alloy. The blades did not appear to be damaged.

Blade Elongation Measurements

Two blades of each grain size were scribed near the trailing edge at 1/2-inch intervals (ref. 9). After every 20 hours of operation (approximately), the elongation of each scribed segment was measured with an optical extensometer having an accuracy of ±0.0001 inch. The accuracy of elongation measurements is, however, controlled by the degree of blade distortion and warpage. The elongation results should therefore be considered approximate rather than exact.

Macroexamination of Blades

Visual examinations of all failures were made to determine, as nearly as possible, the manner in which the failures originated. Failures were classified into the following categories (ref. 9):

1. Stress-rupture - The origin of the fracture is characterized by an irregular granular surface having no evidence of fatigue-type failure. The fracture has an intercrystalline path, and small intercrystalline cracks are present in the area just below the failure zone.

2. Fatigue - A smooth, predominantly transgranular fracture surface occurs at the failure origin, sometimes showing the familiar concentric ring markings.

Blades which were installed in the engine were categorized as fine, medium, and coarse on the basis of the suppliers definition; namely, that blades cast at 2550° F were fine-grained, blades cast at 2700° F were medium-grained, and blades cast at 2900° F were coarse-grained. All failed blades were macroetched to reveal grain sizes after operation. It was considered best to macroetch the blades after operation rather than before so that acid attack of the grain boundaries would not reduce engine performance.

Metallographic Examinations of the Blades

Metallographic examinations were made of the blades that failed in the shortest and longest times of operation. Spot checks were also made of blades that failed at intermediate times. Sections for metallographic examinations were taken of failure origin areas and sound blade areas to permit study of failure mechanism and propagation, microstructural constituents, and grain size.

Stress-Rupture Testing

Stress-rupture specimens were taken from the airfoil section of the blade as shown in figure 3. The tests were made at the engine operating temperature and stress of 1500° F and 21,000 psi, respectively.

RESULTS AND DISCUSSION

Macroexamination of Blades

Figure 4 shows the grain size of the blades investigated. Macroscopic and microscopic examinations have shown the grain size present in the failure zone to be:

Fine-grained blades - A.S.T.M. 2 to 7 (20,000 to 660,000 grains/sq in.)

Medium-grained blades - 60 to 70 grains per cross-sectional area (270 to 360 grains/sq in.)

Coarse-grained blades - 20 to 30 grains per cross-sectional area (90 to 135 grains/sq in.)

Engine Life

The engine life of 73J blades of three different grain-size groups and standard S-816 blades is plotted in figure 5. The engine life of all groups of 73J blades was far superior to that of the forged S-816 blades.

From past performance of cast blades, in this type of engine evaluation, it may be generalized that fatigue is the usual mode of failure. In this investigation, the 73J blades failed predominately by stress-rupture. The stress-rupture failures may have been caused by the stiffening of the blades by the increase in cross-sectional area, as previously noted. Damage failures are not considered true failures and will not be discussed. The first failure of the 73J alloy occurred in the fine-grained blades after 484 hours at rated speed. First failures in the coarse- and medium-grained lots occurred after 609 and 612 hours, respectively. The mean life of the fine-grained group of blades was the shortest (594 hr); the coarse-grained blades had an intermediate mean life of 736 hours; and the medium-grained blades had the longest mean life (843 hr). The scatter in blade life present within each grain-size group may be considered low for a cast alloy. Life ranged from 609 to 844 hours for coarse-grained blades, 484 to 785 hours for fine-grained blades, and 612 to 1023 hours for medium-grained blades.

The relation of blade life as a function of grain size follows the same trend reported in the grain-size study of AMS 5385 (refs. 1 and 4); that is, shorter life is associated with fine-grained materials and the best life is associated with coarse-grained materials. Statistical analysis of the engine operating data shows a significant difference between the engine life of the fine-grained group and the life of the two coarser-grained groups, taken singly or combined. The difference may be attributable to grain size; however, it should be remembered that the grain-size differences resulted from varying the pouring temperatures, and that other factors resulting from the pouring temperature may be the cause of the significant difference in the engine life of these blades.

Engine Life Against Stress-Rupture Life

The engine operating data have been plotted in figure 6, along with stress-rupture data obtained from specimens cut from airfoils. For comparative purposes, curves on cast stress-rupture bars presented in reference 2 are also shown. In all cases, the data from blade specimens fell below the values obtained from cast bars. The engine operating life of the blades follow the trend mentioned before, that is, fine-grained blades have shorter life than the coarser-grained blades. The stress-rupture data for both the cast bars and specimens cut from airfoils also follow this trend. Thus it was shown that the blade life, the blade-airfoil stress-rupture life, and the cast-bar-stock stress-rupture life all follow a pattern of increasing life as the grain size changes from fine, to coarse, to medium.

On the basis of the equicohesive temperature theory, the fine-grained specimens would be expected to be weakest. The coarsest-grained materials would be expected to exhibit orientation effects and possibly be weaker than an intermediate-grained material but stronger than the fine-grained material.

Blade Failures

The locations of failure origin in the blades are listed in table I. The failures occurred primarily by a stress-rupture mechanism in the zone where the combination of stress and temperature is known to be most severe. All failures occurred in this zone, which is located 2 ±0.34 inches above the base platform of the blade. Figure 7 shows that the mode of failure is typical of stress-rupture failures.

Blade Elongation

The elongations occurring in the 1-inch gage length (zones 3 and 4) with the most severe combination of stress and temperature are plotted in figure 8. The total elongations in this zone, where the stress is approximately 21,000 psi at 1500° F, are as follows:

Grain size	Time at rated speed, hr	Elongation, percent
Fine	570	4.5
Medium	588	5.4
Coarse	588	3.3

The slopes of the elongation curves during second-stage creep are essentially the same. Since evidence of third-stage creep appeared in all three grain-size blades before failure, the failures may be considered true stress-rupture failures. Standard S-816 blades operating at the same temperature at a stress of 21,500 psi had an elongation of 4.5 percent in 160 hours (ref. 10). Thus, under similar operating conditions it can be seen that the creep rate of 73J is appreciably less than that of S-816.

Metallographic Results

Photomicrographs of first and last failures of fine-, medium-, and coarse-grained blades are shown in figures 9 to 11. The grain size of the fine-grained blades was determined by use of the metalloscope because the fineness of the grains permitted a large number to be present in the field of view. However, in the case of both the medium- and coarse-grained blades, the interdendritic networks and precipitates made it difficult to detect the true grain boundaries. The only way grains could be separated from each other in many areas was by the change in orientation of the interdendritic carbide networks from grain to grain. It was difficult to observe significant microstructural differences between first and last blade failures since greater differences frequently were found within a given blade. Coring of the cast structure and an anisotropic resistance to etching solutions probably obscured any differences in precipitation with time at temperature.

Carbide precipitation occurred as general matrix precipitate and occasionally in Widmanstätten structures or within slip planes. The greatest quantity of precipitate occurred near the more massive interdendritic carbides. Precipitates which formed in such an interdendritic manner may have occurred by carbide decomposition of Cr_7C_3 to $Cr_{23}C_6$

(ref. 6). However, general precipitation in cored areas could also have accounted for the aging pattern. At least two carbides were observed in the microstructure after electrolytic etching in aqua regia, one of which undoubtedly was TaC. The formations of different precipitates were so random that no correlation could be made between presence or arrangement of any specific carbide or precipitate and blade life.

After 534 hours of rated speed operation the engine caught fire. An aluminum casting was melted, and the leading edges of the blades were sprayed. A typical sprayed area is shown in figure 12. It may be observed that the sprayed alloy adhered to the oxide coating on the blade surface and no alloying or metal-to-metal contact of the aluminum to the 73J was detected. Therefore, it was concluded that the presence of the sprayed metal on the blades did not affect the operating life of the 73J alloy.

With the exception of the two fatigue failures, the remaining true failures occurred by the stress-rupture mechanism. Figure 13 shows the typical stress-rupture crack. The failure propagation proceeded along grain boundaries or interdendritic carbide paths, or both. It was difficult to differentiate between the two.

Blade Dimensions and Possible Effects of Overdimensions

The blades used in this investigation were ordered to standard J33-9 blade specifications. However, the blades were cast oversize. The area oversize varied from 10.5 percent in certain locations of the airfoils to as much as 40.5 percent (fig. 1). At the same time that these 73J blades were obtained from the manufacturer, Stellite 21 blades cast to different grain sizes were also obtained. These blades, also oversize, were run in an engine in a similar test and the results have been reported in reference 4. The Stellite 21 blades did not exhibit improved life over standard-size blades and therefore it appears that the oversize effect in the 73J blades could not have accounted for the excellent performance of this alloy as blade material. To further substantiate this conclusion, three 73J blades were electromachined to an undersized condition, three were electromachined to standard size, and these six along with six oversized 73J blades were run in another turbine wheel with other alloys. Unfortunately all these blades were damaged by impact from fractured blade fragments of other alloys and had to be removed from the engine before actual failure had occurred. It may be somewhat significant, however, that two of the electromachined blades had run 74 hours, one 91 hours, two 188 hours, and one 213 hours before removal without indications of incipient fatigue failure. These data indicate that very early fatigue failure may not occur in blades of standard dimensions.

SUMMARY OF RESULTS

In this investigation, which was conducted to determine whether alloy 73J is suitable for use as a turbojet blade alloy, and to determine the effect of grain size upon the engine operating life, the following results were obtained:

1. Turbine blades of alloy 73J were found to perform excellently in a J33-9 turbojet engine. The best group of blades had failures from 612 to 1023 hours, and the poorest group of blades failed from 484 to 785 hours. The S-816 blades run at the same time had blade failure times after 68 to 175 hours. It should be noted, however, that the 73J blades were cast oversize. Reasons were given to indicate that this condition did not account for the excellent performance of the blades.

2. The best blade life was obtained in the medium-grained group, the intermediate blade life in the coarse-grained group, and the poorest blade life in the fine-grained group.

3. Blade failures occurred primarily by stress-rupture in the regions of the blades known to be subjected to the most severe conditions of stress and temperature. Metallographic examinations showed that the failures occurred along grain boundaries or interdendritic paths.

4. The 73J turbine blades elongated during operation 3.3 to 5.4 percent in approximately 590 hours. Alloy S-816 blades elongate approximately this much in 160 hours.

5. The grain sizes of the blades were uniform and consistent, and the grains in the fine-grained material were unusually fine for a cast material (A.S.T.M. 2 to 7). Grain sizes could be determined by metallographic techniques in the fine-grained specimens only. In the medium- and coarse-grained groups, it was necessary to use macroscopic techniques to determine the grain sizes.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 5, 1954

REFERENCES

1. Hoffman, C. A., and Robards, C. F.: Effects of Some Solution Treatments Followed by an Aging Treatment on the Life of Small Cast Gas-Turbine Blades of a Cobalt-Chromium Base Alloy. II - Effect of Selected Combinations of Soaking Time, Temperature, and Cooling Rate. NACA TN 2513, 1951.

2. Hamilton, N. E., and Grant, N. J.: Controlled Grain Size, Precision Cast Turbine Blades. (BuShips Navy Dept., Contract Nobs-25391 Task 10-12.)

3. Hoffman, C. A., and Gyorgak, C. A.: Investigation of Effect of Grain Size upon Engine Life of Cast AMS 5385 Gas-Turbine Blades. NACA RM E53D06, 1953.

4. Yaker, Charles, Garrett, Floyd B., and Sikora, Paul F.: Investigation of Engine Performance and High-Temperature Properties of Precision-Cast Turbine Blades of High-Carbon Stellite 21 and Controlled-Grain Size Stellite 21. NACA RM E52D10, 1952.

5. Grant, Nicholas J.: The Cobalt-Chromium J Alloy at 1350° to 1800° F. Trans. A.S.M., vol. XL, 1948, pp. 585-610, discussion, pp. 610-616.

6. Lane, J. R., and Grant, N. J.: Carbide Reactions in High Temperature Alloys. Trans. A.S.M., vol. 44, 1952, pp. 113-134; discussion, pp. 134-137.

7. 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.

8. Farmer, J. Elmo: Relation of Nozzle-Blade and Turbine-Bucket Temperatures to Gas Temperatures in a Turbojet Engine. NACA RM E7L12, 1948.

9. Garrett, F. B., and Yaker, C.: Relation of Engine Turbine-Blade Life to Stress-Rupture Properties of the Alloys, Stellite 21, Hastelloy B, Cast S-816, Forged S-816, X-40, Nimonic 80, Refractalloy 26, N-155, and Inconel X. NACA RM E51G13, 1951.

10. Garrett, F. B., Gyorgak, C. A., and Weeton, J. W.: Behavior of Forged S-816 Turbine Blades in Steady-State Operation of J33-9 Turbojet Engine with Stress-Rupture and Metallographic Evaluations. NACA RM E52L17, 1953.

TABLE I. - LOCATION OF BLADE FAILURE ORIGIN

Order of failure	Failure time, hr	Failure type (a)	Location with respect to base, in.	Location with respect to edges (a)
Fine grain				
1	483.8	SR	2.06	LE
2	485.8	SR	2.00	LE
3	492.7	SR	2.16	LE
4	543.5	SR	2.13	LE
5	560.7	SR	2.16	LE
6	572.3	SR	2.06	LE
7	593.9	SR	2.03	LE
8	600.0	SR	2.13	C
9	625.5	SR	2.19	LE
10	634.5	SR	2.09	LE
11	756.5	SR	2.19	TE
12	785.3	SRC	1.78	C
			Average 2.08	
Medium grain				
1	611.8	SR	1.72	LE
2	789.0	SR	2.34	LE
3	818.3	SR	1.91	C
4	830.0	SR	1.94	C
5	866.8	SR	1.75	C-LE
6	873.8	F	2.31	LE
7	874.9	SR	1.91	C
8	897.5	SR	2.25	C
9	1023.2	SR	1.69	C-LE
			Average 1.98	
Coarse grain				
1	609.3	SRC	2.22	C-TE
2	613.1	SR	1.91	LE
3	628.1	SR	2.00	C-TE
4	651.8	F	1.88	LE
5	725.8	SR	1.84	C
6	746.3	SR	2.00	C
7	806.8	SR	1.78	C
8	813.5	SRC	2.13	C
9	820.3	SR	1.84	C
10	837.3	SR	1.72	C-LE
11	844.5	SR	2.03	C-LE
			Average 1.96	

[a]Abbreviations:

F = Fatigue
SR = Stress-rupture
SRC = Stress-rupture cracking

C = Center
LE = Leading edge
TE = Trailing edge

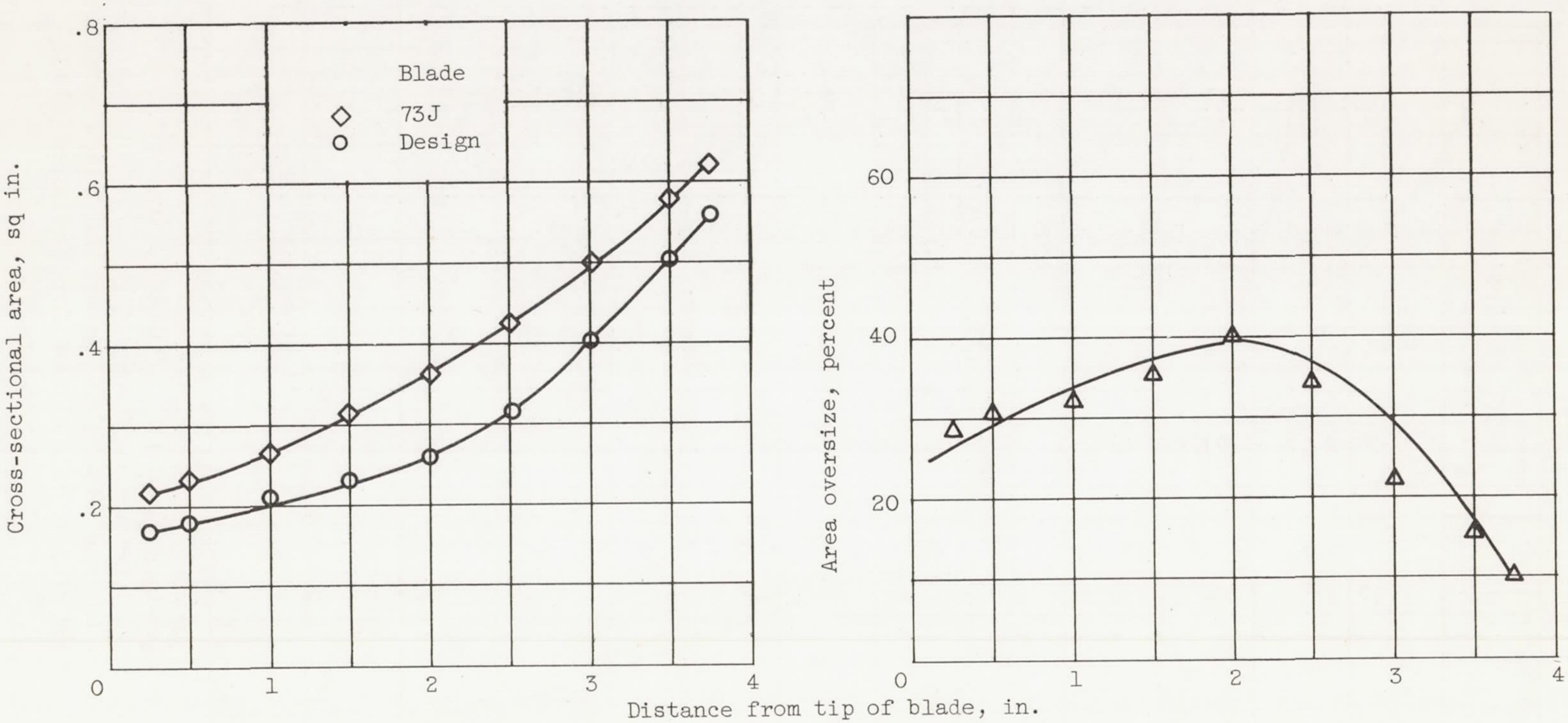


Figure 1. - Comparison of cross-sectional areas of 73J blade and designed blade.

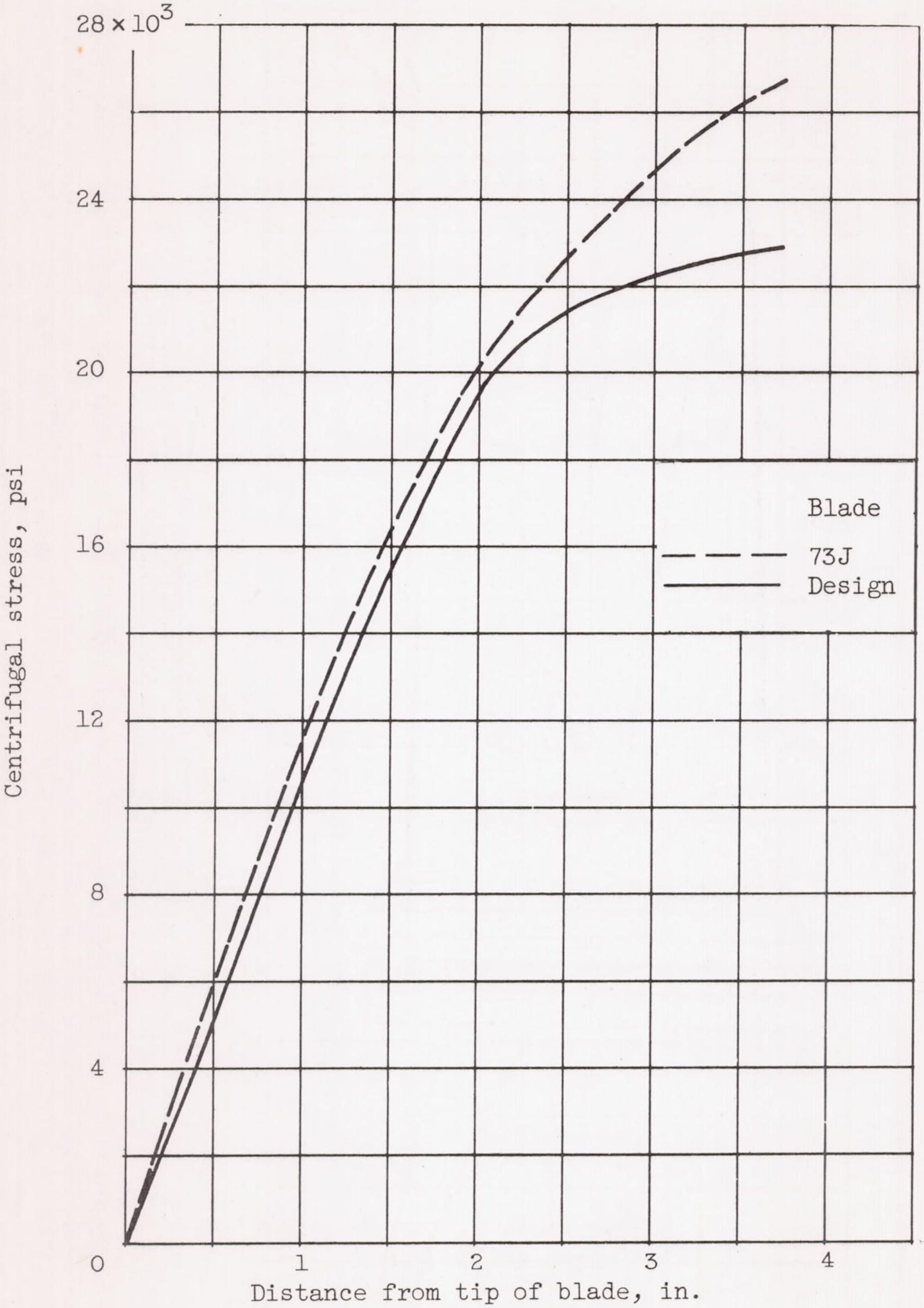


Figure 2. - Stress distribution of 73J blade compared with distribution calculated for designed blade.

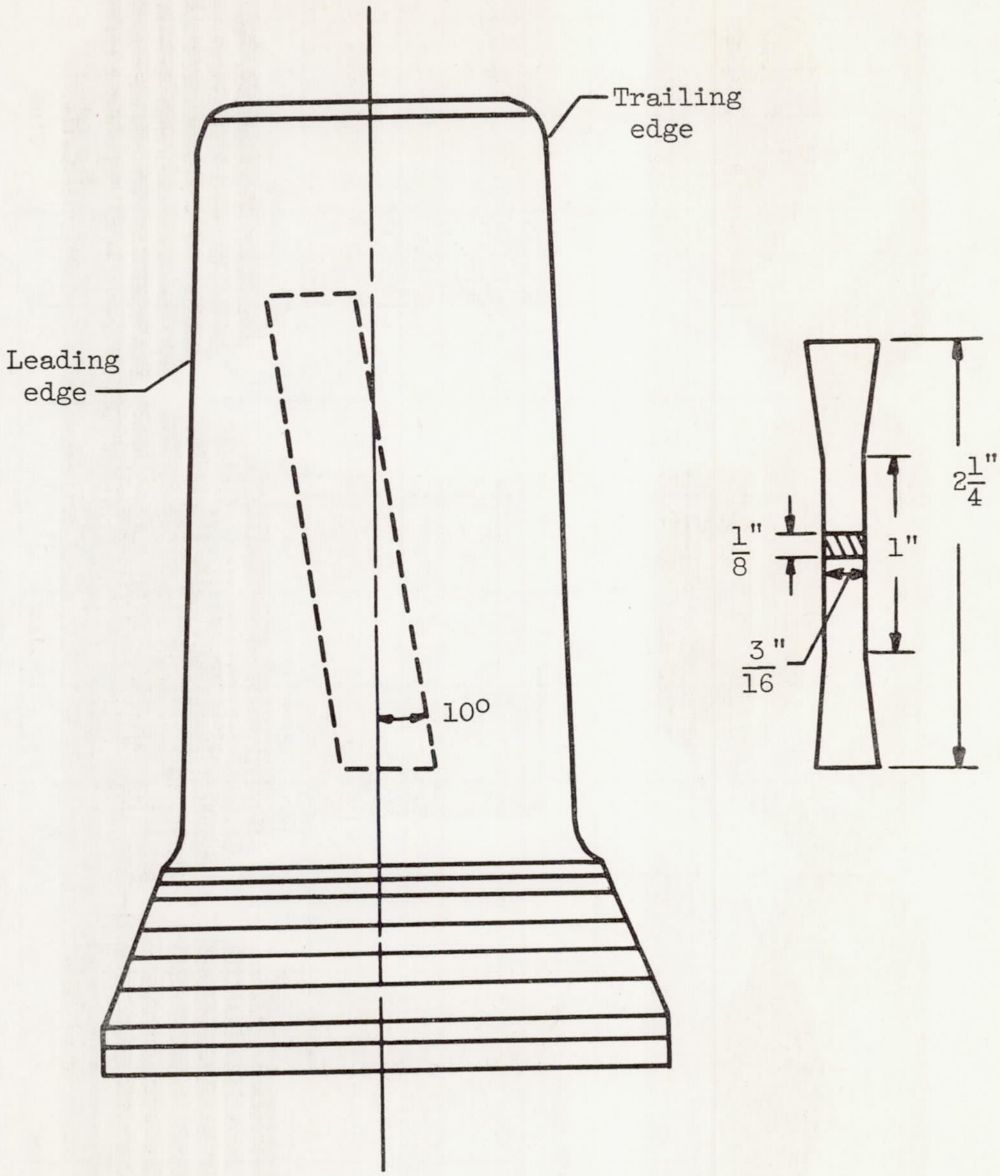
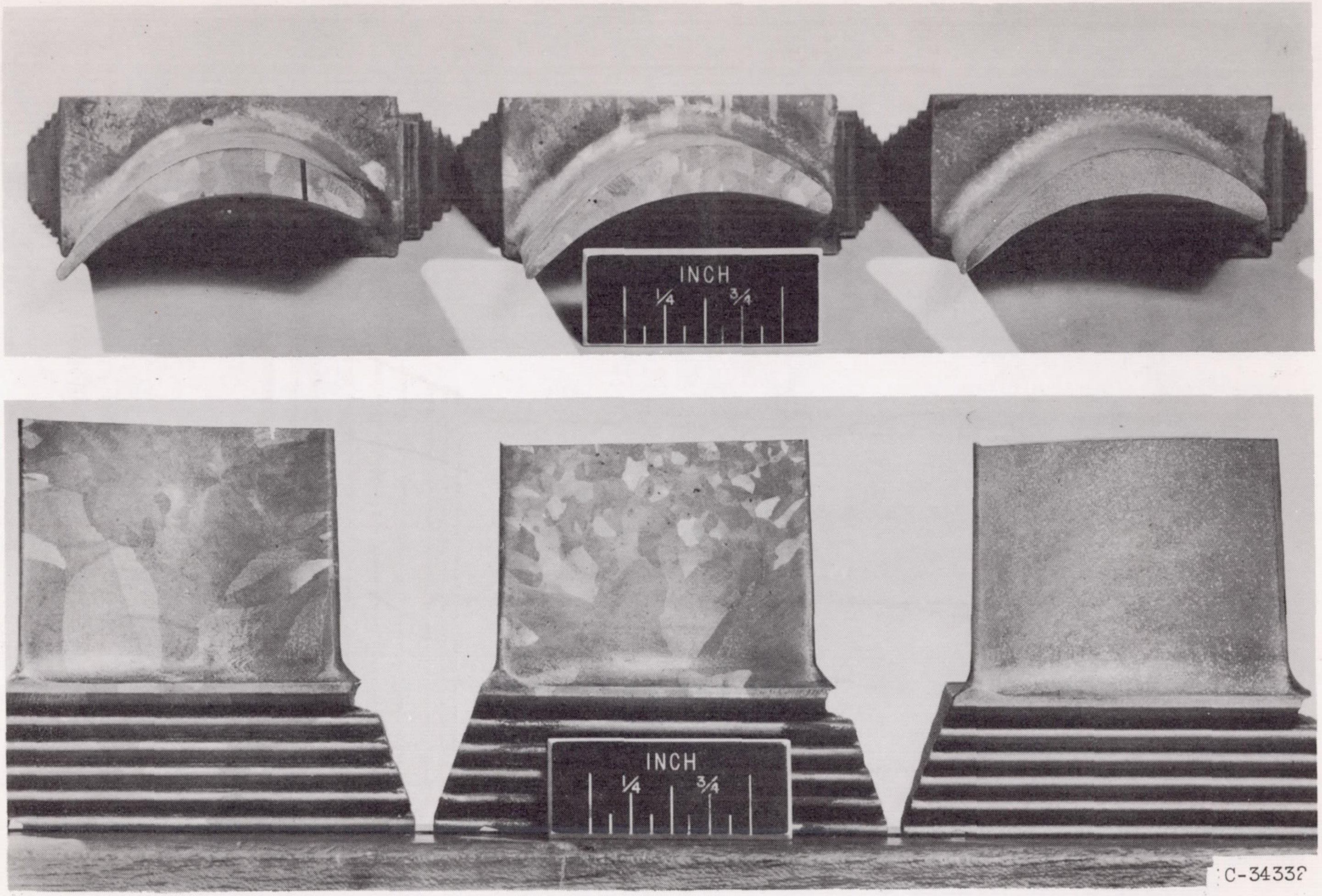


Figure 3. - Blade stress-rupture specimen and zone from which it was machined.



Coarse Medium Fine

Figure 4. - Typical grain size of 73J blades after engine operation.

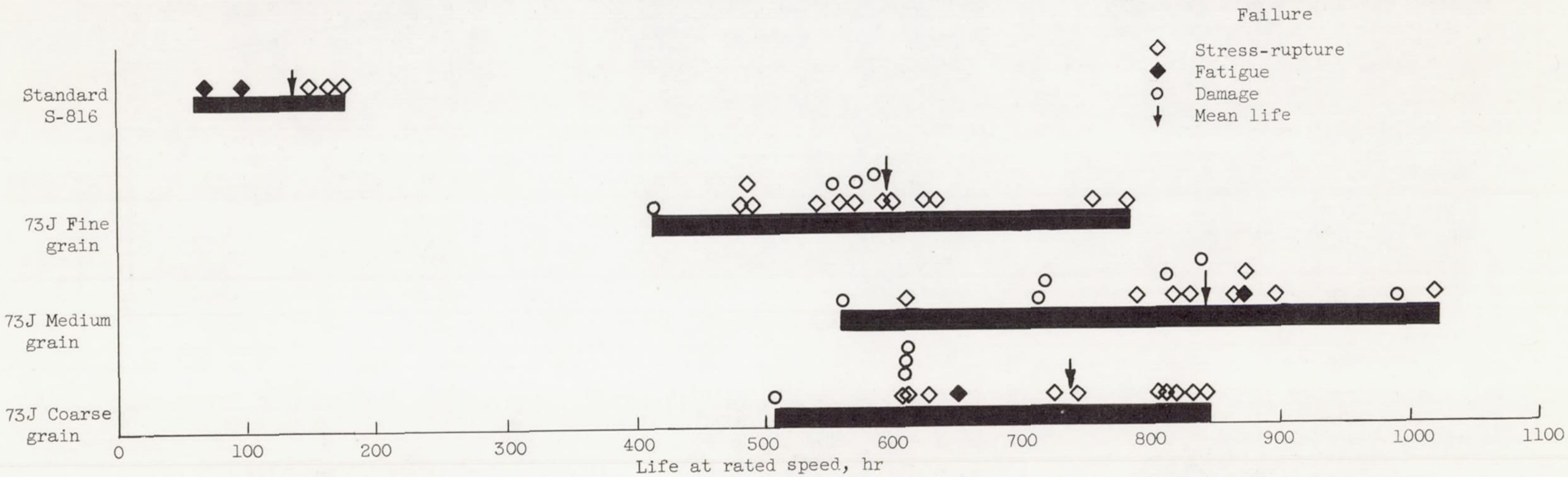


Figure 5. - Blade life of controlled grain-size 73J and S-816 turbine blades.

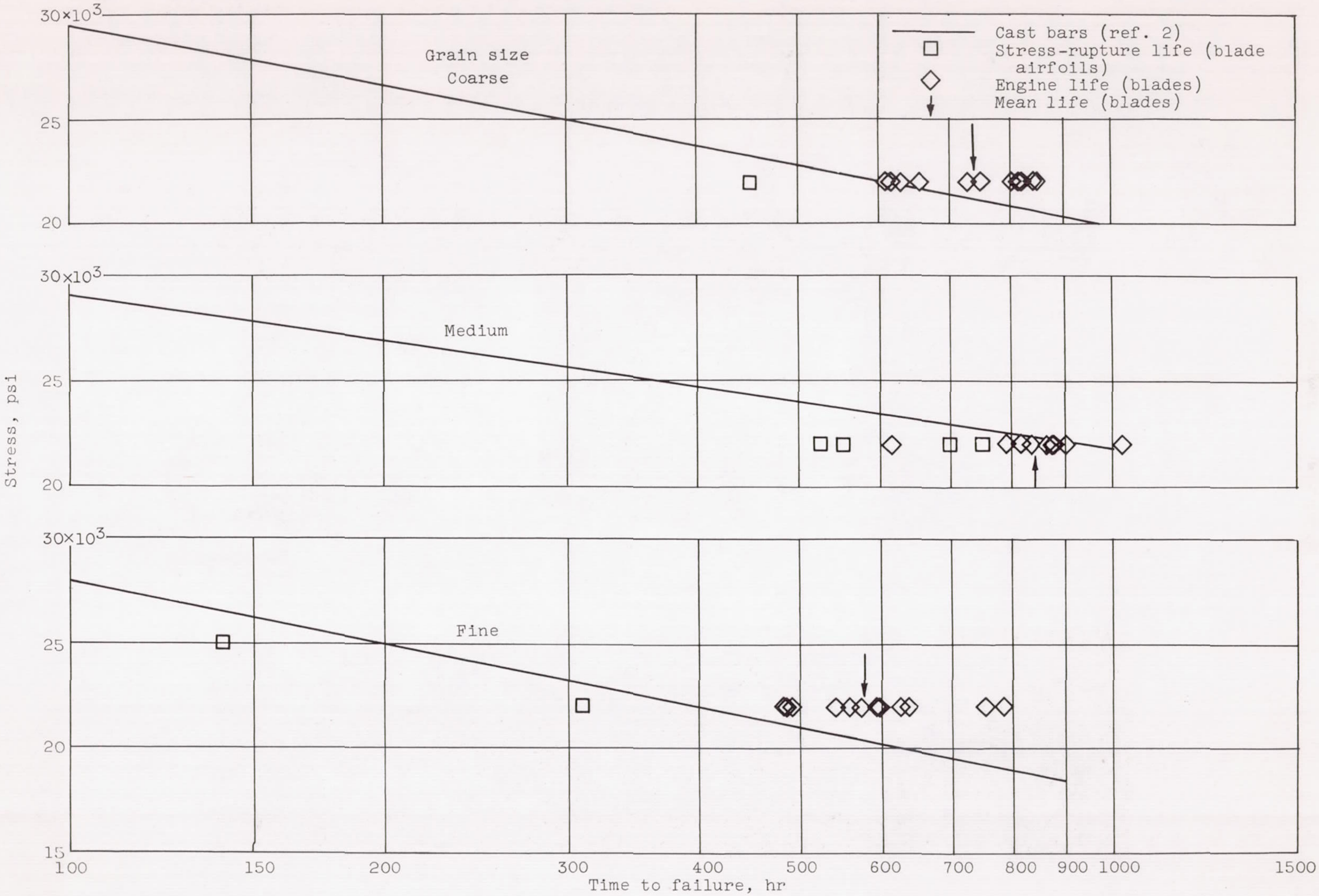
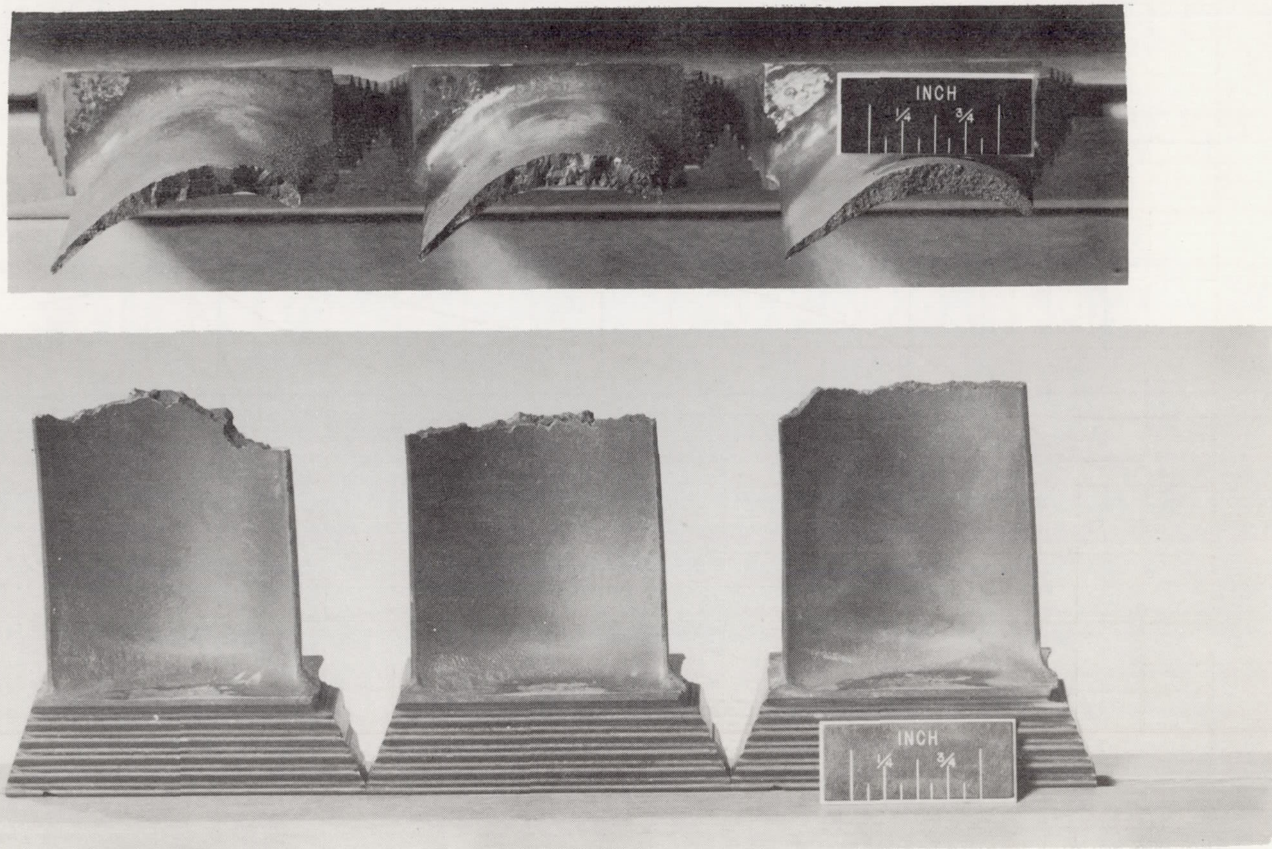


Figure 6. - Comparison of blade life, stress-rupture life of specimens cut from blade airfoils, and stress-rupture life of cast bars. Test temperature, 1500° F.



Coarse Medium Fine C-30525

Figure 7. - Typical stress-rupture failures.

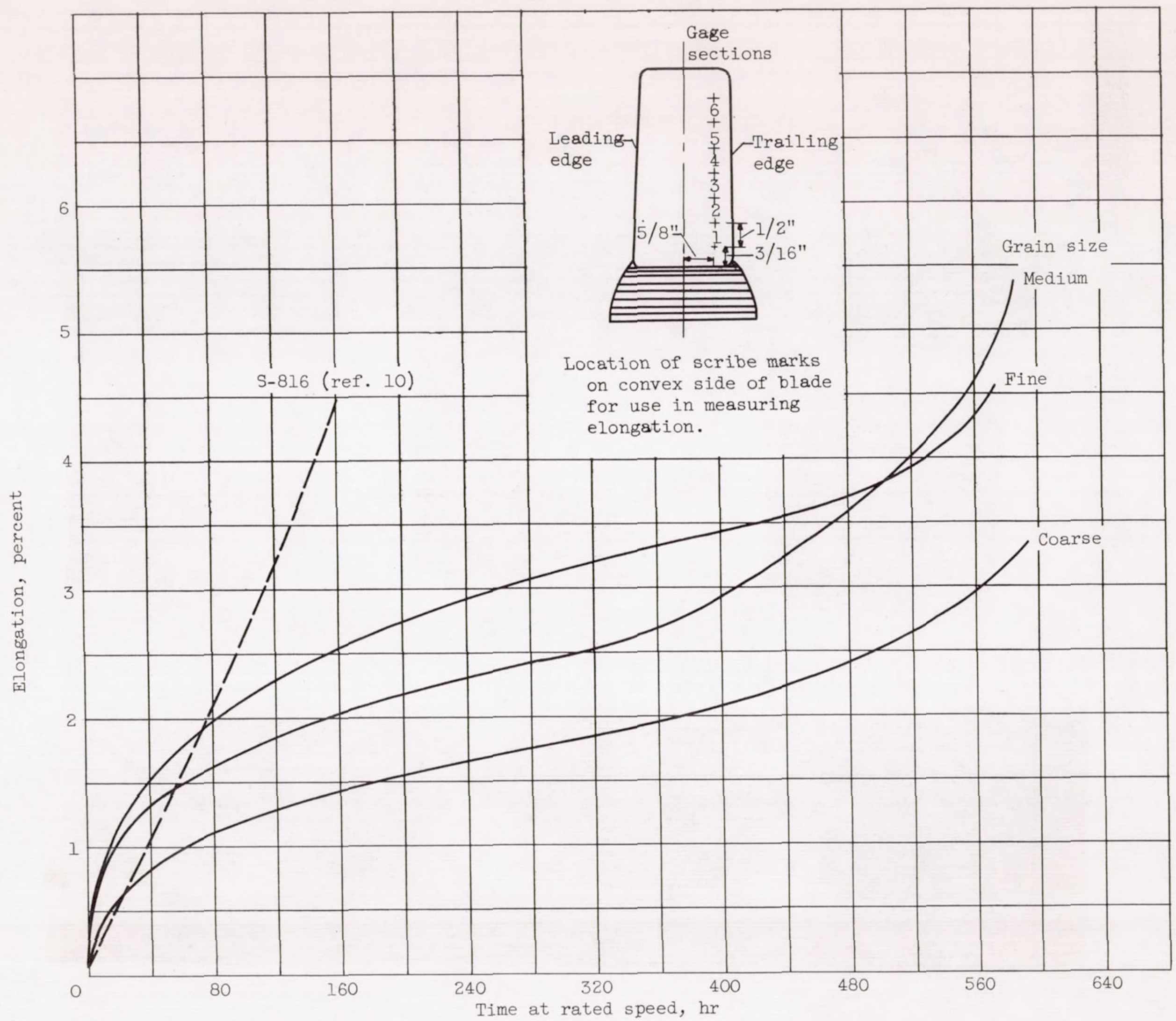
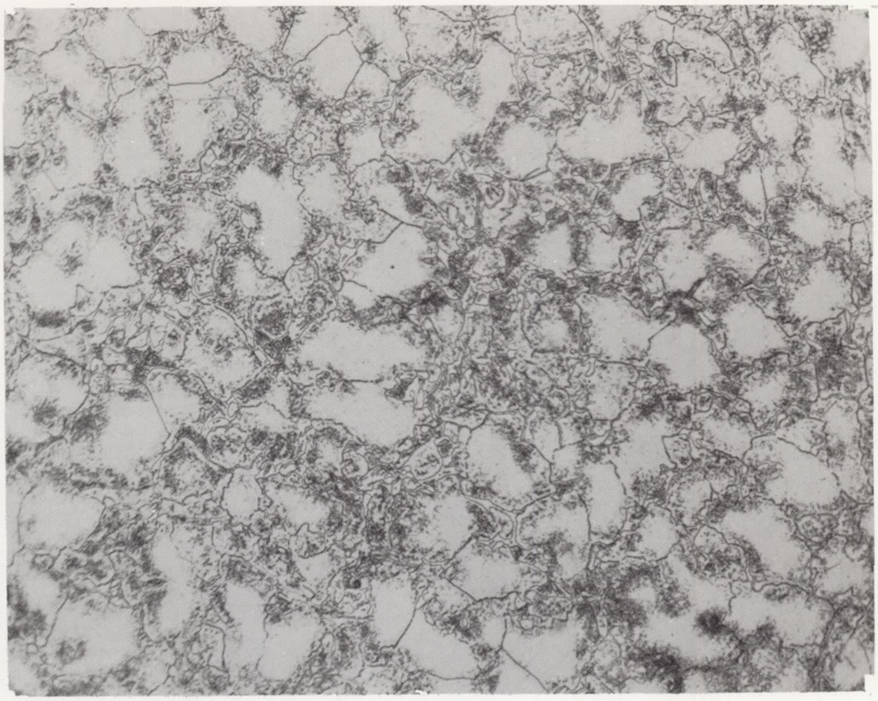
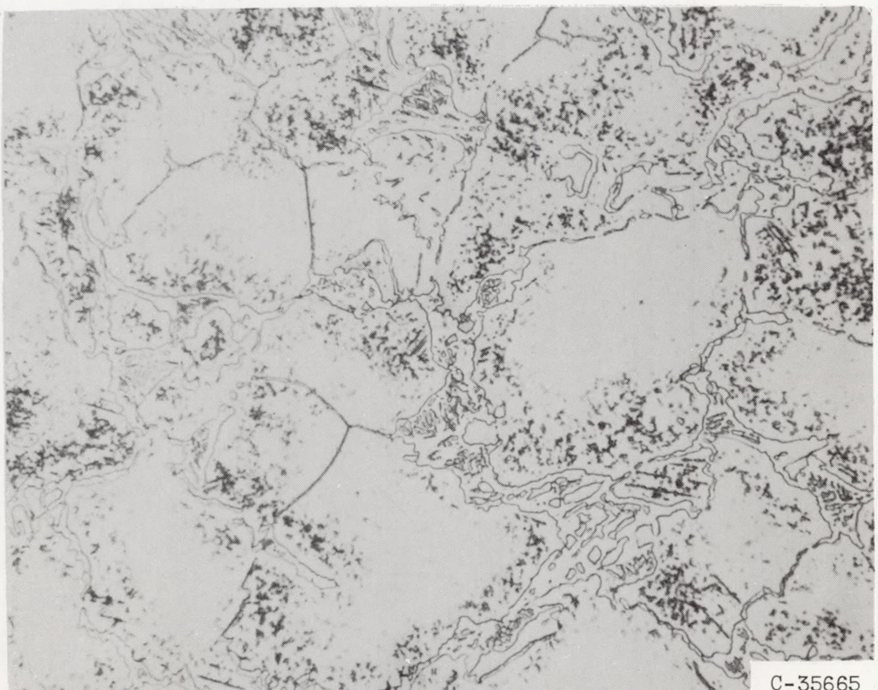


Figure 8. - Elongations of blade airfoils, average of positions 3 and 4.



X250

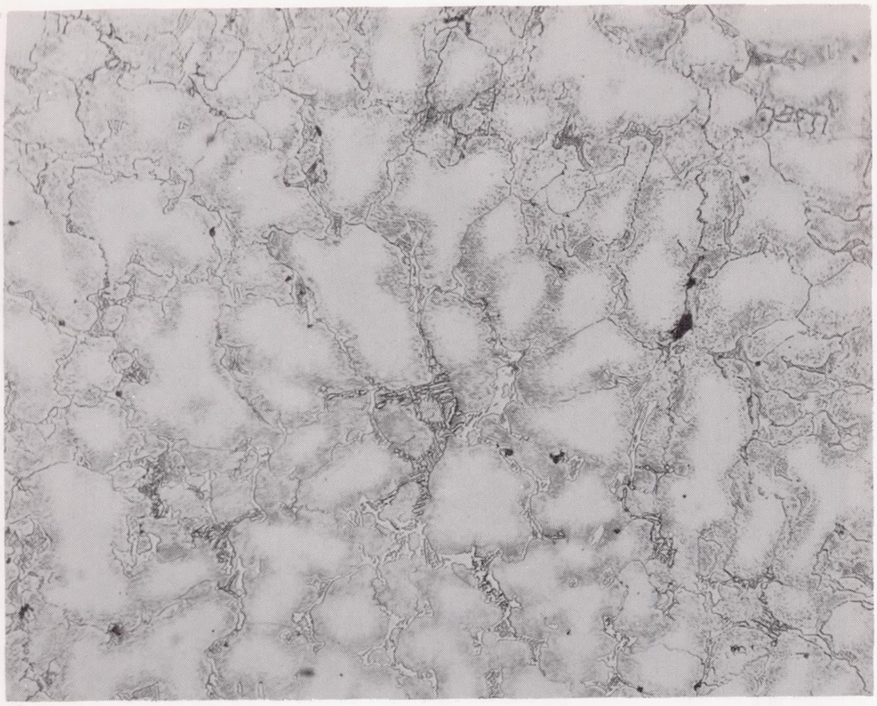


C-35665

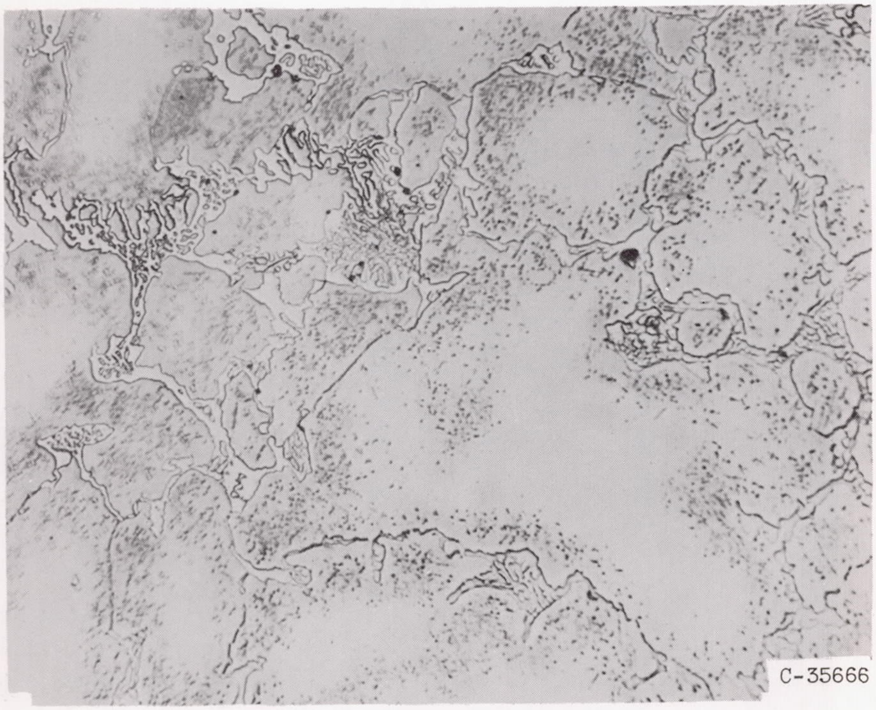
X750

(a) 483.9 Hours.

Figure 9. - Fine-grained 73J alloy operated at rated speed. Electrolytically etched in 5-percent aqua regia.



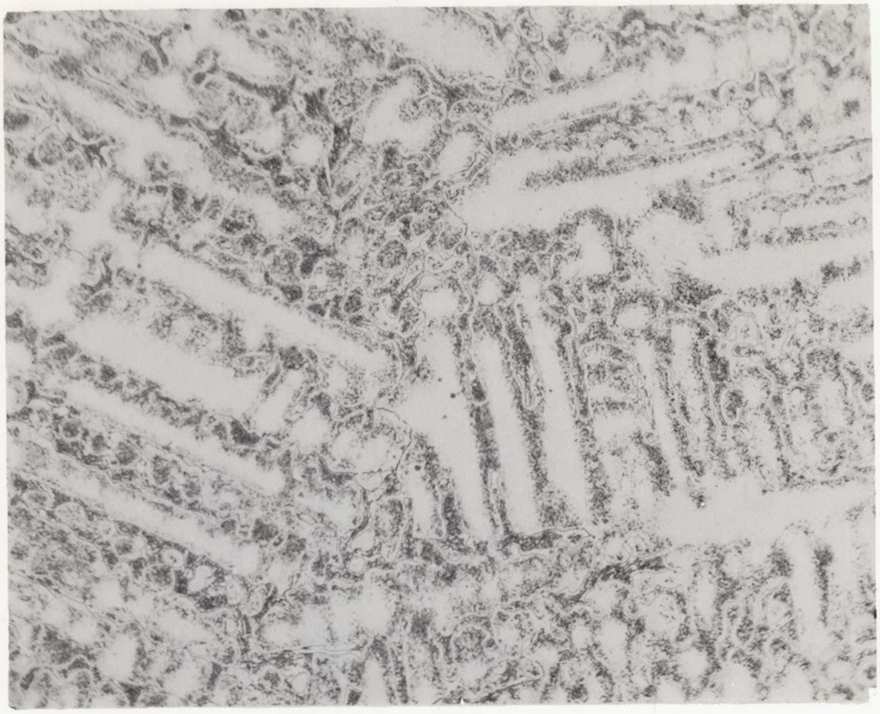
X250



X750

(b) 785.3 Hours.

Figure 9. - Concluded. Fine-grained 73J alloy operated at rated speed. Electrolytically etched in 5-percent aqua regia.



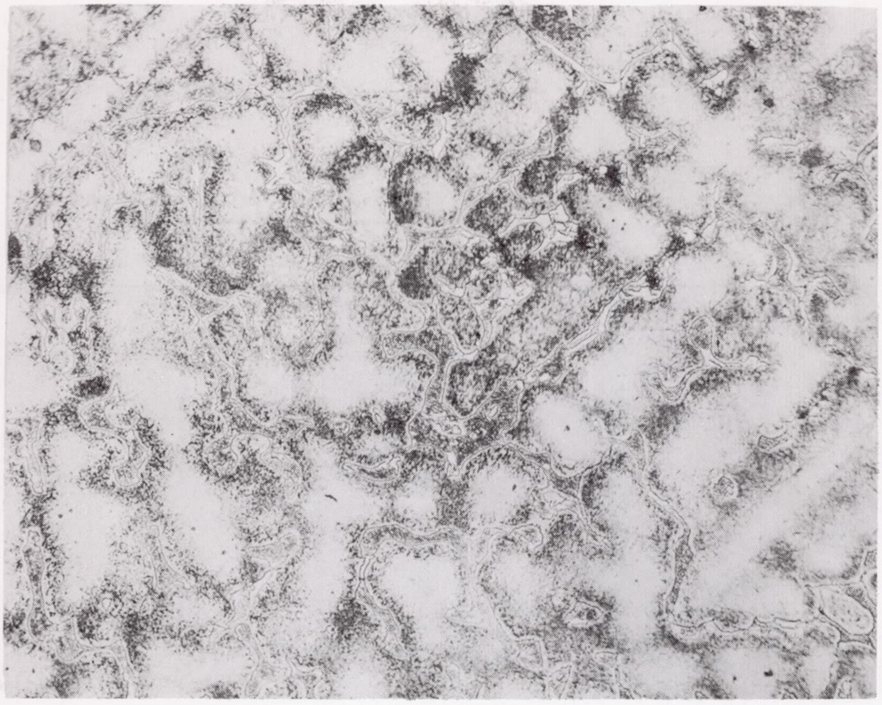
X250

X750

C-35669

(a) 609.2 Hours.

Figure 11. - Coarse-grained 73J alloy operated at rated speed. Electrolytically etched in 5-percent aqua regia.



X250

X750

(b) 844.6 Hours.

Figure 11. - Concluded. Coarse-grained 73J alloy operated at rated speed. Electrolytically etched in 5-percent aqua regia.

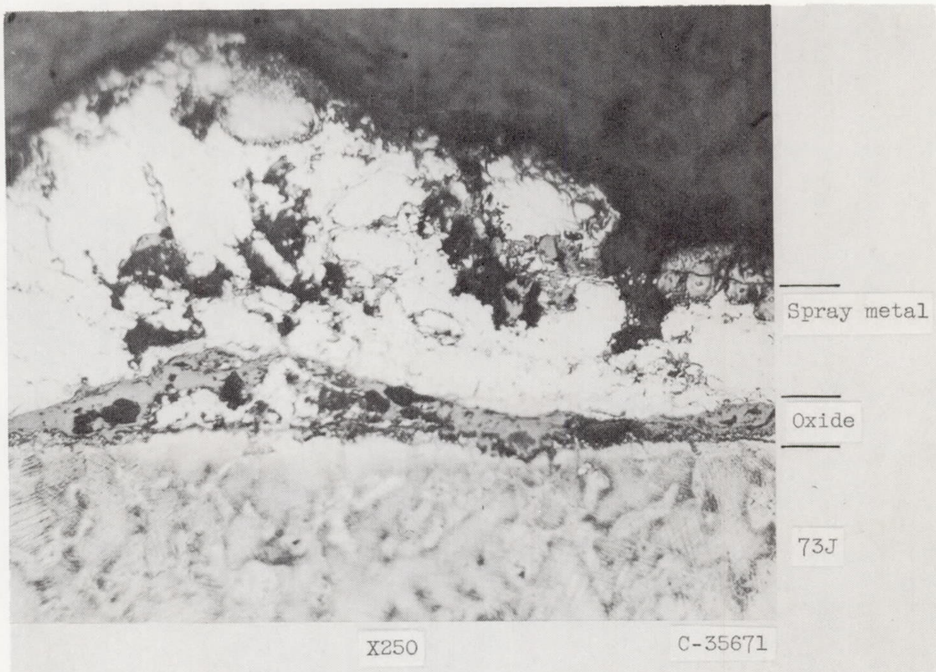
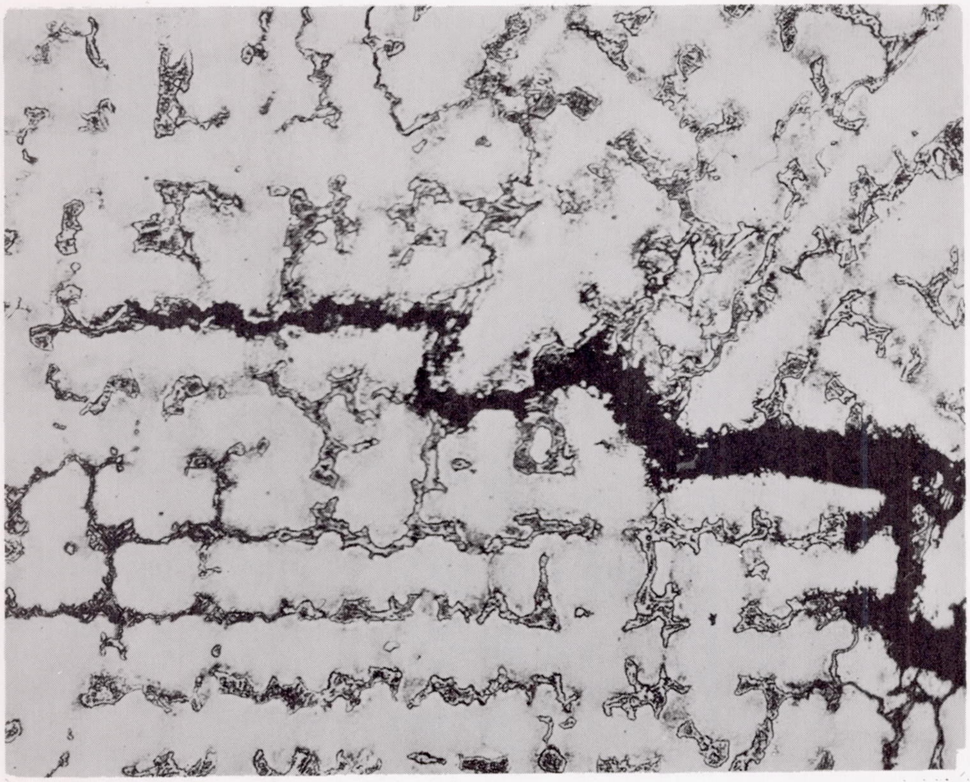


Figure 12. - Aluminum deposited on convex edge of blade as result of engine fire. Electrolytically etched in 5-percent aqua regia.



X250 C-35672

Figure 13. - Typical stress-rupture crack in 73J alloy blade. Electrolytically etched in 10-percent aqueous HCl.