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RESEARCH MEMORANDUM

AN EVALUATION OF ELECTROPOLISHED AND NONELECTROPOLISHED BLADES OF ALLOYS REFRACTALOY 26, M-252, AND WASPALOY IN A J33-9 TURBOJET ENGINE

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted to determine if the engine performance of turbine blades of the alloys Refractaloy 26, M-252, and Waspaloy is improved by removal of the surfaces by electropolishing and to compare the engine performance of blades of these alloys with that of S-816 blades. Electropolished and nonelectropolished blades were run in a J33-9 turbojet engine for cycles of 15 minutes at rated speed and 5 minutes at idle speed. The results obtained indicated that blade performance was not improved by removing the slight surface defects of the blades used in this investigation. The mean life of Waspaloy blades was about equal to S-816 blades, while M-252 and Refractaloy 26 blades had shorter mean lives.

INTRODUCTION

The high strategic alloy content of high-temperature alloys now in widespread use has lead to the development of alternate alloys with greatly reduced strategic alloy content. The alloys used in this investigation, Refractaloy 26, M-252, and Waspaloy, are three of these alloys. Typical of many of the low strategic content alloys, they have a nickel base and, as such, are thought to be particularly susceptible to oxide penetrations, surface defects, recrystallization, and grain growth at the surface layers due to cold work (refs. 1 and 2). The removal of these surface conditions by grinding or electropolishing the blades has been recommended for improved performance. The purpose of this investigation is to determine if the engine performance of turbine blades of the alloys Refractaloy 26, M-252, and Waspaloy is improved by removal of the surface by electropolishing, and, in addition, to compare the performance of blades of these low strategic-element-content alloys with that of blades of S-816, a widely used alloy of high strategic element content.

The alloys were evaluated in a full-scale J33-9 engine test. The engine was operated in 20 minute cycles of 15 minutes at rated speed and 5 minutes at idle speed until all original blades failed. Stress-rupture results were obtained from specimens cut from blade airfoils and from bar stock. Metallurgical studies of the microstructure, grain size, and hardness were made in an attempt to correlate each with blade performance.

MATERIALS, APPARATUS, AND PROCEDURE

Turbine Blades

The alloys were received from commercial vendors in the form of $1\frac{5}{16}$-inch round bar stock of the following nominal composition:

Element	Percent by weight in		
	Refractaloy 26 (AMS 5760)	M-252	Waspaloy
C	0.038	0.17	0.05
Co	20.4	10.5	13.8
Cr	18.3	18.5	19.5
Mo	3.0	10.0	3.0
Ti	2.8	3.0	2.5
Al	.11	1.0	1.25
Fe	15.9	.7	1.0
Mn	.84	.40	1.0
Si	.99	.55	.6
Cu			.1
S			.015
Ni	Balance (37)	Balance (55)	Balance (57)

The bar stock was forged into J33-9 blades and given the recommended heat treatment by commercial forge shops. The Waspaloy blades were forged by one concern and the M-252 and Refractaloy 26 by another. The forging temperatures, heat treatment, and finishing operations used for each alloy are given in table I. All the M-252 blades were lightly electropolished at the forge shop. The light electropolish removed very little material, and the as-received surfaces of these blades were similar to blades without a light electropolish. All blades were received in the as-trimmed condition, and the rough surfaces at the leading and trailing edges were ground to smooth contours at the NACA Lewis laboratory. Fourteen blades of each alloy were run in the engine; half of the blades of each alloy were electropolished at the Lewis laboratory. The surface was removed to a depth of from 0.001 to 0.002 inch by passing current through an electrolytic cell with the blades as the anode. Details are as follows:

Electrolyte	Alloy	Current, amp	Time, min	Cleansing
70 percent concentrated H_3PO_4, 6.5 percent concentrated H_2SO_4, and 23.5 percent H_2O	Refractaloy 26	50 to 70	5	Water
	M-252	(1) 50	$1\frac{1}{2}$	(2) Vapor blast
		(3) 50	5	(4) Water
	Waspaloy	(1) 50	2	(2) Vapor blast
		(3) 30	5 to 10	(4) Water

All blades passed inspection for surface and internal defects using post emulsion zyglo and X-ray radiography before engine operation.

Stress and Temperature Distribution in Turbine Blades During Engine Operation

The distribution of centrifugal stresses in the blade airfoils was calculated from density and area measurements by the method described in reference 3. Stress distributions for the different alloys are shown in figure 1. The stress distribution for Waspaloy blades is considerably below that for Refractaloy 26 and M-252 blades. The stress was lower in the Waspaloy blades because the airfoils were on the thin side of specifications in the upper portion of the blade and on the thick side of specifications near the base. The temperature distribution in blade airfoils also shown in figure 1 was determined by thermocouples, using the method described in reference 4.

The stress-rupture life of the alloys corresponding to the conditions of centrifugal stress and temperature at different sections of the airfoil is shown in figure 2. The curves were constructed by extrapolation of the stress-rupture data from specimens cut from blade airfoils and from the distributions of centrifugal stress and temperature of figure 1. The curves are typical of several constructed using mathematical and graphical extrapolation methods. The results obtained using the different methods were very similar because the extrapolation was limited to small differences of stress and temperature in the blade airfoil. The minimum is the most important section in each curve, and this area is obtained from data and is not extrapolated. The rest of the curve should be considered qualitative. The minimum in each curve represents the blade section that is exposed to the most severe combination of centrifugal stress and temperature. If the failures result solely from the centrifugal stress and the temperature, the blades should fail at this distance above the base and should have operating lives equal to the minimum values given in the figure.

Engine Operation

Six groups of seven blades of the alloys under study were installed in a J33-9 turbojet engine. One group of blades of each of the three alloys was in the as-received or nonelectropolished condition (the lightly electropolished M-252 blades are included in this group) and one group of each alloy was in the electropolished condition. Ten U. S. Air Force stock blades of standard S-816 were included for comparison. The blades were tested for repeated cycles of 15 minutes at the rated speed of the engine (11,750 rpm) and 5 minutes at idle speed until all original blades failed. In the discussions of blade life herein, only the time at rated speed is considered. Blade stress and temperature were controlled by engine speed and exhaust-nozzle opening, respectively. Blade temperatures were measured by thermocouples installed in two blades and connected to a recording device through a slip-ring system (refs. 4 and 5).

Blade Elongation Measurement

From one to three blades of each group were scribed near the trailing edge at 1/2-inch intervals, as shown in figure 3 and described in reference 5. Blade elongation measurements were made at frequent intervals (after blade failures or necessary shutdowns) using an optical extensometer. Elongation data were influenced by the warpage and distortion of the blades. The chronological increase of elongation for each gage section was not obtained for alloys Refractaloy 26 and Waspaloy because the variations caused by the warpage and distortion were large enough to obscure the small elongations obtained for these alloys. The maximum elongation obtained for any section was plotted. The elongation of individual gage sections was obtained and plotted against the time of operation for alloys M-252 and S-816.

Macroexamination of Failed Blades

A blade was said to have failed and was removed from the engine when actual failure occurred or when cracks or severe necking made it apparent that failure was imminent. The failed blades were examined at low magnifications to determine, as nearly as possible, the manner in which failure occurred. The failures were classified (as in ref. 6) into the following categories:

(1) Stress rupture: Blade failures occurred by cracking within the airfoil or by fracturing in an irregular, jagged, intercrystalline path. In addition to the main fracture, other similarly formed cracks sometimes occurred near the origin of the main fracture.

(2) Fatigue: Cracks progressed from nucleation points, usually at or near the leading or trailing edges, in straight paths which frequently were smooth, often showed progression lines or concentric rings, and appeared to be transcrystalline.

(3) Stress rupture plus fatigue: Blade failures appeared to be caused by a combination of the two preceding mechanisms. The fractured surfaces of blades in this group consisted of a small area which had the characteristics described for the stress-rupture category and a larger area with the fatigue characteristics described. A further criterion was that other cracks, which appeared to be stress-rupture cracks, were visible in the area adjacent to the main crack or fracture edge.

In all cases, the blades finally failed in tension because of the progressive reduction in the load-carrying area, so that all blade failures showed a large area of rough fracture surface. Some blade failures are equally representative of two of the preceding categories, and classification is a matter of judgment. The classifications are subject to error even when the appearance of the failure is quite definitely one of these described above. It is shown in reference 7 that stress-rupture specimens can be subjected to large superimposed vibratory loads without showing any evidence of fatigue failure on the manner and appearance of fracture, although the reduction in life caused by the vibratory load makes it clear that fatigue must be a factor in causing failure. Also, there may be thermally induced stresses in the blades that may affect the failure mechanism. Such stresses might result from temperature differences from the leading edge to the midchord of blades (ref. 8).

4. Damage: Blades with nicks or dents in the airfoil that would initiate failure were removed from the test and listed as damage failures. These failures do not indicate the properties of the alloy and are not included in the evaluation of the test results, although they are recorded and plotted.

Metallographic Studies of Blades

Microstructural studies were made of specimens cut from blade airfoils of each alloy in the as-received condition. Specimens from blades of each group with the shortest and the longest time-to-failure in engine operation were also studied. The latter specimens examined were taken from the area of the fractured edge where failure originated. Photomicrographs were also taken of the surfaces of blades in the as-received and electropolished condition.

Grain Size and Hardness Measurements of Blades

Grain size and hardness measurements were obtained from specimens of as-received and first and last failures of each blade group. The specimens were taken from the zone just below the fracture edge of the failed blades and from the midportion of as-received blades. Hardness readings were taken over the entire cross section. The specimens were then polished for grain size determinations of the smallest, largest and most prevalent grains. An A.S.T.M. grain size measuring eyepiece was used.

Stress-Rupture Tests

The stress-rupture properties of each alloy at various stress levels and 1500° F were determined from specimens cut from bar stock and from blade airfoils. The specimen cut from blade airfoils and the zone from which it was machined are shown in figure 4. The stress-rupture results were obtained to correlate the engine performance of blades with bar stock and blade airfoil specimen properties.

RESULTS

Engine Operating Results and Blade Performance

Engine results. - The time, mechanism, and location of blade failures in the engine test are shown in table II and figure 5. The results show that the nonelectropolished blades of each alloy ran about as well as the electropolished blades.

The range of blade failure times and mean life of the three alloys and S-816 (combining electropolished and nonelectropolished blade failures and eliminating damage failures) were as follows:

Alloy	Failure time range, hr	Mean life, hr
Refractaloy 26	26 to 68	45
M-252	89 to 177	122
Waspaloy	137 to 325	226
S-816	106 to 261	229

The Waspaloy blades had a mean operating life and variability comparable with S-816. While M-252 had a somewhat lower mean life, the scatter band was narrow, with a first failure time only 17 hours below the first failure of S-816. Refractaloy 26 had a much shorter blade life than S-816. The lower stress (fig. 1) in the Waspaloy blades was partially responsible for its good blade life.

Elongation of blades during engine operation. - The results of elongation measurements from scribed blades are shown in figure 6. The scatter of data on measuring elongation of Refractaloy 26 and Waspaloy prevented a determination of the elongation for the individual sections of the blade. The maximum elongation of the blades was determined and found to be small, with Refractaloy 26 elongating less than 0.2 percent and Waspaloy less than 0.5 percent. The data permitted a determination of the elongation of the individual sections of the scribed blades of M-252 and S-816. The maximum elongation of M-252 was 1.3 percent, while S-816 had a maximum of 8.7 percent. The maximum elongation occurred just above the center of the M-252 blades, while the S-816 blades elongated most just below the center of the blade.

Macroexamination of failed blades. - The distance of the failure above the base of the blade for the three alloys is shown in table II and figure 7, in which the damage failures are omitted. Seventy-five percent of all blade failures occurred in the zone from 2 to $2\frac{1}{2}$ inches above the base, which is about the zone of minimum stress-rupture life of the blades. The failures above and below this group were divided, with 15 percent occurring from $2\frac{1}{2}$ to $2\frac{7}{8}$ inches above the base and 10 percent from $1\frac{5}{8}$ to 2 inches above the base. The failure mechanisms, excluding failure by damage, were as follows: Stress rupture, 38 percent; stress rupture plus fatigue, 53 percent; and fatigue, 9 percent.

Metallurgical Studies of Blades

Microstructure. - The microstructures of as-received and failed blades of each alloy are shown in figure 8. The general microstructure of the alloys was changed somewhat by engine operation. There was, in the failed Refractaloy 26 blades, some evidence of additional fine, evenly dispersed precipitation in the matrix and some additional spheroidization of the grain boundaries. Also, a depletion zone developed around some grain boundaries. Normal aging such as this is expected in engine operation of a precipitation-hardened alloy. In the M-252 blades, the large residual precipitates were unchanged by engine operation, but there was some additional precipitation in Widmanstätten form. There was, as would be expected, no difference in the microstructure of electropolished and nonelectropolished blades of this or the other alloys. The Waspaloy failed blades showed an increase in the amount of fine, evenly distributed precipitates in the matrix. An oxide layer and depletion zone developed on the outside surface and fracture edge of some failed blades as a result of engine operation.

Surfaces. - Photomicrographs of typical as-received surfaces are shown in figure 9. Photomicrographs of an extreme case of oxide penetration and roughness of Waspaloy and a typical electropolished surface are also shown in figure 9. The surfaces of most as-received blades have very little oxide penetration and roughness. The oxide penetrations and roughness are of the order of 0.0004 inch.

Hardness and grain size. - The hardness and grain size of as-received and failed blades of each alloy are shown in table III. No correlations between blade life and hardness or grain size are evident.

Stress-rupture results. - The stress-rupture life at 1500° F of specimens cut from bar stock and from blade airfoils, and the time to failure of blades at the stress level corresponding to the zone where most failures occurred are shown in figure 10. The Waspaloy and M-252 bar stock stress-rupture life is greater than the life of specimens cut from blade airfoils, indicating a loss in properties in forging. Refractaloy 26 blade-airfoil-specimen stress-rupture life was about equal to bar stock life. Thus, properties of Refractaloy 26 were retained in forging, at least in the midportion of the blade from which the stress-rupture specimens were cut (see fig. 4). For all three alloys, blade failures occurred in shorter times in engine operation than in stress-rupture testing.

BLADE FAILURE MECHANISMS

The results of the determination of the zone of minimum stress-rupture life by the method previously described are shown in figure 2. The minimum of each curve represents the expected life and location of blade failure, if the failures were a result of the centrifugal stress and the temperature. The location and time to failure would be as follows:

Alloy	Distance above base, in.	Time, hr
Refractaloy 26	2	140
M-252	$2\frac{1}{8}$	230
Waspaloy	$2\frac{1}{4}$	285

Seventy-five percent of the failures occurred about the zone of minimum stress-rupture life, as was previously noted.

If stress rupture were the predominant failure mechanism, the location of failure would also be expected to occur in the zone of maximum elongation. The greatest elongation for M-252, the one alloy for which the elongation of individual sections was obtained, occurred in section 4, or from $1\frac{3}{4}$ to $2\frac{1}{4}$ inches above the base. This is also the range of the zone of minimum stress-rupture life and the zone where most failures occurred. The location of failure and the location of maximum elongation in the zone of minimum stress-rupture life indicates that stress rupture should be the predominant failure mechanism. However, blade life was appreciably below that expected from stress-rupture results of blade airfoil specimens (fig. 10). This would indicate that either the specimens taken from the center of the blade airfoils were not indicative of the properties of the blades, or that some mechanism other than stress-rupture acted to reduce blade life.

The possibility that Refractaloy 26 blade life was affected adversely by the forging practice does exist and is subsequently discussed, but neither the description of the fabrication of M-252 or Waspaloy nor the microstructural, hardness, and grain size studies of all three alloys suggest that the properties should vary from edge to center. The reduction in life may have been caused by the vibratory and/or thermally induced stresses that are present in the blade during engine operation. These stresses may shorten the life of the blade while retaining the appearance and location of a stress-rupture failure as described previously and in reference 7. There is some support for this hypothesis, for there was at least some indication of fatigue in 61 percent of the failures.

DISCUSSION OF RESULTS

Blade Performance of Electropolished against Nonelectropolished Groups

The similar performance of electropolished and nonelectropolished blades of each alloy indicates that little advantage is gained by removing the surface layer. The blades used in this investigation were forged by two commercial forge shops, and the surface defects obtained were of the order of 0.0004 inch in depth. The defects reported to be damaging were about 0.003 inch in depth (refs. 1 and 2). Thus, the surface defects and cold work, which are thought to reduce blade performance, were so slight in the blades used in this investigation that no improvement in performance was gained by removing them by electropolishing.

Blade Performance of Different Alloys

The blade performance of Waspaloy and M-252 (table II and fig. 5) suggests that these alloys may be satisfactory as possible replacements for more strategic alloys. Blade performances of Waspaloy and standard S-816, which had mean lives of 226 and 229 hours, respectively, were about equal. While the mean life of 122 hours obtained for M-252 was less than that for S-816, the alloy may be considered satisfactory for engine operation, since the mean life was over 100 hours and the strategic element content is low. Moreover, the properties of both M-252 and Waspaloy have been improved by changes in composition and fabrication since the material for this investigation was obtained. Refractaloy 26 blade performance with a mean life of 44 hours was poor compared with S-816. However, the stress-rupture life of specimens cut from the center of the Refractaloy 26 blade airfoils was about equal to the bar stock specimen life of 165 hours. The optimum forging techniques and temperatures have not been determined for blade airfoils of Refractaloy 26; different forging conditions might result in higher blade lives. The variation of thickness in a turbine blade airfoil may have caused temperature gradients in forging that imparted satisfactory properties to the thick central portion of the airfoil from which stress-rupture specimens were cut and poorer properties at the thin leading and trailing edges where most blade failures begin. The variation in properties from edge to center may have been exaggerated by a too low forging temperature and could perhaps explain the poor performance of the blades. The vibratory and thermally induced stresses mentioned previously could also have been responsible for the low life of these blades.

Elongation or creep of Refractaloy 26, M-252, and Waspaloy, as with most nickel-base alloys, was small compared with S-816. Maximum alongations were 0.2 percent for Refractaloy 26, 0.5 percent for Waspaloy, and 1.3 percent for M-252, while S-816 elongated 8.7 percent (see fig. 6). The lack of ductility usually associated with low creep rates did not preclude good blade performance, for the blades were able to withstand the impact of fragments of failed blades as well as S-816 in this investigation.

SUMMARY OF RESULTS

The purpose of this investigation was to determine if blade performance of alloys Refractaloy 26, M-252, and Waspaloy is improved by removal of the surface by electropolishing, and, in addition, to compare the perof the alloys with S-816. Blades of Refractaloy 26, M-252, and Waspaloy in the electropolished and nonelectropolished condition were run in a J33-9 turbojet engine for cycles of 15 minutes at rated speed and 5 minutes at idle speed. The results obtained are as follows:

1. The similar performance of electropolished and nonelectropolished blades of each alloy indicates that little advantage was gained by removing the slight surface defects of the blades used in this investigation.

2. The performance of Waspaloy blades was about equal to S-816 blades, with mean lives of 226 and 229 hours, respectively, whereas the mean life of M-252 was 122 hours. Refractaloy 26 blade performance was poor with a mean life of 44 hours. However, there is a possibility that the forging practice affected the latter material adversely.

3. Elongation of the three alloys, as with most nickel-base alloys, was low compared with S-816, but the very low ductility nickel-base alloy blades were able to withstand the impact of fragments of failed blades in these tests.

4. The location of 75 percent of the blade failures in the zone of minimum stress-rupture life and the zone of maximum elongation indicated that stress rupture should be the predominant failure mechanism. However, the time to failure was below that of stress-rupture failure, and some evidence of fatigue was found in 61 percent of the failures; this indicates that some factor other than centrifugal stress contributed to the failure mechanism. Vibratory and thermal stresses have been suggested as possible contributing factors.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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REFERENCES

1. Pfeil, L. B., Allen, N. P., and Conway, C. G.: Nickel-Chromium-Titanium Alloys of the Nimonic 80 Type. Symposium on High-Temperature Steels and Alloys for Gas Turbines, Iron and Steel Inst. (London), July 1952, pp. 37-45.

2. Hignett, H. W. G.: High Temperature Alloys in British Jet Engines. Paper presented at A.S.M. meeting (Detroit), Nov. 12, 1951. (Reprinted by The International Nickel Co., Inc.)

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

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

5. 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, Refractaloy 26, N-155, and Inconel X. NACA RM E51G13, 1951.

6. Weeton, J. W., Clauss, F. J., and Johnston, J. R.: Performance of As-Forged, Heat-Treated, and Overaged S-816 Blades in a Turbojet Engine. NACA RM E54K17.

7. Ferguson, Robert R.: Effect of Magnitude of Vibratory Load Superimposed on Mean Tensile Load on Mechanism of and Time to Fracture of Specimens and Correlation to Engine Blade. NACA RM E52I17, 1952.

8. Morse, C. R., and Johnston, J. R.: Temperatures in a J47-25 Turbojet-Engine Combustor and Turbine Sections During Steady-State and Transient Operation in a Sea-Level Stand. NACA RM E54K30a.

TABLE I. - FORGING TEMPERATURES, HEAT TREATMENTS, AND FINISHING OPERATIONS

Alloy	Forging temperature	Heat treatment	Finishing operation
Refractaloy 26	First operation, 1950° F Subsequent operations, 1700° F	1950° F, $1\frac{1}{2}$ hr, oil quenched 1500° F, 20 hr, furnace cooled to 1350° F, 20 hr, air cooled	Sandblasted, inspected, Sandblasted Tampico brushed, inspected
M-252	1950° F	1950° F, 4 hr, air cooled 1400° F, 16 hr, air cooled	Sandblasted, inspected, lightly electromachined Sandblasted, Tampico brushed, inspected
Waspaloy	Information not available	1950° F, 4 hr, oil quenched 1375° F, 16 hr, air cooled	Information not available

TABLE II. - LOCATION OF BLADE FAILURE ORIGIN

Order of failure	Failure time, hr	Failure type	Height above base, in.	Location with respect to edges
Group 1: Refractaloy 26, as-received (nonelectropolished)				
1	38.4	Stress rupture	$2\frac{1}{4}$	Trailing edge
2	44.0	Stress rupture plus fatigue	$2\frac{3}{8}$	Leading edge
3	44.5	Stress rupture plus fatigue	$2\frac{1}{8}$	Leading edge
4	44.5	Stress rupture plus fatigue	$2\frac{3}{8}$	Leading edge
5	44.9	Stress rupture	$2\frac{1}{2}$	------------
6	45.3	Stress rupture plus fatigue	$2\frac{3}{8}$	Leading edge
7	67.5	Stress rupture	$2\frac{1}{4}$	Trailing edge
Group 2: Refractaloy 26, electropolished				
1	26.0	Fatigue (crack)	$2\frac{1}{2}$	Trailing edge
2	38.9	Fatigue	$2\frac{1}{2}$	Trailing edge
3	42.7	Stress rupture plus fatigue	2	Leading edge
4	44.1	Fatigue	$2\frac{1}{8}$	Leading edge
5	47.2	Stress rupture	$2\frac{1}{2}$	------------
6	53.2	Fatigue	$2\frac{3}{16}$	Leading edge
7	54.7	Stress rupture	$2\frac{1}{8}$	Trailing edge
Group 3: M-252, as-received (lightly electropolished)				
1	78.4	Damage		
2	80.1	Damage		
3	88.8	Stress rupture plus fatigue	$2\frac{1}{8}$	Leading edge
4	125.0	Stress rupture plus fatigue	$1\frac{5}{8}$	Leading edge
5	138.9	Stress rupture plus fatigue	$2\frac{1}{4}$	Leading edge
6	151.2	Stress rupture plus fatigue	2	Leading edge
7	177.3	Stress rupture plus fatigue	$2\frac{3}{8}$	Leading edge
Group 4: M-252, electropolished				
1	91.5	Stress rupture plus fatigue	$2\frac{1}{2}$	Leading edge
2	93.7	Stress rupture plus fatigue	$1\frac{3}{4}$	Leading edge
3	105.9	Stress rupture plus fatigue	$2\frac{5}{8}$	Leading edge
4	106.5	Stress rupture plus fatigue	$2\frac{7}{8}$	Leading edge
5	108.7	Stress rupture plus fatigue	$2\frac{7}{8}$	Leading edge
6	125.5	Stress rupture plus fatigue	$1\frac{3}{4}$	Leading edge
7	147.2	Stress rupture	$2\frac{3}{8}$	Leading edge
Group 5: Waspaloy, as-received (nonelectropolished)				
1	80.1	Damage		
2	210.0	Damage		
3	224.4	Damage		
4	228.0	Stress rupture (crack)	$2\frac{1}{2}$	Leading edge
5	230.2	Stress rupture	$2\frac{7}{8}$	Leading edge
6	255.8	Damage		
7	259.7	Damage		
Group 6: Waspaloy, electropolished				
1	137.3	Stress rupture plus fatigue	$2\frac{1}{2}$	Leading edge
2	156.8	Damage		
3	177.8	Stress rupture	$2\frac{1}{4}$	Leading edge
4	204.0	Stress rupture	$2\frac{1}{4}$	Midchord
5	208.2	Stress rupture	$2\frac{1}{4}$	Midchord
6	291.0	Stress rupture	$2\frac{3}{4}$	Leading edge
7	324.8	Stress rupture	$2\frac{1}{4}$	Leading edge

TABLE III. - HARDNESS AND GRAIN SIZE OF AS-RECEIVED AND FAILED BLADES

Alloy	Condition	Hardness, Rockwell C	Grain size,[a] A.S.T.M.
Refractaloy 26	As-received	25.3	2-7 5
	Nonelectropolished, first failure	24.4	1-6 3
	last failure	24.1	1-8 3
	Electropolished, first failure	24.0	1-7 3
	last failure	25.0	(3x1)-6 2
M-252	As-received	30.5	1-8 5
	Lightly electropolished, first failure	33.8	5-7 6
	last failure	34.6	4-7 5
	Electropolished, first failure	33.9	3-7 6
	last failure	34.7	3-8 7
Waspaloy	As-received	30.3	1-8 6
	Nonelectropolished, first failure	26.8	1-6 3
	Electropolished, first failure	29.5	1-8 6
	last failure	32.0	2-8 3

[a]Largest, smallest, and most prevalent grain sizes are given in that order.

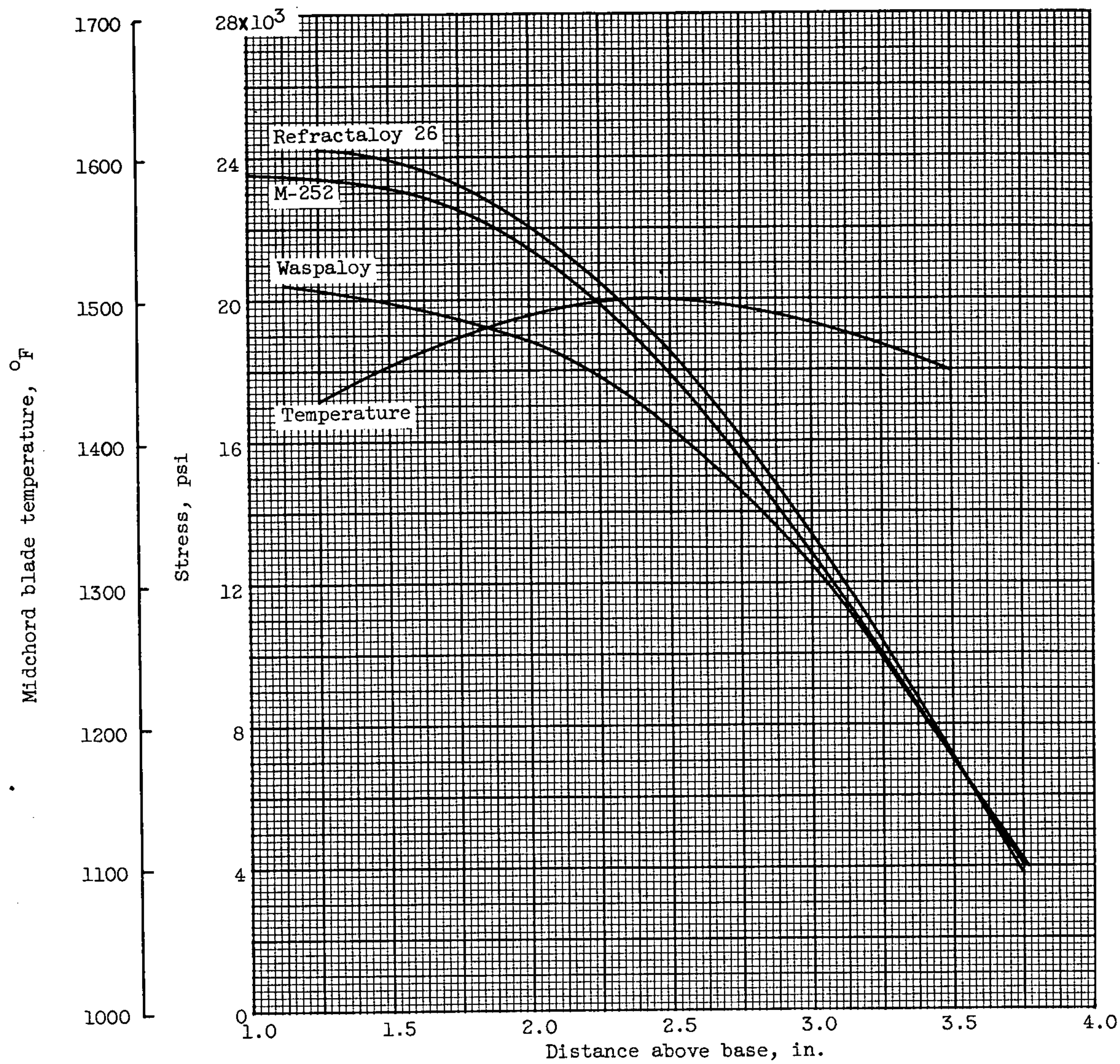


Figure 1. - Blade stress and temperature distributions.

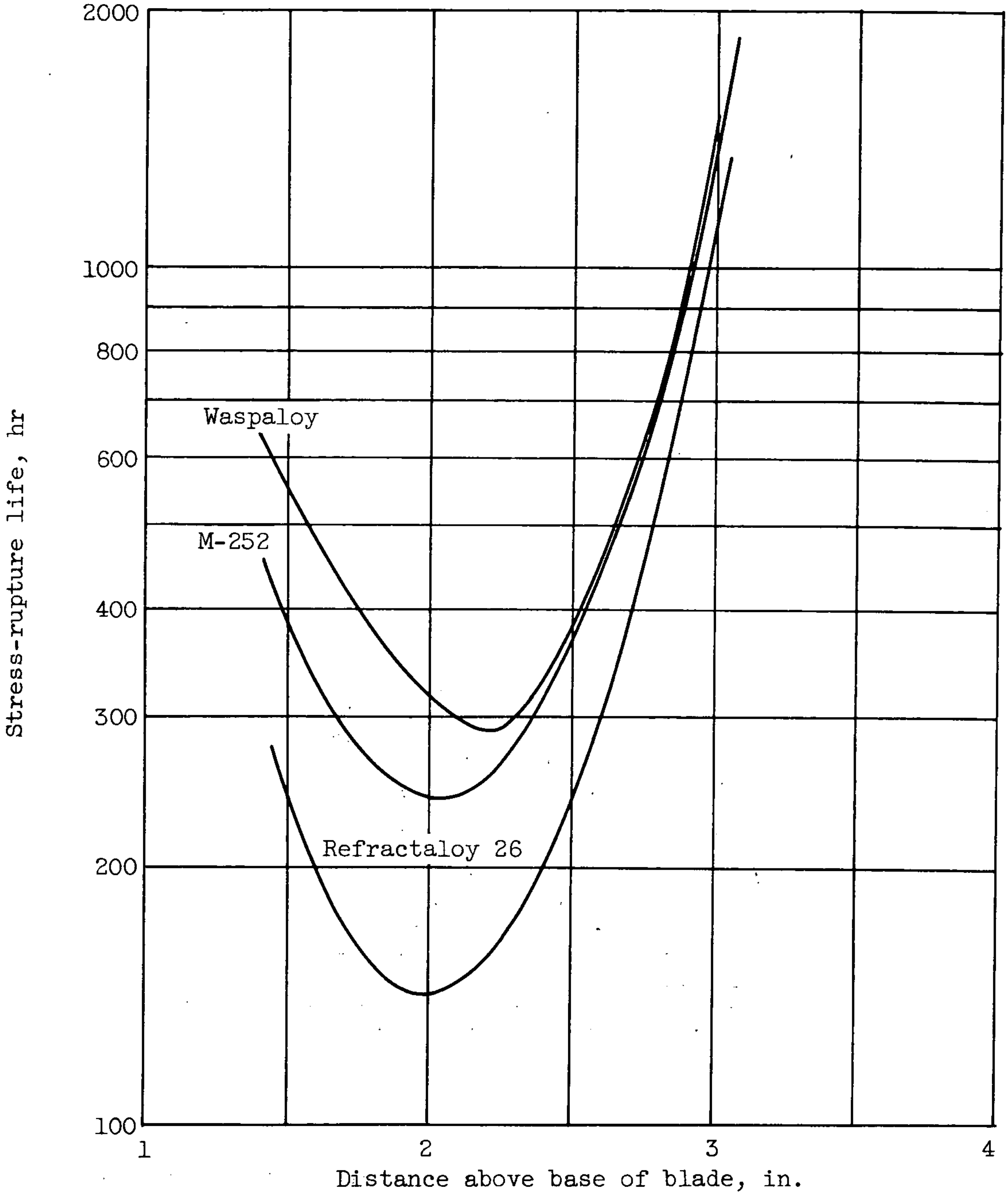


Figure 2. - Stress-rupture life of alloys corresponding to conditions of centrifugal stress and temperature of blades.

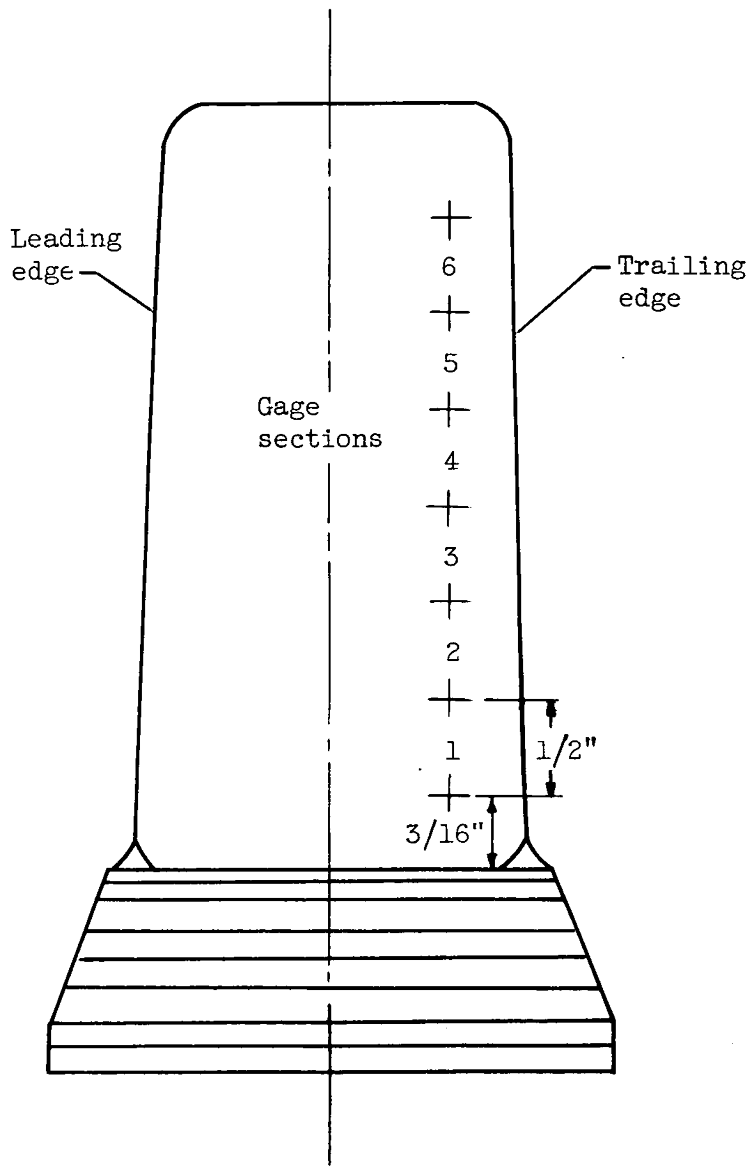


Figure 3. - Location of scribe marks on blades for elongation measurements (ref. 5).

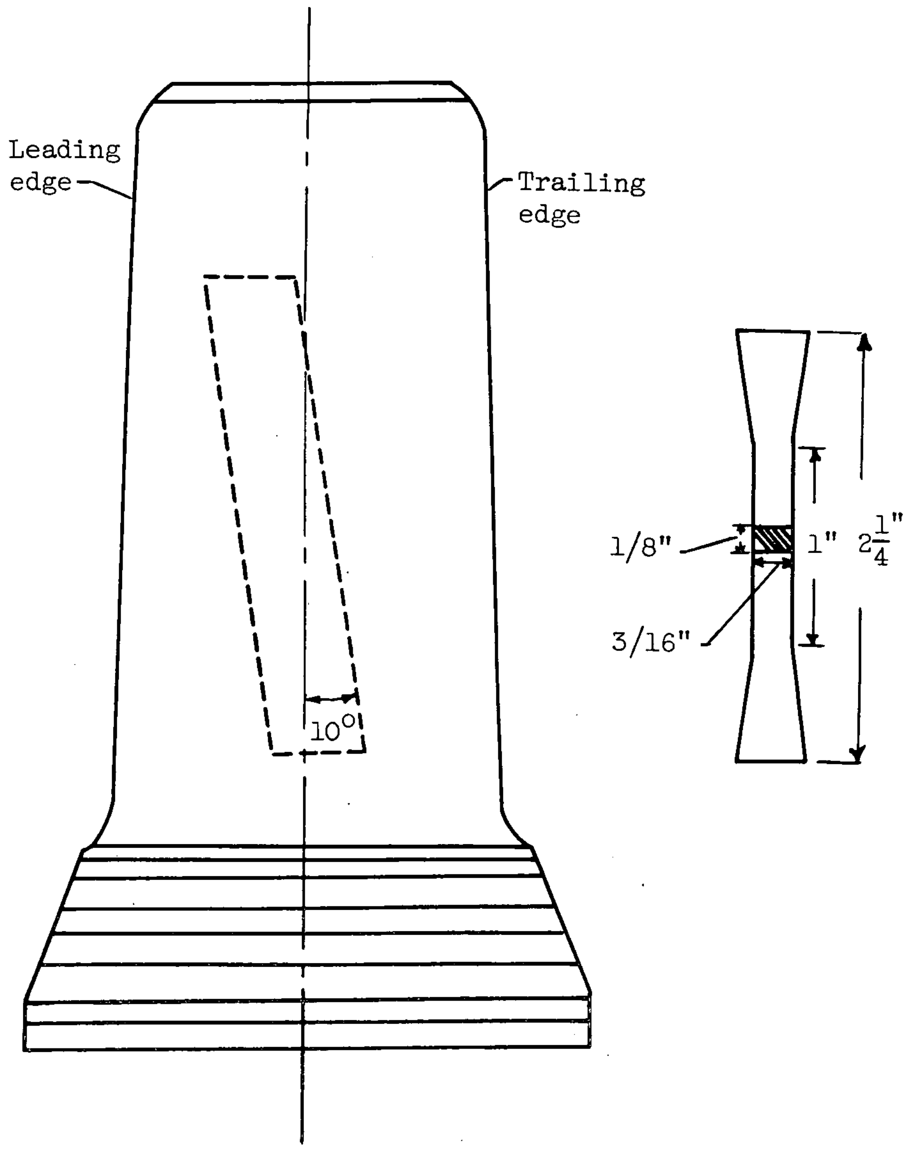


Figure 4. - Blade stress-rupture specimen and zone from which it was machined.

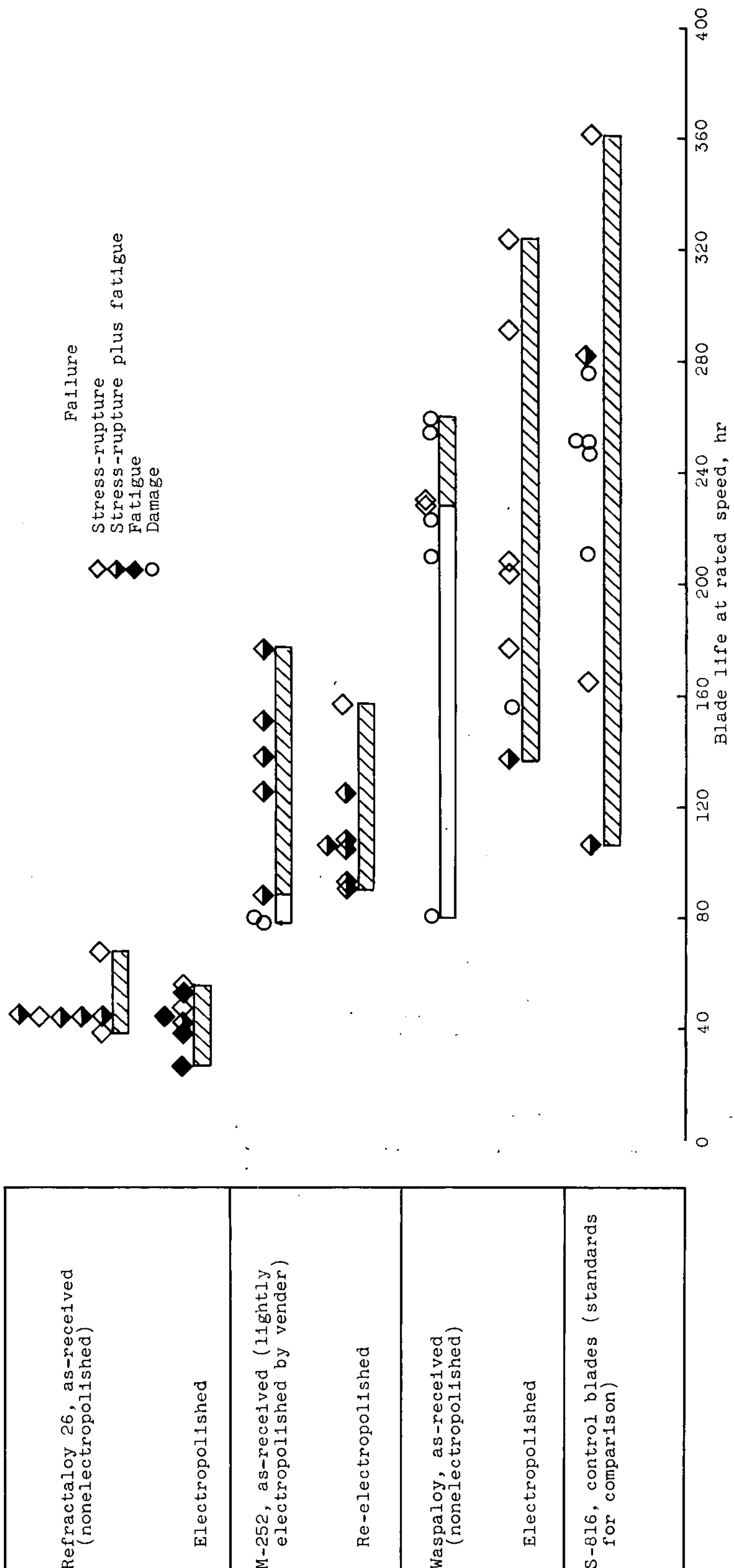


Figure 5. - Blade performance of different blade groups.

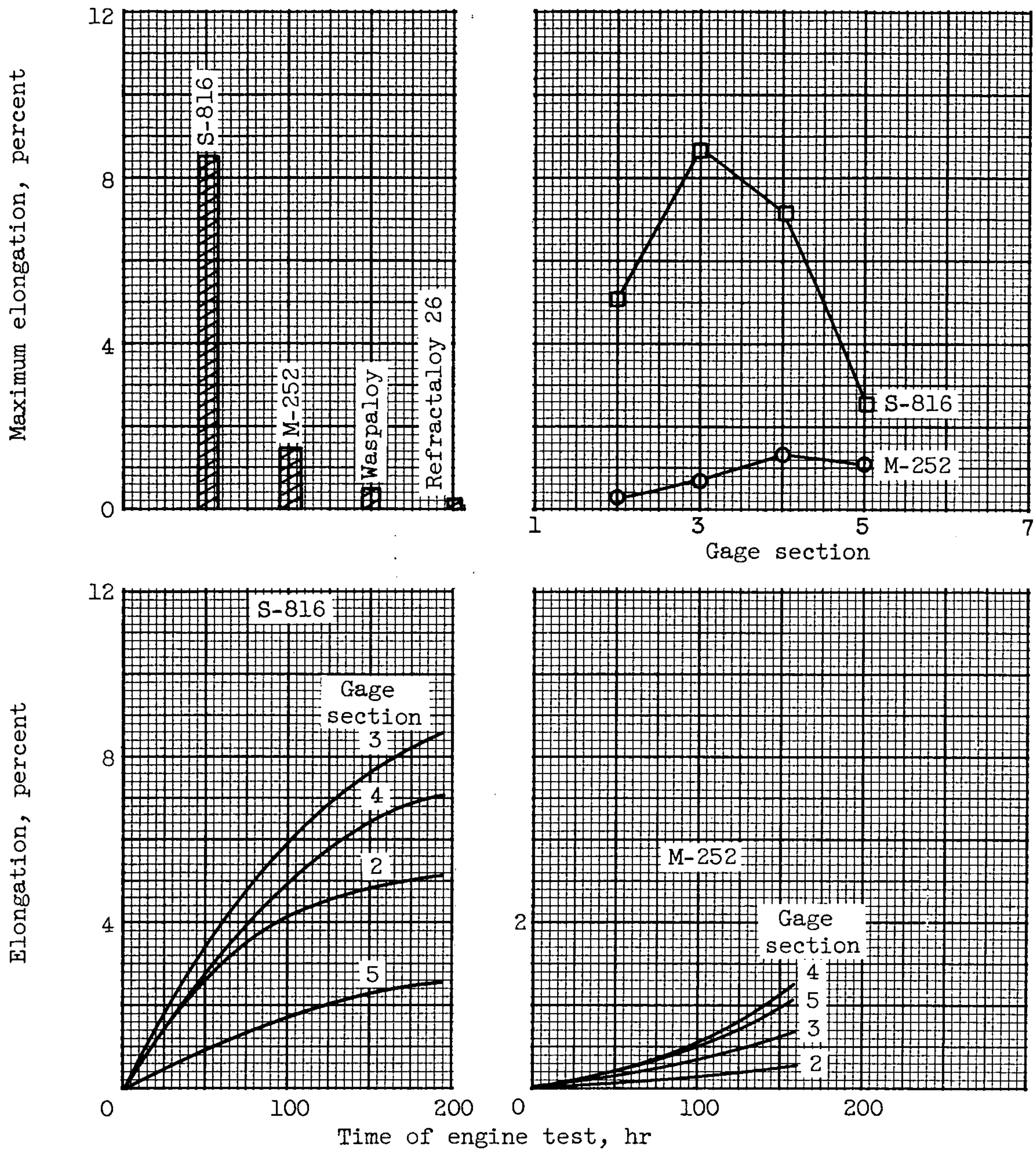


Figure 6. - Elongation of scribed blades in engine test.

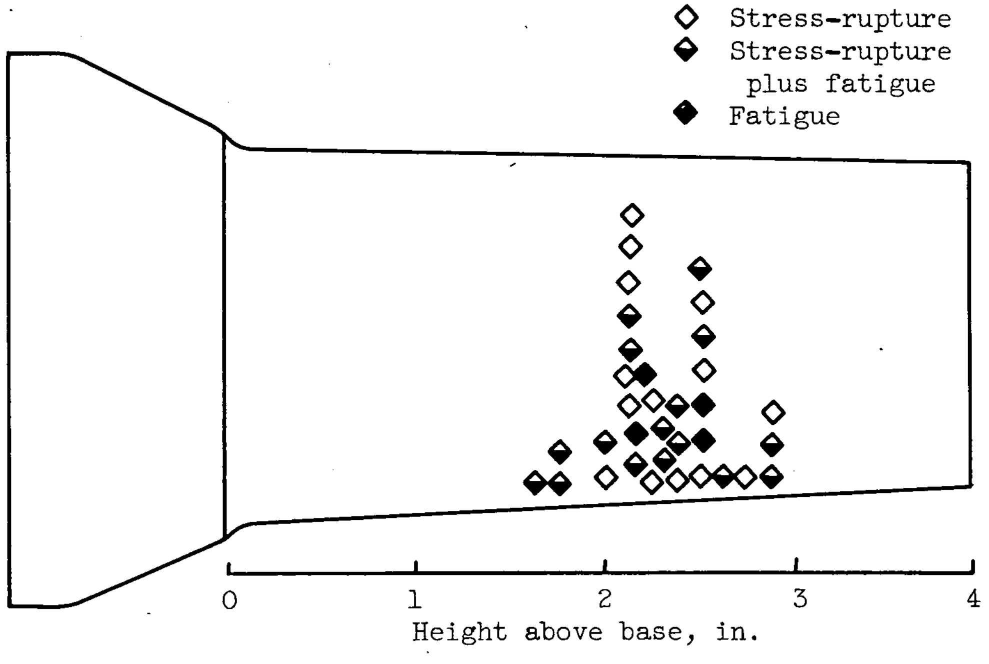
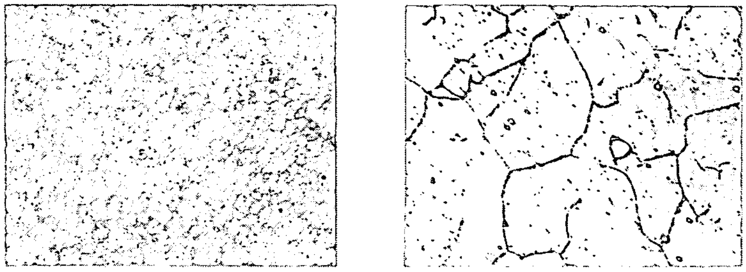
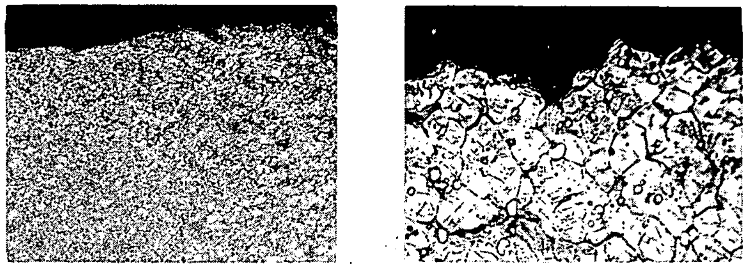


Figure 7. - Distance of failure above base for alloys Refractaloy 26, M-252, and Waspaloy.

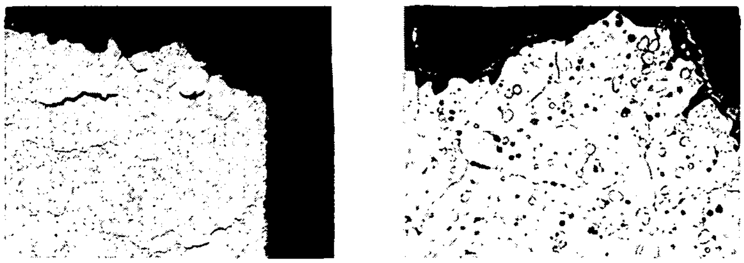
100X 750X



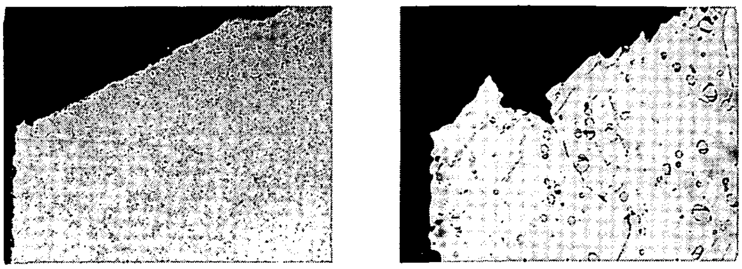
As-received



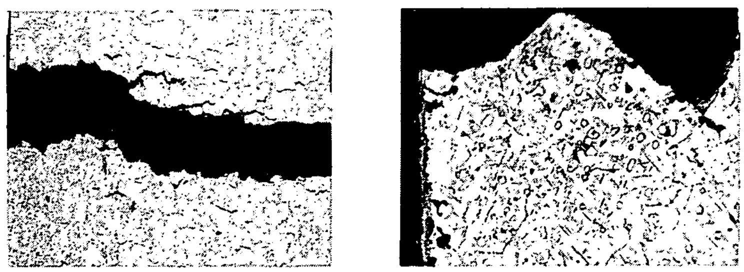
Lightly electropolished by vendor, first failure (stress-rupture plus fatigue) after 88 hr



Lightly electropolished by vendor, last failure (stress-rupture plus fatigue) after 171 hr



Electropolished, first failure (stress-rupture plus fatigue) after 91 hr



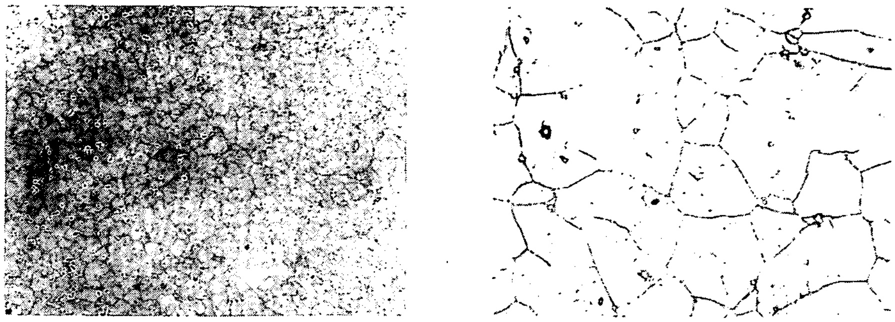
C-37319

Electropolished, last failure (stress-rupture) after 147 hr

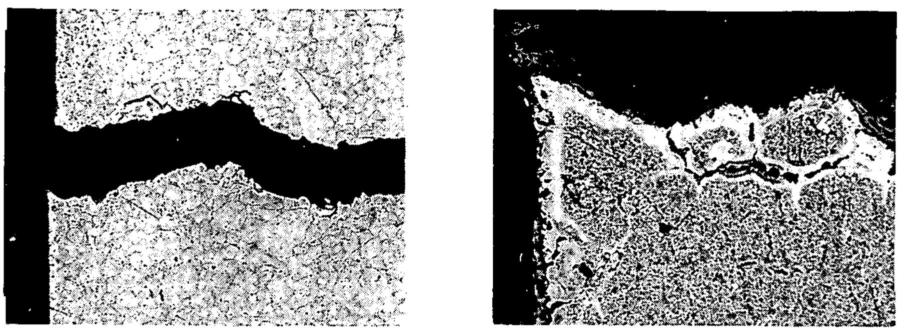
(a) M-252.

Figure 8. - Microstructures of as-received and failed blades.

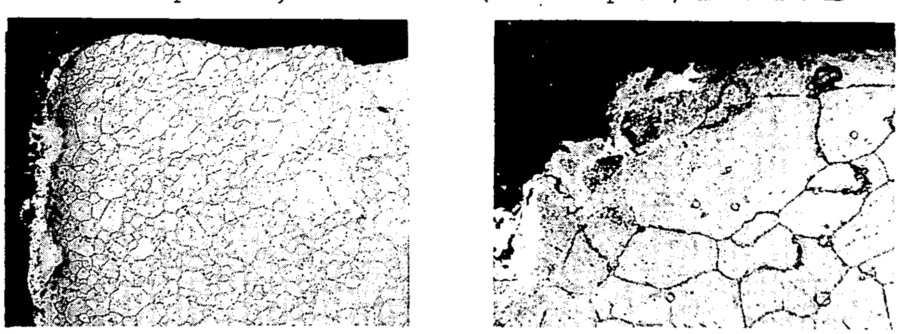
100X 750X



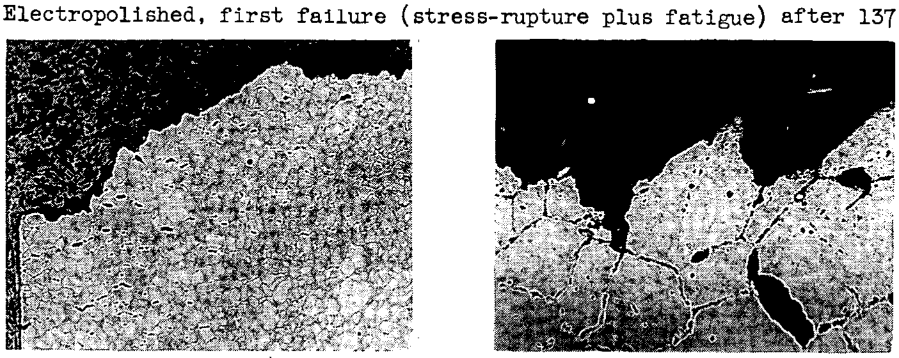
As-received



Nonelectropolished, first failure (stress-rupture) after 228 hr



Electropolished, first failure (stress-rupture plus fatigue) after 137 hr



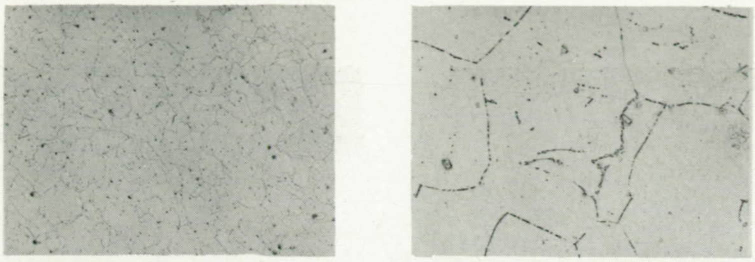
C-37320

Electropolished, last failure (stress-rupture) after 324 hr

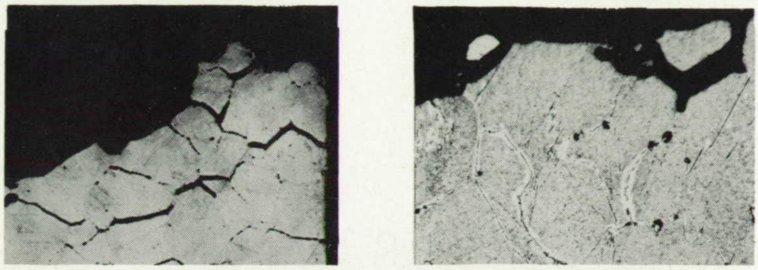
(b) Waspaloy.

Figure 8. - Continued. Microstructures of as-received and failed blades.

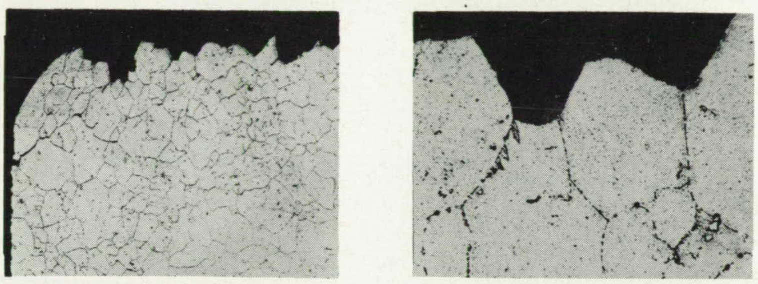
100X 750X



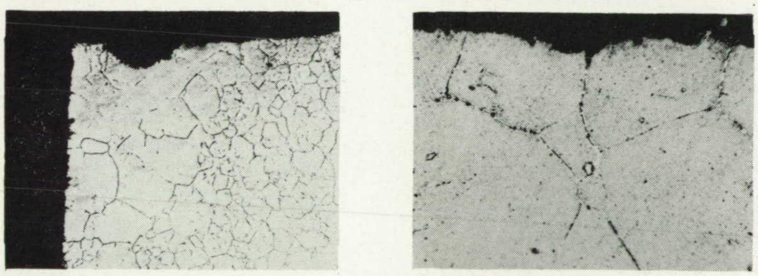
As-received



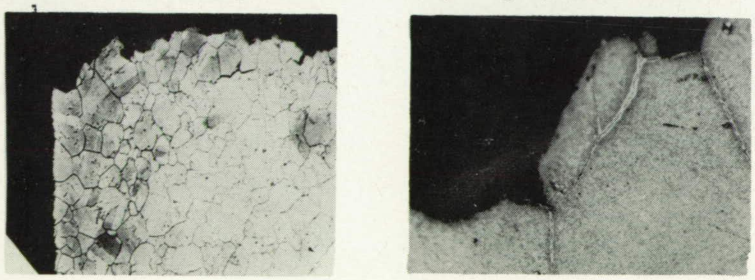
Nonelectropolished, first failure (stress-rupture) after 38 hr



Nonelectropolished, last failure (stress-rupture) after 67 hr



Electropolished, first failure (fatigue) after 44 hr

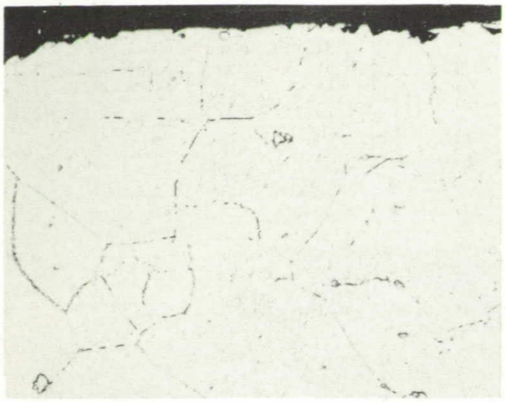


C-37321

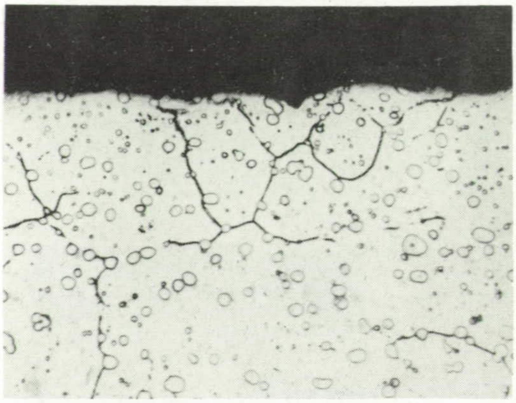
Electropolished, last failure (stress-rupture) after 67 hr

(c) Refractaloy 26.

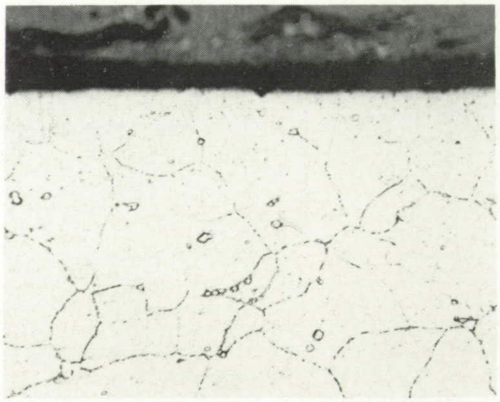
Figure 8. - Concluded. Microstructures of as-received and failed blades.



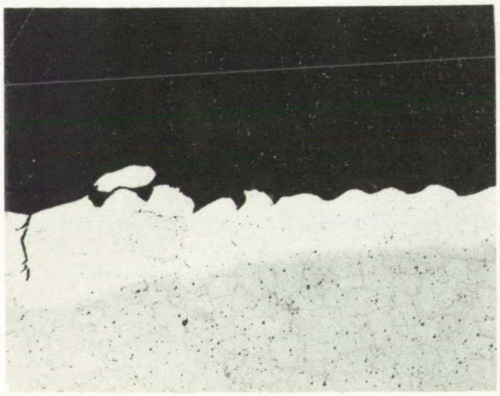
Refractaloy 26, as-received, X750



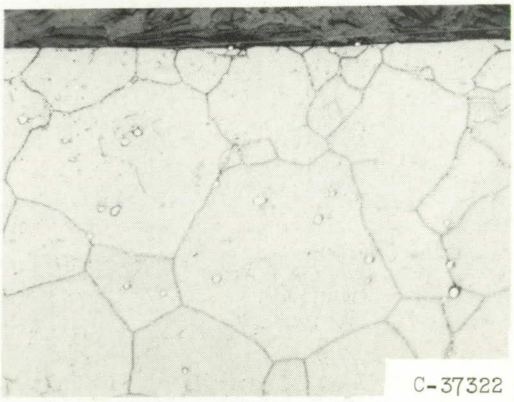
M-252, as-received, X750



Waspaloy, as-received, X750



Waspaloy, as-received, unusually rough area, X100



Waspaloy, electropolished, X750

Figure 9. - Surface of as-received and electropolished blades.

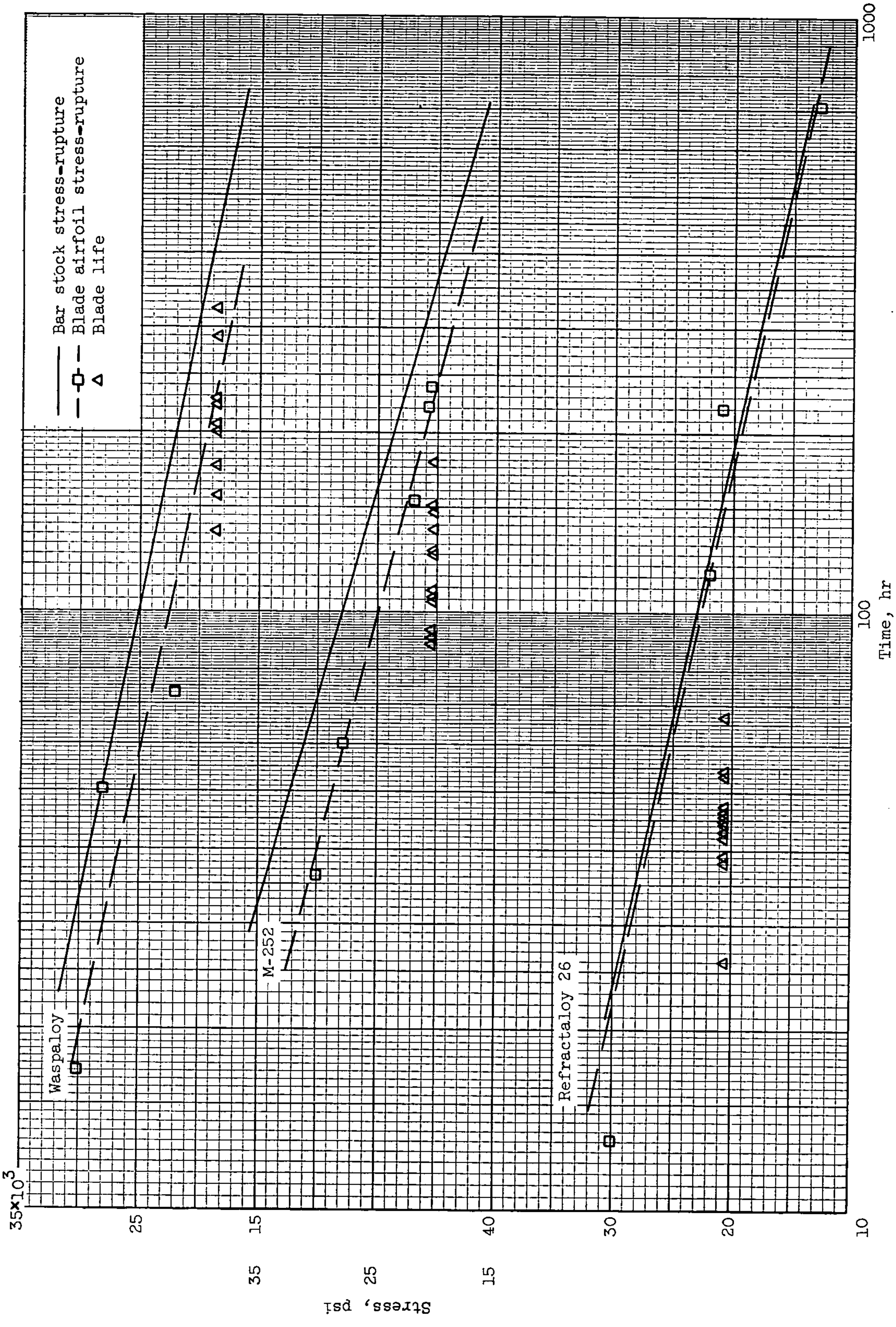


Figure 10. - Bar stock and blade airfoil specimen stress-rupture life at 1500° F and blade life in engine operation.

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