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RESEARCH MEMORANDUM

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XIV - ENDURANCE EVALUATION OF SHELL-SUPPORTED TURBINE ROTOR BLADES MADE OF TIMKEN 17-22A(S) STEEL

By Francis S. Stepka, H. Robert Bear, and John L. Clure

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS
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SUMMARY

An investigation was conducted with a group of shell-supported, air-cooled turbine blades to determine (1) their durability in engine operation over a range of coolant-flow ratio (cooling-air to combustion-gas flow ratio) and (2) a design criterion for the type of air-cooled blades investigated herein. The blades investigated were nontwisted. They had formed shells of Timken 17-22A(S) steel (which contains approximately 96 percent iron) with mild-steel tubes inserted in the blade coolant passage to increase the coolant heat-transfer surface area. The blades were investigated in a modified J33 turbojet engine at rated engine conditions (engine speed of 11,500 rpm and calculated turbine-inlet temperature of approximately 1670 °F) and over a range of coolant-flow ratios from 0.015 to 0.042. At rated engine speed, the calculated average centrifugal stress is about 24,000 pounds per square inch at the 1/3-span region of the blade and about 32,000 pounds per square inch at the root of the blade.

Early fatigue failures of the blades at the root region were experienced at the outset of the investigation. These failures were eliminated by modification of the fillet at the blade root and by altering the heat treatment of the blades. Two of the blades with these modifications were in good condition after 350 hours of endurance-testing at a coolant-flow ratio of 0.027.

The test to determine the durability of the blades indicated that a sharp decrease in blade life occurred with a small change in coolant-flow ratio. The indicated mean value of the stress-ratio factor (ratio of average allowable blade stress-rupture strength to blade average centrifugal stress), the design criterion for the air-cooled blades, was about 2.3 over the range of coolant-flow ratios from 0.015 to 0.027.

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INTRODUCTION

One of the goals of the research on turbine blade cooling is to produce blades of nonstrategic materials capable of sustained operation in gas turbines at present or slightly higher gas temperature levels and at minimum coolant-flow rates. Another goal is to provide sufficient cooling of the blade material to permit the use of materials of relatively low strategic-alloy content which possess higher strength properties than current high-temperature materials. Thus, greater flexibility would be possible in turbine design, which would permit higher turbine 3359
tip speeds and longer blade spans, for example.

Investigations of a variety of air-cooled blade configurations with and without special modifications to cool the leading- and trailing-edge regions (refs. 1 to 10) indicate more uniform chordwise temperature distribution but poorer durability of the blades with the special modifications. An investigation to determine the durability of coatings to protect the blades from the oxidation and erosion effects of the hot gases (ref. 11) indicates that several coatings are satisfactory inhibitors of oxidation of the low-strategic-alloy blade materials. Early blade failures and erratic blade lives, however, were experienced during the investigation. The failures, furthermore, were due to fatigue at the root region of the blade rather than to stress-rupture at the 1/3-span region, which is considered the critical region with respect to temperature and stress.

Consequently, an investigation, reported herein, was necessary to obtain an insight into the causes for the failures, to remove these causes, and to improve the blade lives before proceeding with the primary objectives of the report. These objectives were to establish a design criterion for air-cooled blades of the type used herein and to determine the durability of the blades over a range of coolant-flow ratios (ratios of cooling-air flow per blade to combustion-gas flow per blade) for extended periods of engine operation. This investigation, which was conducted at the NACA Lewis laboratory, concludes the series of investigations of which this report is part.

The air-cooled blade configuration investigated herein was a nontwisted blade with a formed shell of Timken 17-22A(S) steel (which contains about 96 percent iron) and mild-steel tubes inserted in the coolant passage to provide additional cooling surface area. A total of 69 blades were endurance-tested. The tests were conducted in a modified J33 turbojet engine at maximum rated engine speed conditions over a range of coolant-flow ratios from 0.015 to 0.042. At maximum rated conditions, the engine speed is 11,500 rpm (1300 ft/sec tip speed, corresponding to an average calculated blade root stress of about 32,000 psi), and the calculated turbine-inlet temperature is approximately 1670° F.

APPARATUS

Blades

<u>General description</u>. - A photograph of one of the shell-supported, air-cooled blades of the configuration tested is shown in figure 1. The blades were nontwisted and had a span of approximately 4 inches and a chord approximately $1\frac{3}{4}$ inches. The blades consisted of three parts: the airfoil shell, the tubes to increase the coolant heat-transfer surface area, and the blade base. The shell, which was the primary load-carrying member of the blade, was formed from tapered tubes of Timken 17-22A(S) steel. This steel has the following chemical composition, in percent: 0.28 to 0.33 carbon, 0.45 to 0.65 manganese, 0.040 phophorus (max.), 0.040 sulfur (max.), 0.55 to 0.75 silicon, 1.0 to 1.5 chromium, 0.40 to 0.60 molybdenum, 0.20 to 0.30 vanadium, with the remainder iron. The wall thickness of the shell tapered from 0.060 inch at the base to 0.020 inch at the tip. The tubes inserted in the shell were made of mild steel, SAE 1010 or 1020, and were 0.125-inch outside diameter and had a wall thickness of 0.0125 inch. Eleven such tubes were inserted in the blade shell. The base of the blade was precision-cast of SAE 4130 steel. The bases of the first group of test blades fabricated had an integrally cast fillet at the top of the base as shown in figure 2(a). These cast-in fillets, however, were modified as the investigation progressed. The modifications are described in the RESULTS AND DISCUSSION.

<u>Method of fabrication</u>. - After the airfoil shell and the tube inserts were fitted into the cast base, the assembly was ready for brazing. The braze materials were (1) a paste of Nicrobraz powder and Acryloid B-7 (a volatile plastic cement), which were packed around the shell at the blade base, and (2) copper wire, which was laced through the blade shell in the spaces between the tubes. A thin layer of the Nicrobraz powder and the bonding agent was also applied to the leading-edge region of the blades, covering a width of about 1/2 inch from the leading edge along the blade span, in order to provide an oxidation- and erosion-resistant coating in the most critical region (refs. 9 to 11). The blade assemblies were then subjected to the brazing cycle, which consisted in heating the units in a dry hydrogen atmosphere furnace for about 20 minutes at 2075° F and then gas-cooling at a rate equivalent to air-cooling. The blades in the early part of the investigation were then tempered at 1225° F for 4 hours in a dry hydrogen atmosphere furnace. However, this heat treatment was modified as the test progressed, as discussed in a subsequent section. After heat treatment, the serrations were ground in the base and the blades were trimmed to length. The blades were then given the final step in their fabrication, which consisted of immersing them in an acid-nickel solution to obtain an oxidation-resistant coating of nickel on the blades. A more detailed description of air-cooled-blade fabrication procedures is presented in reference 12.

Heat treatments. - The heat treatments employed are given in table I. The modifications of the original heat treatment were required in order to improve the blade lives and to eliminate early blade failures experienced during the investigation reported in reference 11 and in the present investigation. A tabulation of the blades that were given the various heat treatments is shown in table II.

Engine

Description. - Several production turbojet engines were modified to allow cooling air to be supplied to either two or four test rotor blades. The cooling air was supplied to the blades from a compressed-air system external to the engine. The modifications of the engine were essentially those described in reference 1.

Instrumentation. - Measurements of the engine combustion-air and the blade cooling-air flows were made with flow nozzles and flat-plate orifices, respectively. The effective gas temperature (uncooled-blade temperature), which was the control temperature for the endurance tests, was measured by chromel-alumel thermocouples imbedded in the leading edge and at about 1/3 span of each of two standard uncooled blades. No thermocouples were installed on the cooled test blades. The cooling-air temperature at the entrance to the blade base was measured by thermocouples located in each of the cooling-air supply tubes on the face of the rotor. Details of the thermocouple installation are given in reference 1.

PROCEDURES

Experimental Procedure

Endurance investigation of blades in engine. - For the determination of the durability of the test blades at various coolant-flow ratios, constant-speed engine operation was employed. The constant-speed operation was chosen in order to provide a constant blade stress level, which is necessary for determination of the blade design criterion. For this running, the engine was operated at maximum rated speed (11,500 rpm) with the exhaust nozzle adjusted to obtain an effective gas (or uncooled-blade) temperature of 1450° F at the 1/3-span location, which corresponds to approximately 1670° F turbine-inlet gas temperature. At maximum engine speed, the calculated average centrifugal stress at the 1/3-span location of the test blades was about 24,000 pounds per square inch. The blade coolant flow was set at the desired level once the engine speed and gas temperature were established. The blades were tested at coolant-flow ratios (ratios of cooling-air flow per blade to combustion-gas flow per blade) of 0.042, 0.027, 0.022, 0.020, and 0.015.

For flight application, the maximum engine speed for continuous operation is 11,000 rpm, while operation at 11,500 rpm is limited to half-hour periods for take-off or combat. The NACA test speed was set at 11,500 rpm to provide a more severe test for the blades. Tail-pipe temperatures in service are limited to 1292° F except for starting and accelerating; the endurance tests reported herein were conducted at tail-pipe temperatures ranging from 1280° to 1350° F, depending on ambient conditions and the condition of the equipment being used. A tail-pipe temperature of 1325° F was typical of most of the operation.

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<u>Determination of vibrational characteristics of test blades</u>. - In order to obtain an insight into the cause for the fatigue failures at the root of the blades, 16 of the blades reported herein were instrumented with strain gages at the root region on the suction surface and were vibrated by an air-interrupter exciter. This investigation determined the natural frequency of the blades and the variation of the inherent damping.

<u>Calibration of cooling-air leakage</u>. - Because of leakage of cooling air at the labyrinth seal between the stationary cooling-air supply tube in the tail cone of the engine and the rotating air-collector housing at the hub of the turbine rotor, the leakage at this junction was calibrated with the pressure difference across the junction.

The maximum correction to the coolant-flow ratios reported herein was about 20 percent and occurred at a coolant-flow ratio of 0.015.

Calculations of Stress-Ratio Factors

The method of obtaining a design criterion for the air-cooled blades reported herein is based on the stress-ratio factor. This factor is defined as the ratio of the average allowable blade stress-rupture strength for a desired blade life and for a given chordwise temperature distribution to the calculated average centrifugal blade stress. The allowable stress-rupture strength and the calculated average centrifugal stress [calculated centrifugal load divided by total metal area of section (shell and tube inserts)] were evaluated at about the 1/3-span region of the blade, because this region is considered to be the critical region with respect to temperature and stress. (The method for determining the critical region of air-cooled blades is presented in ref. 13.) In evaluating the stress-ratio factor, only the average centrifugal stress, which is considered to be the major stress, was considered. It was thought, however, that the magnitude of the stress-ratio factor would include the effects of the other stresses, such as bending, vibration, and thermal stresses, and thus provide the necessary margin of safety in design. In addition, the stress-ratio factor is intended to provide the necessary compensation, or margin of safety, for the effects that construction may have on the blade material strength.

The average allowable blade stress-rupture strength was determined by first obtaining curves of stress-to-rupture against metal temperature for a range of time to failure from unpublished results of tests of bar stock specimens of Timken 17-22A(S) steel. Next, curves of the temperature distribution around the periphery of a typical test blade at about the 1/3-span region, shown in figure 3 (obtained from unpublished experimental data), were used in conjunction with the curves of the stress-to-rupture against metal temperature to provide curves of allowable blade stress-rupture strength distribution around the blade periphery. These curves were obtained for a range of blade lives and for coolant-flow 3359 ratios of 0.015, 0.020, 0.022, and 0.027. The areas under each of these curves were then integrated and the average allowable stresses obtained. The stress-ratio factors were then calculated.

These calculated data, plotted with coordinates of stress-ratio factor and blade life, result in a series of curves indicating the variation of stress-ratio factor with blade life for each coolant-flow ratio. The experimentally obtained blade lives, when plotted on the respective curves of coolant-flow ratio, give the spread of the stress-ratio factor for the test blades and indicate the magnitude of the factors required in designing the blades.

RESULTS AND DISCUSSION

Investigations Leading to Improvement of Blade Life

Preliminary endurance-testing of the shell-supported air-cooled turbine blades with shells of Timken 17-22A(S) steel reported in reference 11 and the endurance-testing of the first group of blades in the present investigation resulted in early blade failures. A photograph of typical early failures at the root regions of the blades is shown in figure 4.

In order to eliminate these early failures and to improve the blade lives, a number of investigations were conducted to obtain an insight into the causes of the failures. Inasmuch as centrifugal, bending, thermal, and vibratory stresses all contribute to blade failures, factors that were thought to influence these stresses were investigated.

<u>Blade vibrational characteristics</u>. - Examinations of the failures at the blade roots disclosed semicircular areas on the inside of the pressure surface of the blade shells (fig. 5) that indicated areas of fatigue-failure origin. With the knowledge that the failures were due to fatigue, the first thought was that the failures were due to the vibratory characteristics of the blades. An investigation to determine the vibrational characteristics of the blade was made as described in the PROCEDURES section. The results of the investigation indicated (1) that

the natural frequencies of the air-cooled test blades were approximately the same as for the standard uncooled solid blades used in the test engine and (2) that a variation in damping characteristics, probably due to variations in braze contact area, existed among the cooled blades. The first result of the vibration investigation indicated that, since the air-cooled test blades had about the same natural frequency as the standard uncooled blades and since the standard blades operated satisfactorily, no unusual vibration problems of the test blades should be encountered. The effect of the variation of the damping characteristics 3359 of the test blades on blade life, however, had to be investigated by subjecting the blades to an endurance test. The results of the test, however, showed no correlation between blade damping and blade life. The results of this investigation indicate that the vibrational characteristics of the test blades should not be one of the major causes for the failures.

<u>Blade construction</u>. - Since the failures were occurring at the blade root, one of the contributory causes for failure in this region appeared to be the notch effect of the sharp ledge of the cast-in fillet shown in figure 2(a). Reference 14 indicates that, when geometric notches such as section changes and fillets exist in a specimen subjected to an elastic static stress, the stress distribution at the root of the notch changes in such a manner that the peak stress is markedly raised for the same load. Therefore, the construction of the blade root fillets was modified. These modifications, intended primarily to remove the notch effect of the sharp ledge at the shell-base junction or to provide a fillet with a lower elastic modulus to absorb some of the forces causing the failures, or both, are illustrated in figures 2(b) to (d). For the puddled-over fillet (fig. 2(b)), a silverbraze was puddled over the cast-in fillet and faired smoothly with the shell. For the puddled-in fillet (fig. 2(c)), the cast-in fillet was ground off before assembling the blade, and a silverbraze fillet was puddled in at the junction of the shell and the base. The faired-in fillet (fig. 2(d)) was made by grinding the cast-in fillet to fair smoothly with the shell, in order to avoid the use of brazed fillets that might possibly, depending on the technique of application, affect the blade heat treatment.

The results of endurance tests of two groups of blades to determine the effect of fillet modification on blade life indicated (table II) that blades with the modified fillets (14 to 25 and 31 to 42 inclusive) had better lives, in general, than blades 1 to 13 and 26 to 30. The results, however, give no indication that one modification was better than another. The cast-in fillet that was faired smoothly into the shell by grinding was selected as the means of decreasing the geometric notch at the blade root.

The improvement in the average life of blades from about 13 to 49 hours by the modification of the root fillets, however, was not adequate.

Furthermore, blade failures were still occurring by fatigue at the root region rather than by stress-rupture at the 1/3-span region of the blade. Consequently, the metallurgy of the blade materials was next investigated for further blade life improvement.

Metallurgy of blade materials. - Timken 17-22A(S) steel, from which the blade shells were fabricated, is a deep-hardening high-temperature steel. In the normalized and tempered condition (heat treatement 2, table I), it has a hardness of Rockwell C-35 and a small uniform grain 3359
size, as shown in figure 6. Although this steel has a tendency toward chemical segregation and contains more than average nonmetallics, which could adversely affect fatigue properties, the fatigue problems encountered in these blades were not attributed to these conditions. This steel proved very suitable for the high-temperature (2075° F) brazing cycle required in blade fabrication. Although the brazing operation increased the grain size as shown in figure 7(a), subsequent heat treatment returned the 17-22A(S) steel, not affected by braze penetration, to its original condition. Several blade shells made from SAE 4130, a similar alloy steel, showed severe grain growth and evidence of permanent damage.

Copperbrazing and Nicrobrazing of these blades was done in one operation in dry hydrogen at 2075° F (specified temperature). However, examination showed appreciable variation in braze diffusion, indicating inconsistent brazing temperatures primarily caused by furnace limitations. This brazing temperature was approximately 100° F higher than required for copper, yet was necessary to flow the Nicrobraz. Consequently, copper showed considerable diffusion (fig. 8(a)). In blades where specified brazing temperatures were attained, copper diffused into the mild-steel tubes more rapidly than into the 17-22A(S) shell. In a few blades, the cooling tubes showed brittle fractures caused by slight intergranular attack. However, no shell embrittlement was observed, so that, even though diffusion was more than expected, copperbrazing was considered successful in these blades.

Nicrobrazing characteristics were quite erratic in this application, probably because of the profound chemical sensitivity of Nicrobraz to temperature and the temperature variations already mentioned. This braze was heat- and corrosion-resistant; also, good strength was indicated, since no base-shell separations occurred even though some blades were joined in less than 35 percent of the base area. However, this braze presented a difficult compromise for thin sections. At the temperatures employed herein, flowability was limited; yet, when brazing temperatures were raised to 2150° F in another work project, excellent flow resulted but severe chemical attack occurred on 17-22A(S) steel.

Additional grain growth occurred in shell areas adjacent to the Nicrobraz, as shown at A in figure 7(a). Although normalizing refines this grain size, a uniform shell microstructure is not attained, as indicated in figure 7(b). Note also at B how braze accumulation can undercut the shell with serious notch potentialities. With small flow clearances, Nicrobraz alloys with iron to form a bond that has appreciable ductility; but, when clearances are large, the braze was hard and brittle and usually porous, increasing notch susceptability in areas as shown in figure 8(b). Hence, these examinations indicated that Nicrobraz displayed good qualities and also disadvantages that could impair the parent metal strength. These brazing defects, however, were not primarily responsible for the fatigue failures at the blade roots.

<u>Heat treatment</u>. - The next phase of this investigation was to determine whether modification of the heat treatment would eliminate the early fatigue failures. The first modification of the original heat treatment given the blades was to normalize the blades at 1725° F for 1 hour and then temper the blades at 1225° F for 4 hours. Although this heat treatment (heat treatment 2, table I) reduced the grain size and refined the structure as illustrated in figure 7(b), no improvement in blade life or elimination of fatigue failures at the root was obtained. Since unpublished data of the results of stress-rupture tests of Timken 17-22A(S) steel indicate that heat treatment 2 improved the strength properties of the steel, and since the endurance results presented herein show no improvement in blade life, notch sensitivity of the steel appeared more serious than at first realized.

In view of these considerations, it was thought that a more ductile shell was needed, even though reduced stress-rupture properties would result from a softer blade. Eight blades were subjected to heat treatment 3 (table I), in which, in addition to being normalized, they were tempered at 1400° F for 1 hour. Two blades were given heat treatment 4 with lower draw temperature (1325° F 1 hr), in the event the blades with the 1400° F draw were too ductile and did not possess enough strength to permit extended operation in the engine. Four of the blades with heat treatment 3 were operated at a coolant-flow ratio of 0.042 for 51 hours without a failure. In view of time and expense, testing at this relatively high coolant-flow ratio was terminated, and the remaining four blades with heat treatment 3 were operated at a coolant-flow ratio of 0.027. Two of these blades operated for approximately 90 hours, one for 296 hours, and the other for 292 hours without a failure. However, because of their high ductility, the blades elongated and bent by leaning in the direction of rotation, as shown in figure 9(a). The higher shell temperature near the tip, in combination with the gas bending forces, could account for the bending of the blade as a creep phenomenon. The lack of bending along the entire span as a result of the gas bending moments, which are largest at the root, could be due to the lower blade metal temperatures at the root region.

The endurance-testing of one of the blades with heat treatment 4 (blade 51) resulted in a fatigue failure at the root after 55 hours of operation. In view of this failure and of the satisfactory lives obtained with the blades that had heat treatment 3, it was thought that a modification of heat treatment 3 to eliminate the blade distortion should be attempted. The endurance-testing of the second blade with heat treatment 4 (blade 52), however, was continued for 350 hours without a failure and without bending or distortion. Although the results with this blade were satisfactory, the early fatigue failure of blade 51 and the satisfactory lives obtained with the larger number of blades with heat treatment 3 did not appear to warrant further investigation of heat treatment 4. 3359

The final heat treatment given the blades (heat treatment 5) consisted of normalizing at 1725° F for 1 hour, tempering at 1225° F for 4 hours, and retempering the root region (extending approx. 3/4 in. above the base platform) at 1400° F for 1 hour. The normalizing and first tempering were accomplished in a dry hydrogen atmosphere furnace, while the retempering of the root region of the blade was accomplished by immersing this portion of the blade in a salt-bath furnace. The purpose of this heat treatment was to supply the necessary ductility at the blade root to resist failures by fatigue, but also to provide sufficient strength along the blade span to prevent bending and distortion. The endurance-testing of the first two blades with this heat treatment (blades 53 and 54) resulted in blade lives of over 100 hours at a coolant-flow ratio of 0.027 without bending or distortion. Blade 53 failed at the root after 145 hours, while blade 54 ran for 350 hours, when testing of the blade was terminated because little could be learned from running a single blade to destruction in consideration of the time and expense of testing. Although heat treatment 5 may not be the optimum heat treatment for air-cooled blades of Timken 17-22A(S), no further heat treatments were attempted because of the satisfactory results obtained with heat treatment 5. These results are: (1) the elimination of the early fatigue failures at the root region, (2) the elimination of blade bending and distortion, and (3) the indicated potential of the blades for extended engine operation. The endurance results obtained with heat treatment 3 further support the first result, because both groups of blades had the same heat treatment at the root region. Consequently, heat treatment 5 was considered satisfactory for application to the group of blades intended for the determination of the primary objectives of this report, that is, the durability of the blades over a range of coolant-flow ratios and the determination of a design stress-ratio factor.

Determination of Durability of Blades in Engine Operation

<u>Variation of blade life with coolant-flow ratio</u>. - The results of the endurance tests of 21 air-cooled blades with heat treatments 3 and 5 (blades 47 to 50 and 53 to 69) operating at rated engine conditions and at coolant-flow ratios of 0.015, 0.020, 0.022, and 0.027 are listed in

table II. A plot showing the variation of the endurance life of the blades with coolant-flow ratio is shown in figure 10. The large spread in the blade life obtained can be attributed to a number of causes, such as defects in the blade material and variability in the material strength induced as a result of blade fabrication or brazing. The results, nevertheless, show that a sharp drop in blade life is experienced with small changes in coolant-flow ratio. Although the data were limited and the spread in blade life was relatively large, a line through the data was drawn in an attempt to obtain the variation of blade life with coolant-flow ratio. A mean line was drawn by arbitrarily giving the blades damaged by failure of other blades or on which testing was terminated more weight than the blades that failed. The mean-life line shows the sharp drop in blade life with coolant-flow ratio. At a coolant-flow ratio of 0.022, for example, the indicated average expected life was about 66 hours; while, with a decrease in coolant-flow ratio to 0.015, the indicated average life decreased to only 3 hours.

<u>Blades and blade failures</u>. - The failures of the blades with decreased coolant-flow ratios were due to stress-rupture at the critical 1/3-span region. The failure appeared to originate at the leading edge, as shown in figure 9(b), and thereafter to fail rapidly in tension, as shown in figure 9(c). Metallographic examinations showed that reduced coolant-flow ratios greatly increase corrosion of the tube inserts. In addition, reduced hardness values at the blade leading edges indicate that these areas ran hotter than the remaining shell section, with decarburization resulting in some leading edges.

<u>Blade coatings</u>. - The oxidation- and erosion-inhibiting qualities of the Nicrobraz coating at the leading edge, plus the nickel coating of the blade shell, were good. For example, blades with 350 hours of operation at a coolant-flow ratio of 0.027 showed only slight signs of oxidation, as shown in figure 11. Oxidation of the blades operated at the lower coolant-flow ratios was more evident. The coating, however, appeared adequate, since mechanical failures of the blades occurred before breakdown of the coatings.

Determination of Design Stress-Ratio Factors

The design criterion or design factor for air-cooled blades, used herein, is based on the stress-ratio factor, defined as the ratio of allowable blade stress-to-rupture strength based on material life and the blade chordwise temperature distributions to the calculated average centrifugal blade stress. The calculated average centrifugal stress at the 1/3-span section of the blade at rated engine speed, used in calculating the stress-ratio factor, was approximately 24,000 pounds per square inch (at the root section it was about 32,000 psi). The calculated values of the factors at coolant-flow ratios of 0.015, 0.020, 0.022, and 0.027 for a range of blade lives are plotted in figure 12.

The experimentally determined blade lives are also plotted, as points on respective coolant-flow-ratio lines, to give the experimentally obtained spread of stress-ratio factor.

The results indicate that the spread in the magnitudes of the stress-ratio factors over the range of coolant-flow ratios investigated was between 1.9 and 3.0. An indicated mean value of the factor was about 2.3. This value was obtained by arbitrarily giving extra consideration to the blades damaged by failures of other blades and to those on which testing was terminated. 3359

The magnitudes of the stress-ratio factors obtained indicate that a large compensation is required for such factors as (1) the detriment to the blade material caused by such factors as braze penetration of shell material and notch effects in blade material as a result of blade fabrication; (2) the blade stresses other than centrifugal, such as gas bending, vibratory, and thermal, which were not considered because of the complexity of the calculations and the unavailability of accurate values of physical properties of materials at elevated temperatures needed in these calculations; and (3) the difference in the stress-rupture properties of Timken 17-22A(S) bar stock material used in calculations and that of sheet stock material for which data were not available.

The results of the investigation, though obtained with a limited number of test blades, indicate that, in designing air-cooled blades of the type investigated, with the same material, operating in a J33 turbojet engine for a desired mean endurance life, a stress-ratio factor of 2.3 is required. The applicability of this value of stress-ratio factor to other blade configurations with other materials and operated in other engines is not known at present. It appears reasonable, in the absence of other information, to use this value of the stress-ratio factor in the first attempt in designing other air-cooled shell-supported blades.

SUMMARY OF RESULTS

Investigations to determine the durability and a design criterion for forced-convection air-cooled shell-supported blades of Timken 17-22A(S) steel (a low-alloy steel containing approximately 96 percent iron) were conducted at rated engine conditions (turbine-inlet temperature of about 1670° F and an engine speed of 11,500 rpm). At rated engine speed, the tip speed of the blade is about 1300 feet per second. This speed corresponds to a calculated average centrifugal stress of about 24,000 pounds per square inch at the critical 1/3-span region of the blade and about 32,000 pounds per square inch at the root of the blade. The results of these investigations are as follows:

1. Early fatigue failures of the blades at the root region were experienced at the outset of the investigation. These failures were eliminated by modification of the fillet at the blade root and by a heat treatment resulting in a blade with a ductile shell at the root region and a high-strength and less ductile shell along the blade span above the root region.

2. Although the final heat treatment to improve blade lives is not necessarily an optimum heat treatment, it nevertheless served the purpose of eliminating the early fatigue failures at the root and resulted in blade lives of over 100 hours at a coolant-flow ratio of 0.027. One of the blades with this heat treatment was in good condition after 350 hours of endurance-testing at a coolant-flow ratio of 0.027, indicating a potential for extended engine operation with these blades.

3. The endurance tests of the durability of the blades over a range of coolant-flow ratios indicated that a sharp decrease in blade life occurs with a small change in coolant-flow ratio. At a coolant-flow ratio of 0.022, for example, the average expected life was about 66 hours; while, with a decrease of coolant-flow ratio to 0.015, the indicated average life was decreased to only 3 hours.

4. The protection of the blade shells from the oxidation and erosion effects of the hot gases was well provided by the nickel coating of the blade shell and the undercoating of Nicrobraz along the blade leading edge. Blades that operated for as long as 350 hours showed only slight signs of oxidation.

5. The indicated mean value of the stress-ratio factor (ratio of the average allowable blade stress-rupture strength to blade average centrifugal stress), the design criterion for air-cooled blades, was about 2.3 over the range of coolant-flow ratios from 0.015 to 0.027. These results indicate that, based on mean blade lives, a stress-ratio factor of 2.3 is required in designing the air-cooled blades of the configuration and material investigated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 28, 1954

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TABLE I. - SUMMARY OF HEAT TREATMENTS 3359

Heat treatment	Process
1	Blades tempered at 1225° F 4 hr in dry hydrogen atmosphere
2	Blades normalized at 1725° F 1 hr and tempered at 1225° F 4 hr in dry hydrogen atmosphere
3	Blades normalized at 1725° F 1 hr and tempered at 1400° F 1 hr in dry hydrogen atmosphere
4	Blades normalized at 1725° F 1 hr and tempered at 1325° F 1 hr in dry hydrogen atmosphere
5	Blades normalized at 1725° F 1 hr and tempered at 1225° F 4 hr in dry hydrogen atmosphere; base region (extending from base to approx. 3/4 in. from platform) then retempered at 1400° F 1 hr in salt-bath furnace

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CP-3

TABLE II. - SUMMARY OF ENDURANCE TEST

Fillet	Blade	Coolant-flow ratio	Endurance life, hr:min	Remarks
Heat treatment 1				
Cast-in	1	0.042	6:33	a
	2	.042	24:08	b
		.027	1:12	c
	3	.042	30	b
		.027	1:31	a
	4	.042	5:52	a
	5		1	a
	6		51:57	b
	7		20:38	a
	8		50:57	b
	9		6:16	a
	10		8:27	a
	11		4:06	b
	12		1	a
	13		1	d
Cast-in, puddled-over	14	0.042	100	b
		.027	1:12	c
	15	.042	33:07	b
	16		33:07	b
	17		33:07	c
	18		23:44	a
	19		100	b
		.027	1:12	a
	20	.042	40:40	c
Puddled-in	21	0.042	78:27	b
	22		73:37	b
	23		33:07	a
Cast-in, faired smooth	24	0.042	100	b
	25	.042	:39	a
Heat treatment 2				
Cast-in	26	0.042	2:57	a
	27		2:04	a
	28		4:20	a
	29		6:24	c
	30		5:42	a
Cast-in, puddled-over	31	0.042	131:47	b
	32	.027	35:06	b
	33	.042	81:24	e
	34	.027	5:30	a
	35	.027	4:06	b
	36	.027	35:14	a
	37	.042	23:06	a
	38	.027	35:06	b
	39	.027	25:28	a
Puddled-in	40	0.042	35:30	b
	41		66:24	b
	42		35:30	b
Heat treatment 3				
Cast-in, faired smooth	43	0.042	51	b
	44		51	b
	45		51	b
	46		51	b
	47	.027	296:11	f
	48		90:21	g
	49		90:21	g
	50		292:15	f
Heat treatment 4				
Cast-in, faired smooth	51	0.027	55:07	a
	52	.027	350	b
Heat treatment 5				
Cast-in, faired smooth	53	0.027	144:53	a
	54	.027	350	b
	55	.020	27:08	h
	56		12:16	h
	57		41:10	c
	58		18:01	h
	59		2:30	h
	60		14:02	h
	61		3:24	h
	62	.015	5:56	i
	63	.015	1:19	h
	64	.015	4:37	h
	65	.022	97:37	j
	66		94:42	h
	67		48:14	b
	68		84:12	c
	69		47:16	c

[a]Failed at blade root.
[b]Blade still in good operating condition.
[c]Damaged by other blade failure.
[d]Cracked at root, suction surface.
[e]Failed at about 2/3 span.
[f]Elongated and bent after 90 hr.
[g]Elongated and bent after 40 hr.
[h]Failed at about 1/3 span.
[i]Cracked at 1/3-span leading edge.
[j]Cracked at 2/3-span leading edge.

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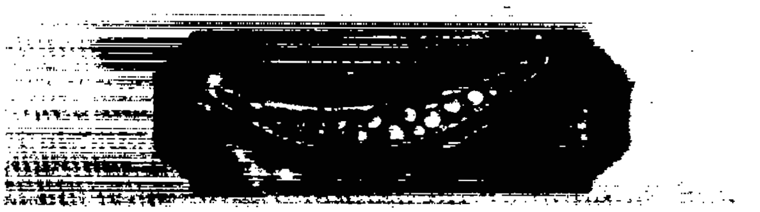
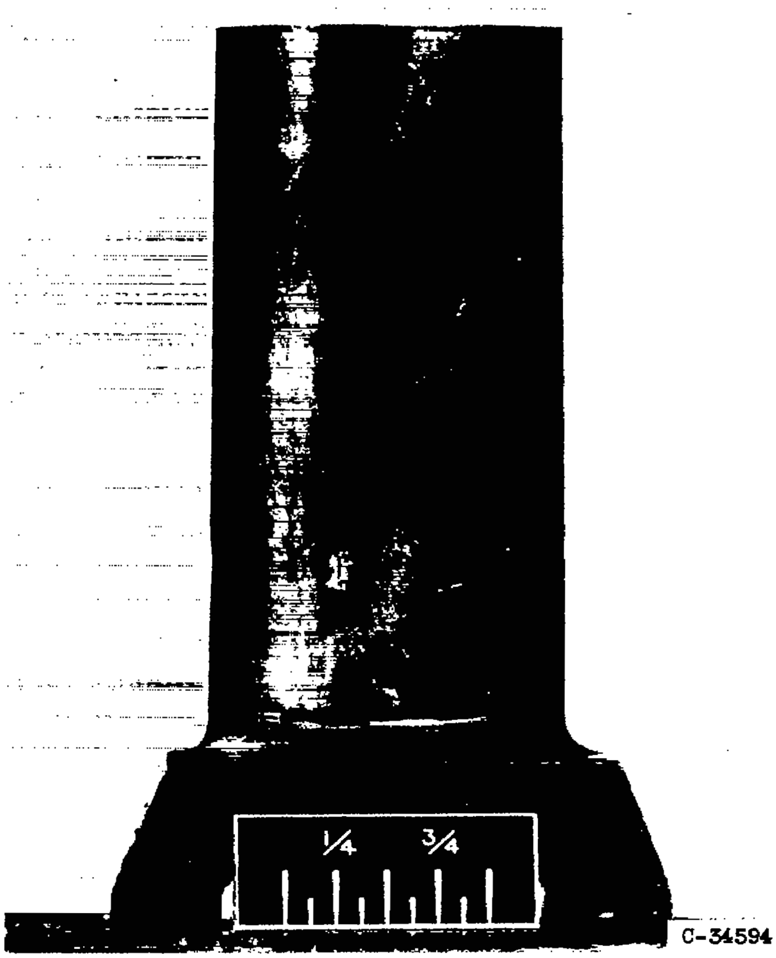


(a) Top view.



(b) Suction-surface view.

Figure 1. - Configuration of air-cooled blades with formed shells of Timken 17-22A(S) steel.

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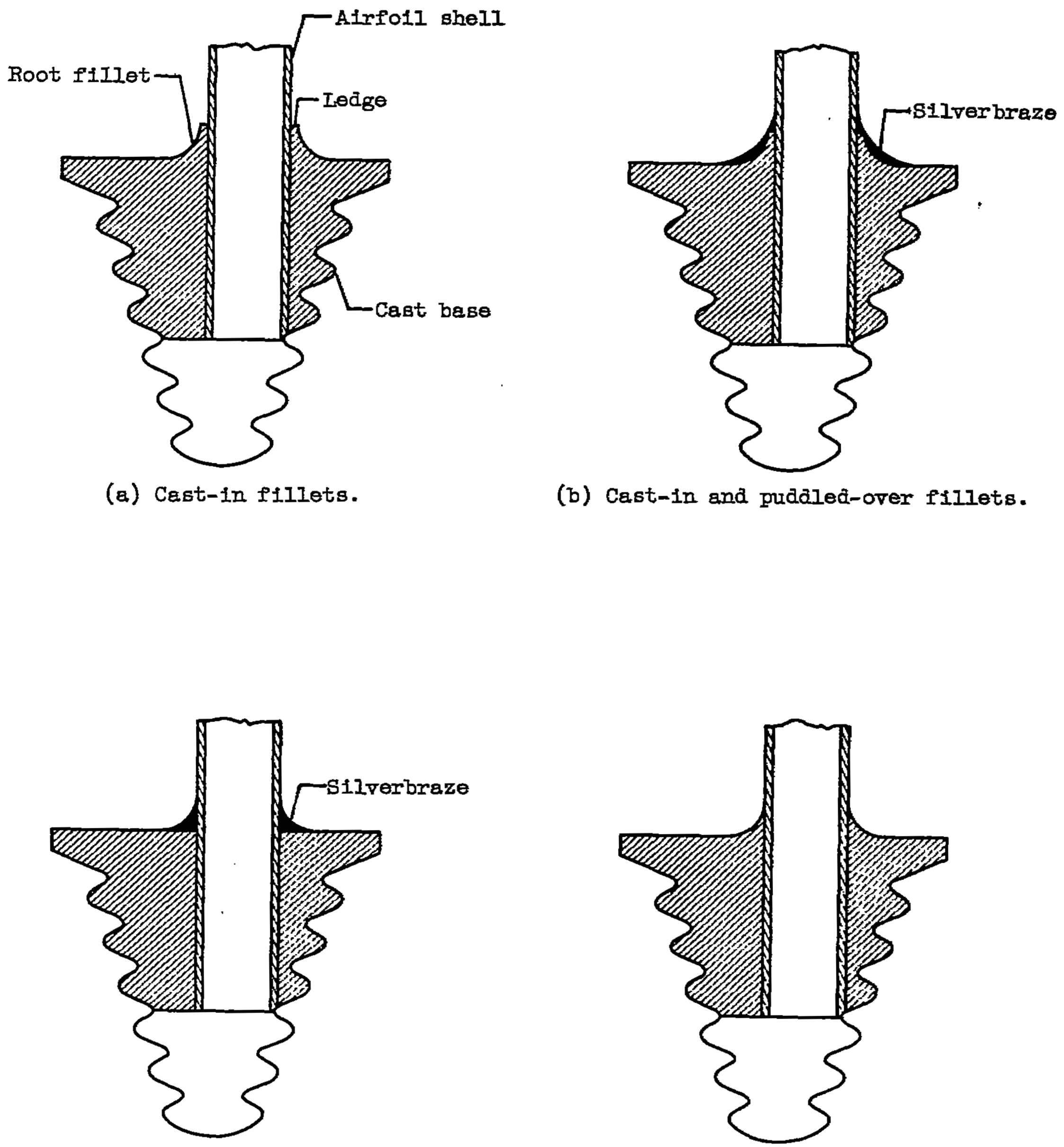
CP-3 back



(a) Cast-in fillets.

(b) Cast-in and puddled-over fillets.

(c) Puddled-in fillets.

(d) Cast-in fillet faired smooth.

CD-3685

Figure 2. - Blade base construction and fillet modifications.

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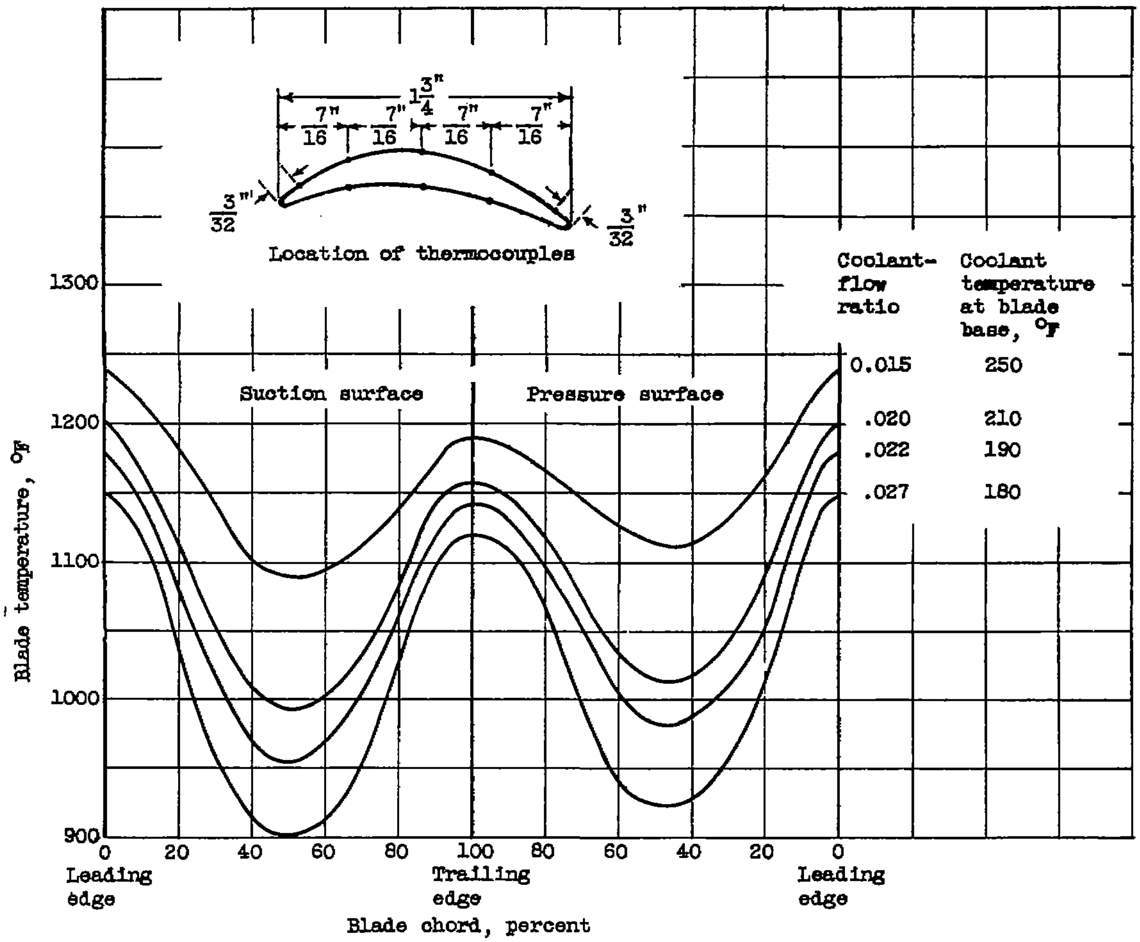

Figure 3. - Blade temperature distribution at 1/3 span of shell-supported blades, with tube inserts, made of Timken 17-22A(S) steel. Engine speed, 11,500 rpm; effective gas temperature, 1450° F.

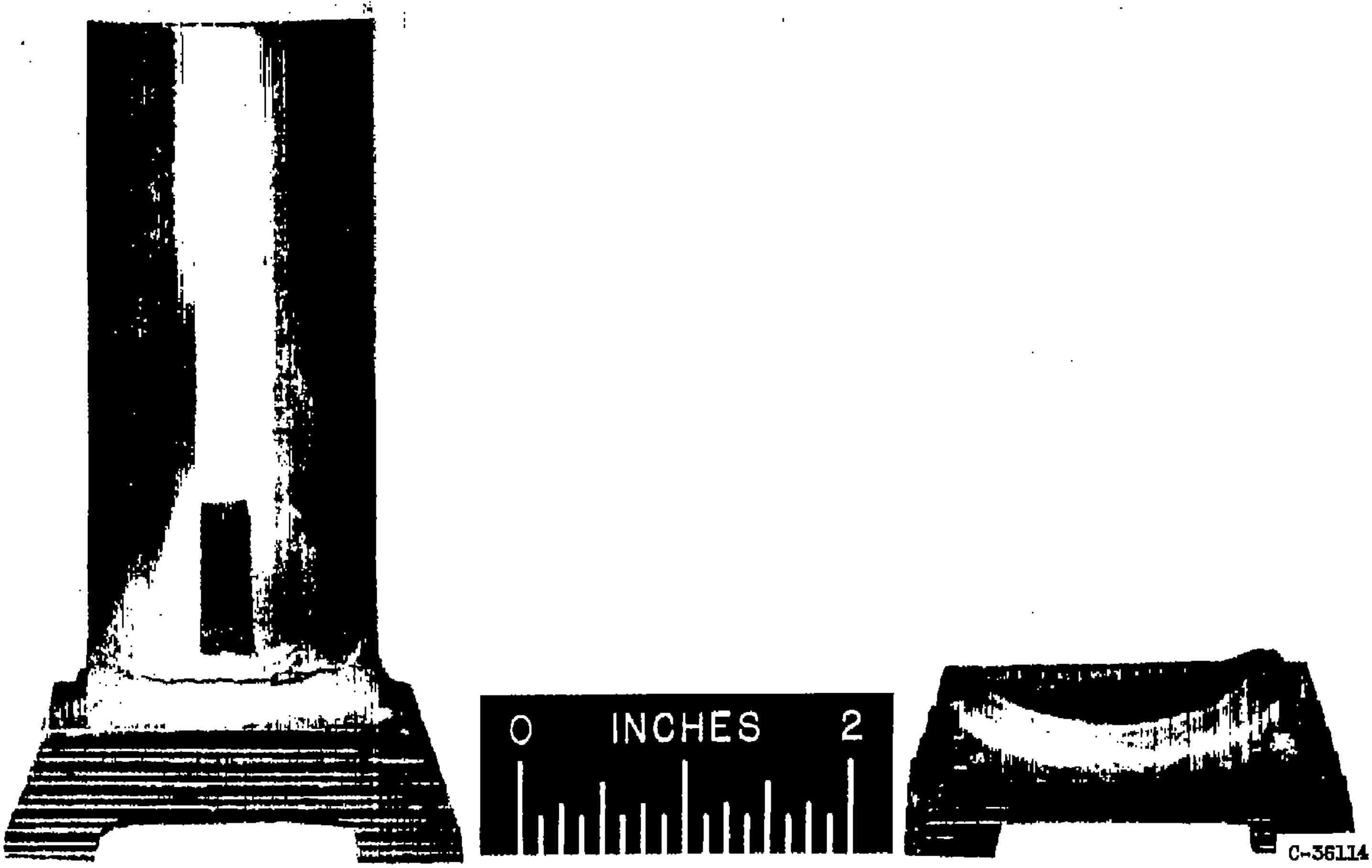

Figure 4. - Typical early blade failures.

Transverve view of fracture (section removed from blade at right)

C-36115

Figure 5. - Fatigue failures at region of blade root.

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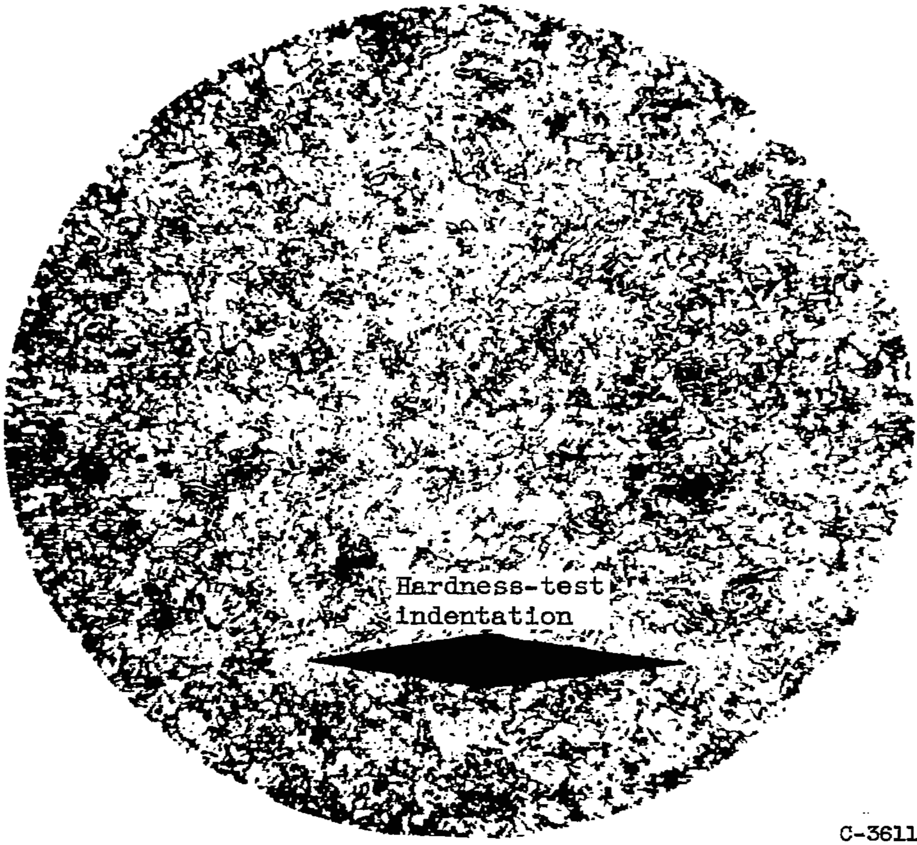
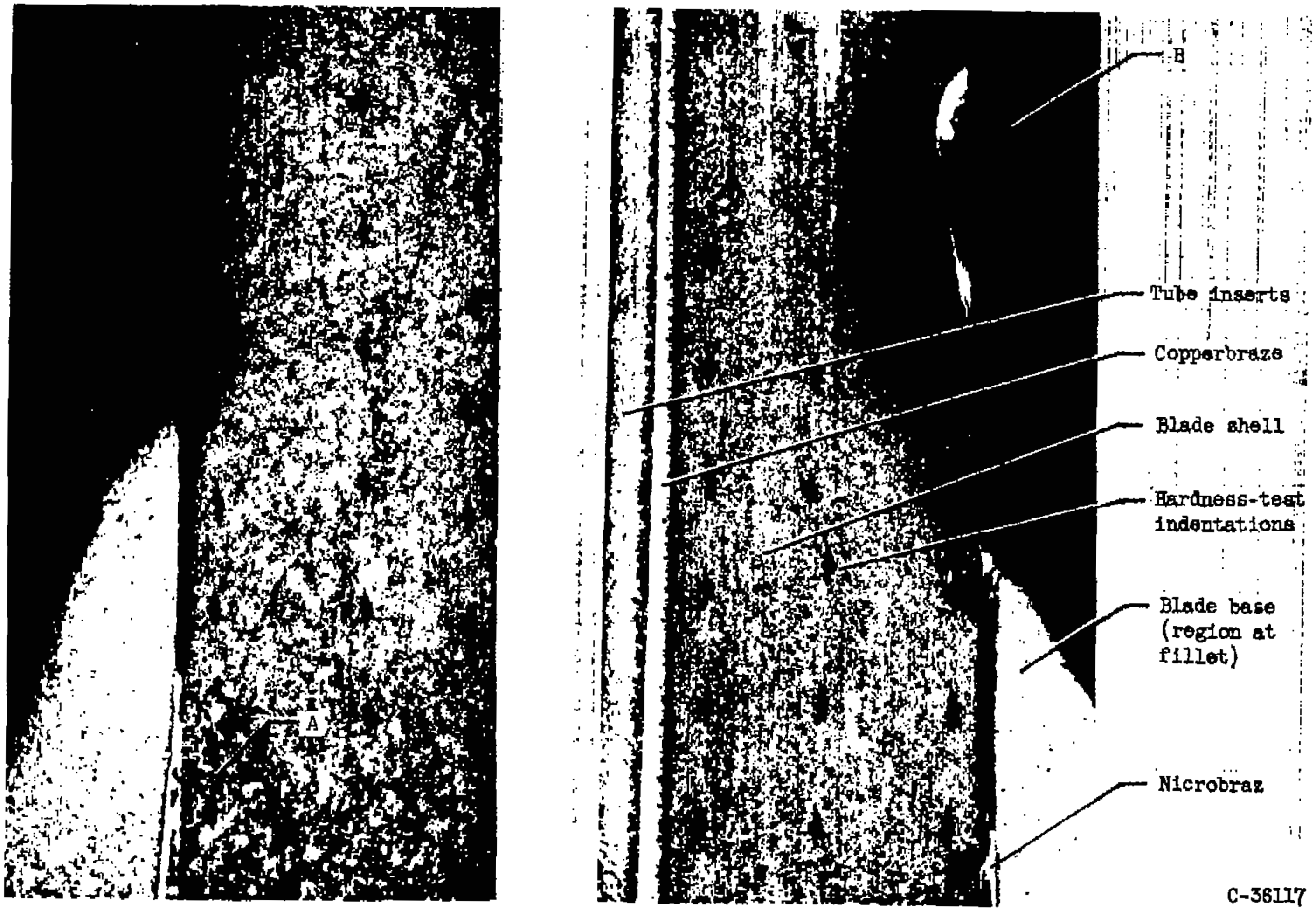


C-36116

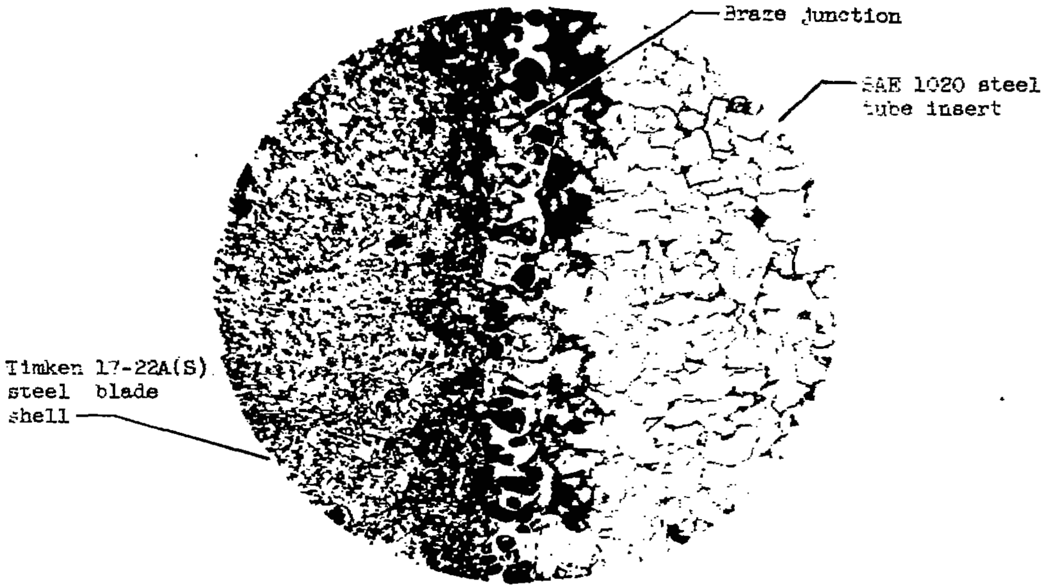
Figure 6. - Microstructure of Timken 17-22A(S) steel shell normalized 1725° F for 1 hour, tempered 1225° F for 4 hours, and air-cooled. Hardness, Rockwell C-35. Nital etch, X250.



(a) As brazed and tempered.

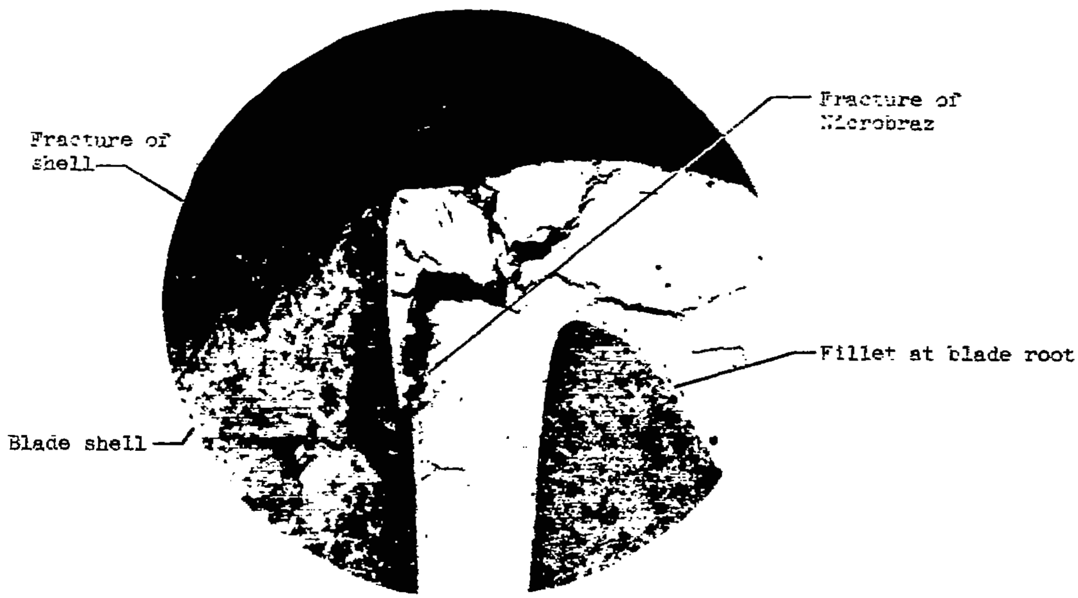
(b) Brazed, normalized, and tempered.

Figure 7. - Cross section across blade shell and base fillet. Same blade; before and after heat treatment. Two blade halves shown. Nital etch, X37.



X250

(a) Copper penetration of mild-steel tube inserts at inner surface of formed airfoil shell of Timken 17-22A(S) steel.



X75

C-36119

(b) Brittle fracture of Nicrobraz at junction of shell and base fillet.

Figure 8. - Effects of brazing and brazing materials on blades.

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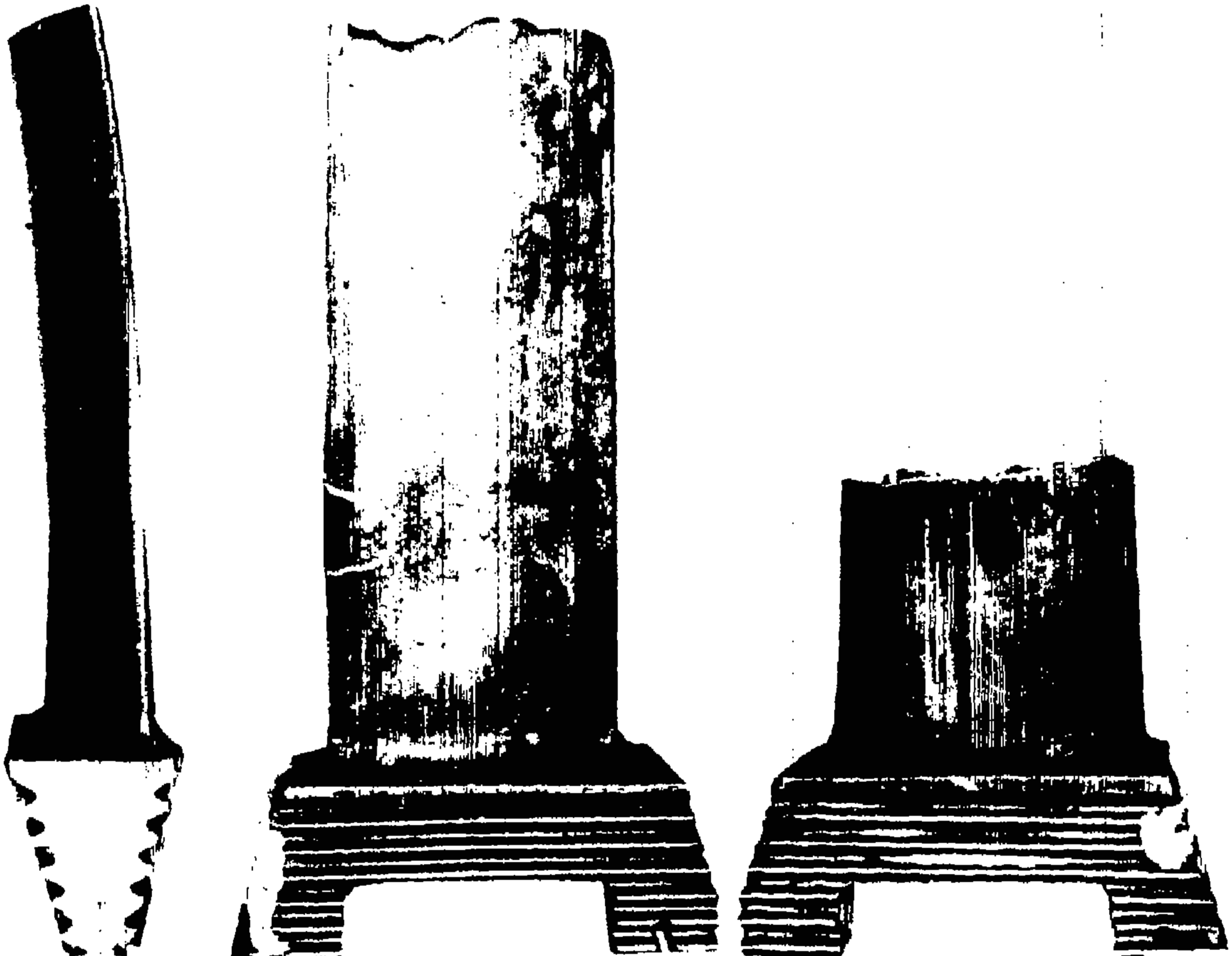

(a) Blade 47. (b) Blade 62. (c) Blade 56. C-36118

Figure 9. - Blade failures by bending and stress-rupture.

[redacted]

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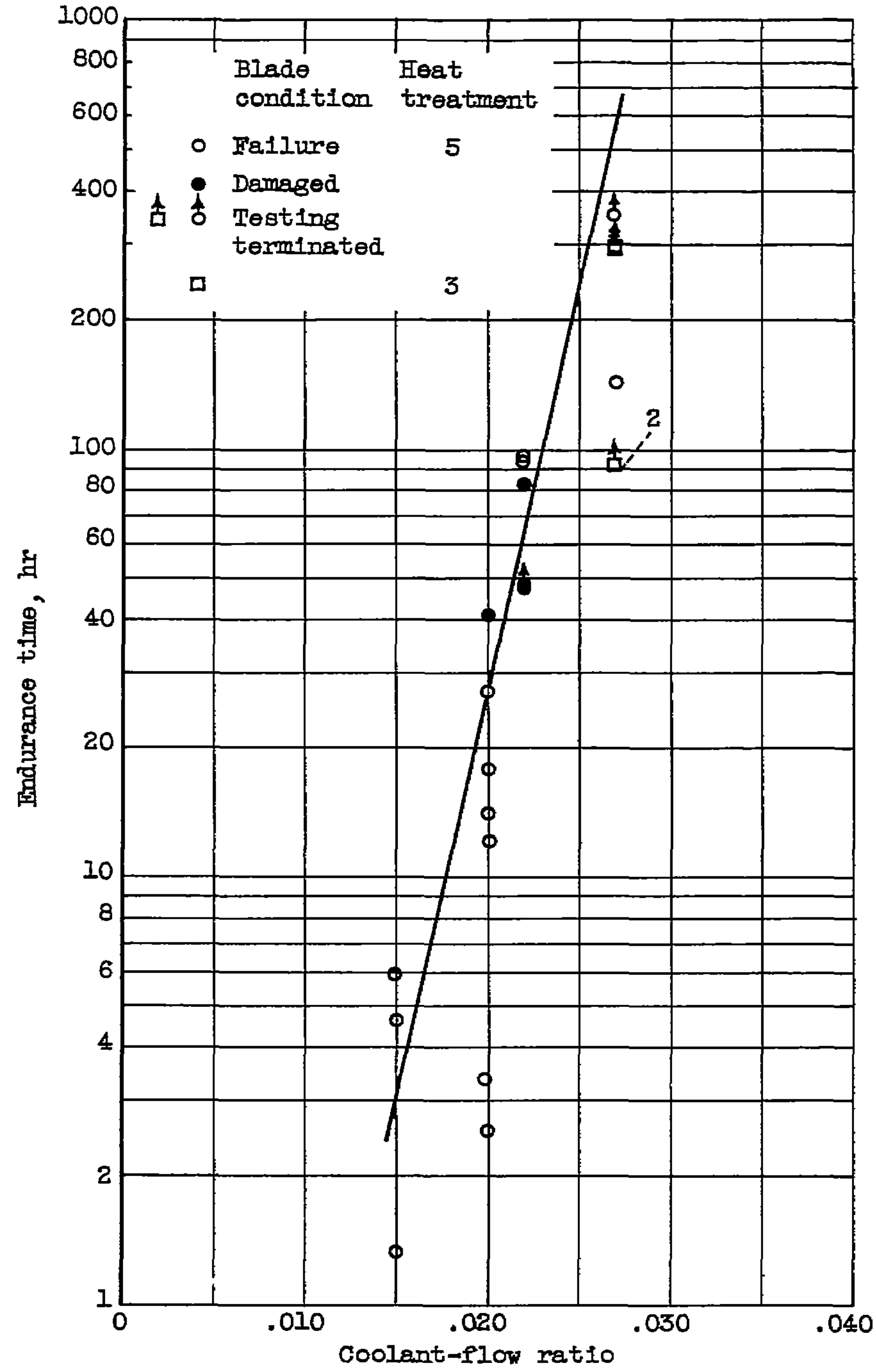

Figure 10. - Indicated mean life line of the change of blade life with coolant-flow ratio. (Shell-supported air-cooled blades with formed shells of Timken 17-22A(S) steel.

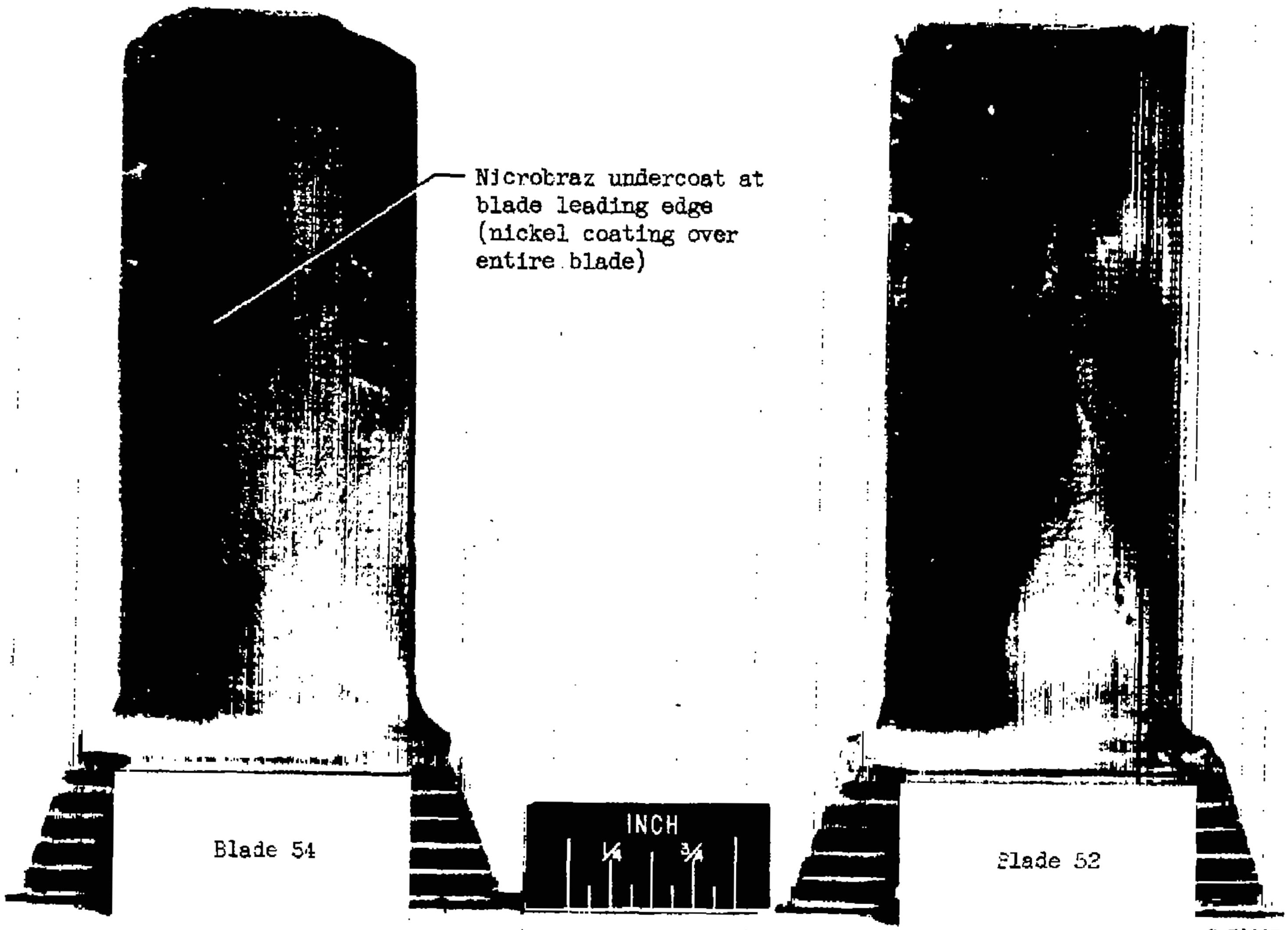

Figure 11. - Condition of blades and blade coating after 350 hours of operation at maximum rated engine conditions at coolant-flow ratio of 0.027. (Blade tips damaged by failures of other blades.)

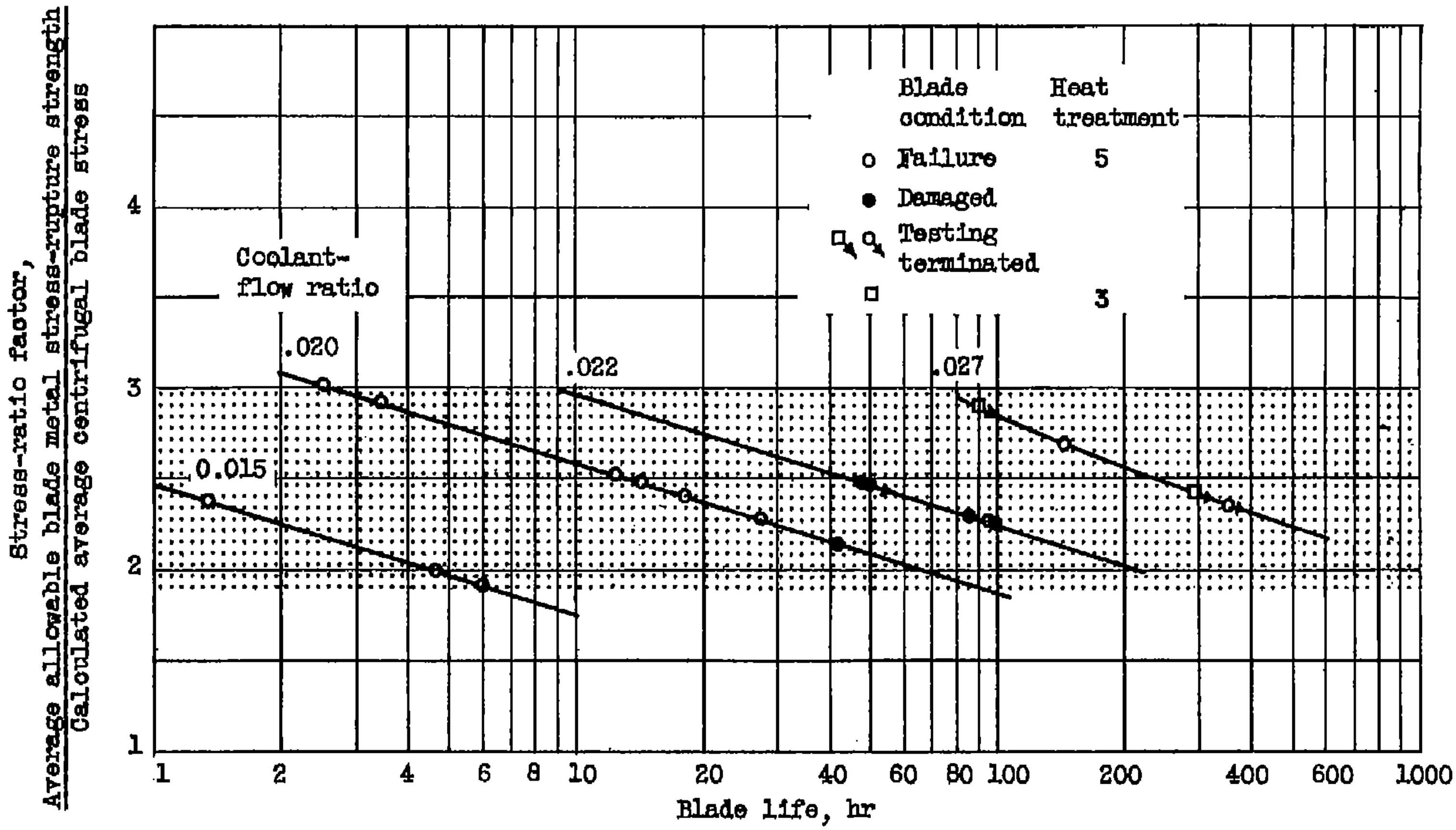

Figure 12. - Stress-ratio factor required over range of blade lives for air-cooled blades with shells of Timken 17-22A(S) steel.