



RESEARCH MEMORANDUM

FABRICATION AND ENDURANCE OF AIR-COOLED STRUT-
SUPPORTED TURBINE BLADES WITH STRUTS
CAST OF X-40 ALLOY

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SUMMARY

An investigation was conducted to develop the fabrication method for air-cooled strut-supported turbine blades with struts cast of a high-temperature alloy, X-40 (Haynes Stellite 31), and to determine the durability of these blades in a modified turbojet engine. Thirty blades were investigated at three engine speeds corresponding to blade root stress levels of 15,000, 27,000, and 35,000 psi. Twenty-six of the blades were tested uncooled at the maximum gas temperature permitted in the test engine (about 1650° F) in order to simulate the strut metal temperature expected at gas temperatures of about 2300° F, a cooling-air to combustion-gas flow ratio of about 0.015, and a blade cooling-air inlet temperature of about 500° F. In order to impose thermal stresses larger than those in the uncooled blades, four blades were investigated cooled to determine whether the larger thermal stresses significantly affect blade life. Details of the developed fabrication method are also included.

Early failures at the root region of the uncooled blades were experienced at the outset of the investigation at the two highest stress levels. At the stress of 15,000 psi, however, the blades tested successfully completed 100 hours of operation. The failures at the higher stress levels, however, were eliminated by modification of the blade structure and method of blade fabrication. Lives of over 50 hours were obtained with the modified blades at the stress of 35,000 psi without a failure, after which times the endurance tests on the blades were terminated.

The stress-ratio factors (ratio of the average allowable blade stress-rupture strength to the calculated average centrifugal stress) obtained for the blades were as low as 1.2 for uncooled operation at 35,000 psi at the life at which tests on the blades were terminated.

INTRODUCTION

The desirability of operating gas-turbine engines at elevated gas temperature for gains in engine performance and the methods for cooling

the turbine blades for operation at the elevated gas temperature have been discussed in many reports (e.g., refs. 1 to 4). One type of air-cooled forced-convection turbine rotor blade that appears promising for high-temperature operation is the strut-supported blade (refs. 5 to 8). The principle of this blade is that the main load-carrying member of the blade, the strut, is thermally insulated from the hot gases. The strut is surrounded by cooling air and is protected from the hot combustion gases by means of an airfoil-shaped shell which is attached to and supported by load-carrying fins on the strut. Because the shell is not a principal load-carrying member of the blade, it is capable of operation at higher temperature than the strut.

Initial investigation of the durability in engine operation of strut blades (refs. 7 and 8) in which the struts were machined from a low-alloy material (Timken 17-22A(S)) resulted in early blade failures. The endurance results indicated that further research was required before mechanically successful strut-supported turbine blades could be obtained. The failures occurred at the highly stressed root region of the blades. Some of these failures were attributed to the braze penetration in the strut which occurred during the furnace brazing of the blade components and to stress concentrations in this region of the strut. The design of these blades was such as to require that the strut be subjected to a minimum of two braze cycles in order to braze the blade components. Reference 8 indicated that the time at braze temperature or the number of braze cycles influences the degree of diffusion of the braze material into the strut.

As a consequence of the shortcomings of the previous method of fabricating the strut blades and because of the indicated causes for failures, modifications of the blades and blade fabrication methods were undertaken to improve blade life. The strut and bases of the blades were cast integrally in order to eliminate one of the brazing cycles required for the blades of references 7 and 8 which had the strut and base fabricated as separate units. In addition to reducing the severity of the braze penetration at the critical root region, as compared with previous blades, casting of the strut also eliminated the somewhat intricate machining previously required. The material used for casting the strut and base was a high-temperature alloy X-40 (Haynes Stellite 31). As part of a program on the evaluation of strut-type blades, the purpose of the investigation reported herein was to determine (1) the durability of the strut blade with a strut cast of the high-temperature alloy X-40 and (2) the stress-ratio factor (ratio of the allowable blade stress based on metal temperature and blade life to the calculated centrifugal stress) for the blades.

The data for the strut-blade durability were obtained in full-scale turbojet engines modified to permit testing of one to four test blades with or without cooling air. The tests were conducted at three nominal,

calculated, centrifugal blade root stress levels of 35,000, 27,000, and 15,000 psi. For the major part of the investigation the blades were tested uncooled, because facilities were not available to endurance-test cooled blades at higher than current gas-temperature levels. The metal temperature at the root of the strut for the uncooled phase of the investigation was between 1200° and 1275° F. For the remainder of the investigation the blades were cooled, the metal temperature at the root of the strut for these tests being about 700° F. The resulting calculated temperature difference between the shell and strut was of the order of 250° F. The endurance investigation of the cooled blades was primarily intended to determine whether or not the thermal stresses between the strut and shell imposed by the cooling air are sufficiently large even at current inlet temperatures to cause failures before a reasonable blade life can be obtained.

APPARATUS, INSTRUMENTATION, AND PROCEDURE

Blades

The general design features of the strut blade reported herein are the same as those in references 7 and 8. The aerodynamic profile of the blade is both twisted and tapered. Its chord is approximately 2 inches and the span approximately 4 inches. The blade consists of two parts, a formed airfoil shell and a strut cast integrally with the blade base. A photograph of the blade components is shown in figure 1. The strut and base were cast of high-temperature alloy X-40 (Haynes Stellite 31). The attached shell was a formed sheet of L-605 alloy (Haynes Stellite 25). The constituents of the strut and shell material are shown in table I. The strut material, X-40, was chosen primarily for two reasons: (1) the material has high strength in the range of temperatures considered, and (2) experience with the material at the NACA Lewis laboratory indicates that the finned support member of the blade could be cast with this material.

Cross-sectional drawings of the blade at three span positions are shown in figure 2. Illustrated is the configuration of the strut, which consists of the body of the strut, the fins to which the shell is attached (called primary fins), and the cooling fins (called secondary fins). The primary fins and the secondary fins have constant thicknesses of 0.040 and 0.020 inch, respectively, from the tip of the strut to the base. At the base of the blade, the primary fins increase in thickness to 0.100 inch and the secondary fins terminate 3/16 inch above the blade platform. The radius of the fillet between the primary fins and the blade platform is about 1/8 inch. Spacing between the fins is 0.080 inch. The blade airfoil shell has a nominal thickness of 0.020 inch. Since the strut span of 3.55 inches is approximately 1/2 inch less than the span of the shell, it is necessary to add two supporting sheet-metal fins in the tip

region to prevent "oil canning" of the shell in this region. The two fins of 0.020-inch thickness and 1/4-inch height extend from the suction surface of the shell to the pressure surface at two chord positions. Since the secondary fins are intended to cool only the strut, a clearance of 0.015 inch is maintained between the secondary fins and the shell in order to prevent the two parts from attaching while the primary fins are being brazed to the shell.

The development of the strut-casting technique and the method of shell attachment to the strut, as related to blade durability, is discussed in the RESULTS AND DISCUSSION section.

Engine

The cooled and uncooled strut blades were endurance-tested in modified production turbojet engines. The engines were modified to permit cooling air to be supplied to as many as four test blades. The cooling air was supplied to the blades by a laboratory compressed-air system. The tail cones of these engines were also modified by having a thin shroud around the turbine rotor so as to permit failed blades to penetrate the shroud easily without causing damage to other blades in the rotor. The modifications of the engine were essentially those described in reference 9.

Instrumentation

Blade metal temperatures were obtained with chromel-alumel thermocouples and a slip-ring-type rotating thermocouple pickup system similar to that described in reference 9. The metal temperatures of the blade were obtained at the base (1/16 in. below platform) and in the strut at 3/8 span ($1\frac{1}{2}$ inches above platform), as illustrated in figure 2. These locations were chosen because they were indicated to be near critical regions of the blade, the root based on previous endurance investigations (refs. 7 and 8) and the 3/8 span based on calculations. Another reference temperature measured was that of the leading-edge region of two of the standard blades of the test engine. The thermocouple for this measurement was also located at 3/8 span.

The general instrumentation of the engine was similar to that described in reference 9.

Experimental Procedure

The durability of the strut-supported blades was obtained at constant-speed engine operation. The constant-speed operation was chosen in order

to provide an endurance test of the blades at constant stress levels. The investigation was conducted at three engine speeds which corresponded to nominal calculated centrifugal stresses at the root of the blade (assuming that the blade is supported by the total metal cross-sectional area at the root) of 35,000, 27,000, and 15,000 psi. These "root" stresses were calculated for a span position of 1/8 inch, which is above the fillet region of the blade. The lower two stress levels were selected as representative of anticipated strut operation in present-day gas-turbine engines. The highest stress level was selected to permit evaluation of the blades at higher than current stress levels, as is indicated to be desirable in reference 4. Operation at the three stress levels would also indicate whether stress level had any effect on the type of blade failure. The engine speeds at which these stresses were obtained were 7,500, 10,000, and 11,500 rpm (rated engine speed).

The procedure for investigating the durability of the blades was to run a group of blades until each blade of the group failed. Visual and metallurgical examinations of the failed regions of the blade were then made to determine possible causes for the failures. Succeeding blades were then fabricated incorporating changes in the blade design or in the fabrication process so as to eliminate or reduce the indicated causes for failures. These modified blades were then tested to evaluate the effects of the changes on the life of the blades. Thirty blades were endurance-tested. Only four of the blades were cooled, the others being tested uncooled.

Testing of uncooled blades. - In order to simulate the strut metal temperatures that would be experienced when the blade is cooled at high turbine-inlet temperatures, the blades were tested uncooled in the test engine at current inlet temperatures. The measured metal temperature at the root of the strut obtained when the blades were uncooled, at the inlet gas temperature of the test engine, was of the order of 1200° F. This temperature corresponds to that analytically determined for a strut blade operating at a turbine-inlet gas temperature of 2300° F, a coolant-flow ratio of the order of 0.015, and a coolant inlet temperature of about 500° F. The strut metal temperature obtained in the test engine could not be kept at the same value for the three engine speeds because of the limits of control of the gas temperature. As a consequence, the measured metal temperatures at the blade base, which were assumed to be the same as those of the strut, ranged between 1200° and 1275° F. The measured strut temperatures at the 3/8-span position ranged between 1400° and 1450° F, temperatures which would also be expected at 2300° F operation.

Testing of cooled blades. - Since the thermal gradients in the uncooled test blades were small, several blades were tested cooled in order to determine whether the larger thermal stresses imposed by cooling significantly influence blade life. The blades were tested with a very small quantity of cooling air so as to keep the strut metal temperature

reasonably high. The blades, because of their high cooling effectiveness, however, operated in the test engine at a strut metal temperature considerably below that which would be expected at high inlet gas temperatures. It was nevertheless thought that operation of the blades at these conditions and at the high centrifugal stress level of 35,000 psi at the blade root would provide an insight into whether or not the thermal stresses are sufficiently large to result in early blade failures. The strut metal temperatures for these tests were measured at the root and 3/8-span regions of the blades (fig. 2). The temperatures obtained at these locations were 700° and 950° F, respectively. The difference between the strut and shell temperatures was approximately three-fourths of that expected at operation at an elevated gas temperature of 2300° F.

Calculation Procedure

Blade stresses. - The blade operating stress levels discussed throughout the report are calculated centrifugal stresses. These stresses were calculated by assuming that the centrifugal force exerted on the blade is uniformly supported by the total cross-sectional metal area of the strut and shell. The thermal and vibratory stresses were not calculated herein because of the complexity of the calculation and because sufficient data for the determination of these stresses were not available. The bending stresses were approximately compensated for in the blade design by orientation of the blade centroids and therefore are neglected.

Stress-ratio factor. - The stress-ratio factor SRF is defined as the ratio of allowable stress-rupture strength of bar stock (based on the temperature of the blade and the time of blade operation) to the calculated centrifugal stress σ of the blade. It is a factor whose magnitude indicates the compensation for the effects that fabrication processes may have on the blade structural strength and for the effects of other stresses such as bending, vibratory, and thermal stresses. In equation form, as used herein, the stress-ratio factor for any span location may be written as

$$\text{SRF} = \frac{(A_1 S_1 + A_2 S_2)}{(A_1 + A_2)} / \sigma$$

For the purpose of this report the average allowable stress-rupture strength of the strut blade was obtained by an arithmetic weighting of the allowable stress-rupture strength of the shell S_1 and the strut S_2 on the basis of their respective cross-sectional metal areas A_1 and A_2 . The allowable stress-rupture strengths for the shell and the strut at these locations were based on (1) the respective average temperatures of the shell and the strut and (2) the time to failure for the blades or the time at which tests of the blades were terminated. This simplified

method of determining the stress-rupture strengths was used to avoid the complexity of evaluating the effects of the interrelation of the creep of the shells and struts on the stress-rupture strengths of the blades. The temperatures of the strut and shell for the uncooled blades were assumed to be the same because of the small difference in the measured temperatures at the leading edge of the standard blades and the midchord of the strut. The SRF was determined for two span locations which were considered critical, the root ($1/8$ in. above the blade platform) and the $3/8$ span ($1\frac{1}{2}$ in. above the platform). This factor was not obtained for the cooled blades because of the lack of stress-rupture strength data for the strut material at the relatively low metal temperature at which the blades were operated.

RESULTS AND DISCUSSION

The results of an investigation of the fabrication and endurance of 30 strut-supported turbine blades with struts of cast X-40 material are presented. Early in the investigation, blade failures occurred and modifications were made to the blades in an attempt to eliminate the failures and improve blade life. Also presented is a discussion of the possible causes of blade failures and other pertinent design and fabrication information for strut blades with cast struts.

Development of Strut-Casting Technique

Before fabricating test blades, development of the technique of casting the strut and blade base integrally was necessary. The casting was done by the lost-wax process. The dies for the wax patterns were made of a low-melting alloy of lead-bismuth which was cast around master patterns (machined of brass) of the strut and base. The strut needed only one pattern, while the base required two. A photograph of the resulting waxes is shown in figure 3. The wax patterns of the strut-base units were made by fitting the base patterns to the strut and bonding the unit with wax. The patterns were completed by adding gates and risers to the bottom of the base. The wax patterns were then invested into molds containing Kerr's Ferrolite in such a manner that the risers were "buried." Shrinkage cracks and porosity, which were experienced at the start of the investigation, were eliminated in the base region of the blade by the use of buried risers. Spalling of the mold, also experienced early, was eliminated by increasing the temperature at which the wax was removed from the mold from a value of 200° to 225° F. The molds were cured at 1800° F. The X-40 casting stock, heated to a temperature of 2850° F, was then centrifugally cast into the 1800° F molds. After the blade was cooled and then removed from the mold, the coolant passages in the base region (which were formed with the Kerr's Ferrolite) were leached out in a bath of sodium hydroxide which was at a temperature of 1100° F.

The first integral strut-base castings (which were not used for the blades reported herein) had the 0.020- and 0.040-inch secondary and primary fins, respectively, extending into and through the blade base. Because of the resulting small rectangular passages and the thin fins (both primary and secondary) at the base (fig. 4(a)), some shifting of the passage cores and shrinkage cracks in the fillet in the primary fins at the blade root occurred. Changes in the original dies were then made to remedy these casting difficulties. To provide larger passages the thin secondary fins were terminated $3/16$ inch above the base platform and the thickness of the primary fins as they entered the base was increased to 0.100 inch (figs. 1 and 4(b)). The increase in primary-fin thickness was to compensate for the loss of the shear area previously provided by the secondary fins. Shrinkage cracks in the fillet were eliminated by the increased primary-fin thickness and by increasing the radius of the fillet in these fins at the root from $1/16$ to $1/8$ inch (fig. 1). The acceptability of castings was determined by inspections with X-ray.

Fabrication Procedure and Endurance Results for Uncooled

Blades 1 to 14

Fabrication. - The strut and the base of the blades 1 to 14 were cast integrally, as previously described, by the lost-wax process. The airfoil shell, which was in either one or two pieces, was press-formed in cast Kirksite dies. The shell was flared at the root so that it conformed to the fillets in the primary fins at the strut root (fig. 1). The shell was next fitted to the strut (the one-piece shells were split along the trailing edge for fitting purposes). To prevent the shells from opening along the leading or trailing edges during the brazing operation, these regions were tack-welded. The tack welds were located at three locations along the span, near the root, the midspan, and the tip of the shell. Blades were also fabricated which were not brazed at the leading or trailing edges, but which had these regions heliarc-welded along the entire length of the shell. The details of fabrication as applied to specific blades are shown in table II.

The blades were brazed with either of two commercial brazing compounds designated as brazes I and II. The constituents of these compounds are listed in table I. Because of previous experience with the use of braze I for other air-cooled blades (refs. 7 and 8), the first group of blades reported herein used braze I. However, after unpublished test results were obtained indicating that braze II had less effect in reducing the strength of sheet tensile specimens of several high-temperature alloys than braze I, braze II was used. Several of the blades tested had the shells attached to the primary fins of the strut by resistance-welding rather than brazing. The use of resistance-welding was tried in an effort to eliminate possible detrimental effects of braze penetration.

The braze materials were applied to the blades in the form of a slurry of powdered braze compound and a binder. Regulated amounts of the slurry were inserted in the air passages (adjacent to the primary fins), after which the blades were placed in a brazing fixture. The purpose of this fixture (shown in fig. 5) was to provide the proper fit between the shell and the strut during the brazing operation. The brazing was done in a vacuum furnace at a pressure of 4 microns and a temperature of 2100° F. The blades were held at 2100° F for 12 minutes and then furnace-cooled to room temperature. As a consequence of the flaring of the shell at the root region of the blades, small openings at the junctions of the shells at the leading- and trailing-edge root regions resulted. Considering that the blade design is eventually intended to be cooled and that the openings would be sources for cooling-air leakage, the openings were filled with Inconel weld material. After this operation, the blades were heat-treated, the base serrations ground, and the airfoil cut to the proper length. The details of the heat treatments, designated A, B, and C, are described in table III. Heat treatments A and C were aging processes intended to increase the yield strength of the strut in an attempt to improve blade life. The blade condition as-brazed was considered as a heat treatment and designated heat treatment B.

Endurance results. - Nominal blade root stress of 35,000 psi (blades 1 to 9): The life of the nine blades operated at the 35,000-psi root stress level ranged from minutes to a few hours. The lives of the individual blades are tabulated in table II. The blades generally failed in the root region of the strut, as shown in figure 6 (blade 5), which was typical of the failures.

The results of the endurance tests on the blades did not indicate which of the heat treatments or which of the brazing compounds was better. It is believed that the higher ductility of the strut obtained with heat treatment B (blades in the as-brazed condition) may be more conducive to longer blade life. An endurance investigation of air-cooled, shell-supported turbine blades (ref. 10) showed that greater blade life was obtained with increased ductility. The resistance-welded blades (blades 7 to 9), intended to eliminate braze penetration and its detrimental effect on blade life (ref. 10), did not show an improvement in blade life as compared with the brazed blades. Limitations of the resistance-welding equipment and fixture equipment resulted in considerable pitting of the 0.020-inch-thick shells of the blades. Pitting causes stress concentrations that may have been a contributing factor in the failures encountered. Considerable time would be required to further develop the resistance-welding of the 0.020-inch-thick shells. Because of this, efforts were concentrated on the use of brazing, even though resistance-welding was not given a true evaluation.

Nominal blade root stress of 27,000 psi (blades 10 to 12): The three blades that operated at a root stress of 27,000 psi failed after lives of

6, 22, and 47 hours. The lives of the latter two blades were extended by repairing cracks in the blade shell that developed during the endurance test. The repairs are discussed in more detail later. The general location of the failures was the same as for the higher stressed blades (35,000 psi).

Nominal blade root stress of 15,000 psi (blades 13 and 14): The two blades subjected to a root stress of 15,000 psi completed 101 hours of engine operation without a strut or shell failure. Tests on the blades were terminated after this time, since completion of 100 hours was considered sufficient to demonstrate the durability of the blades at the test conditions.

Possible causes of failures (blades 1 to 12). - The endurance results of the blades listed in table II give evidence of three possible causes for blade failures: (1) vibratory characteristics and stress concentrations, (2) failures in the blade shell, and (3) braze penetration into the strut.

(1) Vibratory characteristics and stress concentrations: Consideration was given in the design of the blade to the centrifugal and gas bending stresses. The thermal and vibratory stresses, however, were not calculated herein because of the complexity in the calculation of these stresses and because sufficient data for the determination of these stresses were not available. The other factor in blade design which could not be evaluated was the magnitude of stress concentrations at the root region of the blades. These are the result of the manner of stress distribution at the fillets in the blade base and the manner in which the centrifugal load of the strut is transferred through the primary fins in the strut to the blade base. Because of the type of failures that occurred at the root regions of the blades, the stress concentrations and the vibratory characteristics of the blades may be factors having significant influence on blade life.

(2) Failure in shell material: During the endurance investigation it was observed that cracks developed in the blade shell in a number of the test blades. The cracks were detected during periodic inspections of the blades during testing. It is believed that the cracks that developed in some of the blades were a result of the method of fabrication and influenced the life of the blades.

As mentioned earlier, tack-welding of the shell was used in the fabrication of some of the blades. Failure patterns observed on several blades indicated that tack-welding was one of the causes for shell failures. Photomicrographs of two tack-welded regions of the leading edge of a typical blade shell are shown in figure 7. Shown are sections through the leading edge of the shell halves as viewed upstream of the turbine blade. The region surrounding point A in figure 7(a) is the tack weld,

B is a slight crack in the shell material, and C is the braze that bonds the shell halves. Figure 7(b) illustrates another tack weld, observed on the same blade. The letter designations are the same as for figure 7(a). An excess of braze that flowed over a portion of the outer shell surface is designated D. The pockets or weld burn-outs (E) are filled by braze. The resulting stress concentration at this point could cause blade failure.

Six of the blades listed in table II (9 to 14) had the blade shell halves bonded by welding along the length of the leading and trailing edges of the blades. Complete welding of the shell was used in order to eliminate the use of tack-welding and perhaps to reduce cracking of the shell. Shell failures and complete blade failures, however, were obtained for all but the two blades tested at a root stress level of 15,000 psi. Typical of the blades with a shell failure was blade 12 (fig. 8), which was tested at a root stress of 27,000 psi. A crack first developed in the fillet region after 12 hours of operation as shown in the view in figure 8(a). To establish whether shell failures were causing strut failures, a thin metal patch was brazed over the crack to prevent the crack from spreading. This patch extended from the leading to the trailing edge on the suction surface and had a width of 1/2 inch. After 10 additional hours of operation, another crack developed in the shell but in the trailing-edge region and on the pressure surface (fig. 8(b)). It should be noted that the crack extended from a region immediately adjacent to a large weld build-up (point A). It is thought that stress concentrations in these regions cause the cracks to originate. To further extend the blade operation, this crack was brazed shut and operation continued for an additional 25 hours (a total of 47 hr), when failure of the blade (fig. 8(c)) terminated the tests. Examination of the failure indicated that the crack that caused the blade to fail originated at a weld build-up in the leading edge (point A), then progressed to the strut, and was followed by a fatigue failure.

Failure of the shell due to weld build-up was also observed during engine operation of blade 11. Examination of all of the blades after failure gave evidence on several blades that the shell may have failed and then caused the strut to fracture. Attempts to eliminate failures in the shell through the use of slight modifications to the strut and shell are discussed in a later section.

(3) Braze penetration: References 8 and 10 indicate that braze penetration into the load-carrying member of air-cooled blades may considerably reduce blade life. For the cast strut blades, braze penetration may also be a serious factor. The effect on blade strength of the penetration with either of the two braze compounds used could not be determined from the results. Neither do the results give evidence that one braze was superior to the other, as stated earlier. It was noted, however, that, when braze I accumulated at any particular location on the primary

fins of the strut, there was a tendency for the blade to fail through the area with the accumulated braze. The proximity of the braze accumulation to the location of strut failure is shown in figure 6 (blade 5). Failures of this type were not observed on the blades that were brazed with braze compound II.

Fabrication Procedure and Endurance Results for Uncooled

Blades 15 to 26

Six different types of strut configurations were made in an effort to eliminate the blade failures described previously. The blades were then endurance-tested uncooled at a nominal root stress of 35,000 psi (actual range of 29,900 to 35,700 psi). Each of the modifications is described and the effect on blade life presented. The first three modifications did not show any improvement in blade life, while the improvement with the last three modifications was considerable. Fabrication details and endurance results for the blades are summarized in table IV.

Modification 1: Insertion of hollow tube in leading-edge coolant passage (blade 15). - Shell failures at first were attributed to stress concentrations in the leading-edge fillet region of the shell. These concentrations were a result of the required weld build-up in closing the hole in the shell at this location, as discussed earlier. In order to reduce the stresses in this region a tube was brazed into the leading-edge coolant passage of one blade. The tube was brazed to the inner surfaces of the shell (pressure and suction side) and to the strut that bound the leading-edge coolant passage. The life of this blade, as shown in table IV, is slightly under 3 hours, a life comparable with those blades without the modification. Failure occurred 1/8 inch above the blade platform, a failure similar to that shown in figure 6. The results obtained from the testing of this blade indicated that it offered no appreciable improvement in blade life.

Modification 2: Double shell at blade base region (blade 16). - The use of a double shell at the base region of the blade was intended to reduce the vibration of the blade and the stresses causing fatigue-type failures. The modification consisted of a second shell that was brazed completely around the blade periphery at the base of the airfoil section. The thickness of this shell was 0.022 inch, and its height approximately 5/8 inch. The life of this blade was approximately 3 hours, which is not much different from that of the blades without the modification. Failure of this blade was also in the base region of the strut and appeared to be the same as that shown in figure 6.

Modification 3: Elliptical coolant passages in blade base (blades 17 and 18). - As stated earlier, the primary fins in the blade base must

transfer the centrifugal load of the strut to the blade base. Stresses are expected to be high in the fins as evidenced by cracks in the primary fins in several blade failures (fig. 6). A reduction of any stress concentrations in this region should therefore improve blade life, if this transfer of load is a primary cause of blade failure. Stress concentrations can be reduced by the elimination of the sharp corners in the rectangular coolant passages in the blade base. A simple modification to the strut configuration was made by altering the shape of the coolant passages from rectangular to elliptical. The elliptical holes were obtained by using elliptical cores of alumina silicate compound having major and minor diameters of $1/8$ and $1/16$ inches, respectively.

Two blades containing elliptical coolant passages in the blade base failed in 2 and 3 hours, a life comparable with that before strut modifications. The 3-hour blade (blade 18) failed 1.5 inches from the blade platform ($3/8$ span) as shown in figure 9. This failure was different from the earlier failures in that the blade failed at a greater distance from the blade base and severe cracking of the shell was observed. The cracks shown on the leading edge progressed through a tack-welded region. The failure at the 1.5-inch span appeared to have originated below a tack-welded region. Examination of the strut showed that it failed in fatigue in the strut leading edge. This fatigue may have been due to a shell crack progressing to the strut and causing a fatigue failure. This type of blade failure provides additional evidence that the tack-welding of the shell may have a detrimental effect on blade life. Failure of the 2-hour blade occurred $3/8$ inch from the blade base.

Since the life of the two blades with the strengthened bases was comparable with that without this strut modification, the stress concentration caused by the transfer of the load in the base fins may not be a primary cause of strut blade failure. Nevertheless, the use of fillets in the rectangular coolant passages in the blade base is a desirable feature in any design. As a result, subsequent blades contained fillets of approximately $1/32$ -inch radius in the coolant passages. These fillets were obtained by dipping the strut and base wax assembly (prior to insertion in the casting molds) into molten wax to a depth $3/4$ inch above the base platform for a predetermined length of time. This immersion of the wax pattern assembly also provided a smoother surface on the pattern.

Modification 4: Extension of shell into blade base (blades 19 to 21). - Modification 4 consisted in extending the shell directly into the base as shown on the left in figure 10. Previously, the shell did not extend into the base but was flared and brazed to the top of the blade platform as shown on the right in figure 10. Extending the shell into the base eliminated the need for the closing of the holes in the fillet region of the blade base and shell at the leading and trailing edges. As mentioned earlier, this welding may have been a cause for shell failures. In addition, with modification 4 the shell in the fillet region is in the direction of the centrifugal loading on the blade, which may provide more rigidity.

To fabricate this type of blade the shell was brazed to the strut primary fins over the entire length of the strut, which included the primary or supporting fins in the blade base region. A two-piece base cast with a contour that matched the shell contour in the blade base was brazed to the shell and the strut assembly. A cast fillet was provided on the top of the blade platform.

The life of the three blades tested (blades 19, 20, and 21) with this modification ranged from 12 to 53 hours. These results indicate that the modification increased blade lives over those previously tested. Tests on blade 19 were concluded when a shell failure (shown in fig. 11(a)) occurred after 12 hours. The failure occurred at the top of the cast fillet. A microscopic examination of the blade, which was sectioned, showed that the brazed joint between the shell and the strut along the suction surface was poor. The results of this examination also showed that the shell necked down under the tensile load. The second blade (blade 20) failed completely at the top of the fillet after 24 hours of operation (fig. 11(b)). Tests on the third blade (blade 21) were terminated after the blade completed 53 hours of operation. A very small crack on the suction surface and at the top of the fillet, however, was observed in this blade. The notch effect at the junction of the shell and the top of the fillet may have been the cause of the failure of the shell.

Modification 5: Platform at leading and trailing edges and supporting fin at leading edge (blades 22 and 23). - Modification 5 was intended to reduce shell failures by the addition of a supporting platform at the base of the leading- and trailing-edge regions and by a supporting fin extending from the strut to the leading edge of the shell (fig. 12). The platform had a height of $3/8$ inch and was cast integrally with the strut and blade base. Passages were provided in the platforms for coolant. The blade shell, which was flared in the usual manner in the fillet region, was brazed to the sides of the platforms. This method of fabrication eliminated welding in these regions. The fin in the leading edge, which was brazed to the shell, provided added support to the shell. For the two blades tested, the shells were of one-piece construction, so formed that only the trailing edge needed heliarc welding. The two blades successfully completed 50 and 66 hours of engine operation, after which testing was terminated. During the testing of the blades a $1/2$ -inch spanwise crack developed at the trailing edge of the shell at the blade tip. This crack was rewelded and operation continued. The test results indicate that the use of the support platform, the supporting fin, and the one-piece shell with a welded trailing edge (no welding at the leading edge) had a significant effect on increasing blade life. It appears that a further improvement could be made if a blade shell could be fabricated without welding of either the leading or the trailing edge.

Modification 6: Cast leading and trailing edges (blades 24 to 26). - Elimination of welding of the leading- and trailing-edge regions and of

the weld cracks was attempted by casting the leading and trailing edges integrally with the strut. A photograph of a blade having this modification is shown in figure 13 along with a sketch illustrating the general assembly of the shell halves to the strut. The elliptically shaped leading-edge coolant passage (fig. 13) was obtained by the use of a shaped core of alumina silicate in the wax pattern. The rectangular trailing-edge coolant passage was obtained by hand removal of the wax from the wax pattern. The shell half that served as the pressure surface of the blade also served to enclose the trailing-edge cooling passage. For cooled-blade operation this modification would result in higher leading- and trailing-edge blade temperatures as compared with the preceding blades.

The life of the three blades of this configuration (blades 24, 25, and 26) ranged from 18 to 54 hours. A shell failure in blade 24 after 18 hours (fig. 14) due to poor braze of the shell to the strut, terminated the tests of the blade. The two other blades completed 54 hours of operation, which was considered adequate to indicate the merits of this configuration. One of the two blades (blade 25) had a slight shell crack in the fillet region on the suction surface. This crack was also a result of a poor braze. Because the failures of the shells of blades 24 and 25 were due to poor brazing, the shell failures should not be considered in the evaluation of this modification. The lives obtained with the blades of this modification are attributed to the elimination of the welding of the shells, as well as possible reduction in vibratory stresses due to the sturdier leading- and trailing-edge sections of the blade.

Endurance Results for Cooled Strut Blades 27 to 30

To obtain an insight as to whether thermal stresses in cooled strut blades cause early failures, four blades of modification 5 (arbitrarily chosen) were subjected to cooled-blade endurance tests. The tests were conducted at a root stress of 35,000 psi (rated engine speed), a turbine-inlet gas temperature of about 1650° F, and an estimated cooling-air to combustion-gas flow ratio per blade of 0.01. The measured strut temperatures at the root and 3/8 span were 700° and 950° F, respectively. Operation at these conservative values, as stated earlier, was necessary because the test engine could not be operated safely at higher than current gas-temperature levels for a considerable length of time. The calculated temperature difference between the shell and strut (temp. difference across primary fins) was 250° F, which is approximately three-fourths of that expected at an elevated gas temperature of about 2300° F.

Two of the four blades had the shells welded along the trailing edge, as in modification 5. The shells of the two other blades were modified by changing the location of the weld from the trailing edge to the midchord of the suction surface. This slight modification was used

in an attempt to reduce the possibility of cracks in the shells, which, as discussed earlier, originated at the welds at the trailing edge.

Three of the four blades successfully completed 50 hours of operation without any visible shell failures. The fourth blade successfully completed 40 hours of operation but was observed to have a small piece of the shell missing after the completion of 50 hours. This was not surprising, considering that the blade shell was damaged during fabrication. The results of these tests indicate that the thermal stress caused by a temperature difference of about 250° F between the shell and strut does not appear to be a significant factor affecting blade life.

Stress-Ratio Factors for Blades 1 to 30

Uncooled blades 1 to 14. - Stress-ratio factors obtained from the endurance investigation of uncooled strut blades 1 to 14 are shown in figure 15. The factors are tabulated for the root region (fig. 15(a)) and the 3/8-span region (fig. 15(b)) of the blades. The average stress-ratio factors obtained at the root region for the three nominal stress levels of 15,000, 27,000, and 35,000 psi were 3.5, 2.0, and 1.7, respectively. The largest factor of 3.5 was obtained at the lowest stress level of operation. It should be noted that these factors are large because the blades were not operated to destruction. Stress-ratio factors were calculated on the assumption that failures occurred. Additional testing life, of course, would reduce this factor. The additional cost of testing, however, becomes very large for even small decreases in the stress-ratio factor.

The stress-ratio factors for blades 1 to 14 were relatively large because, in many instances, the shell caused an early failure. Nevertheless, stress-ratio factors were determined assuming the failure was in stress-to-rupture so as to arrive at some type of design factor for the strut-type blades.

Uncooled blades 15 to 26. - Stress-ratio factors obtained from the endurance investigation of uncooled blades 15 to 26 are shown for the root region of the strut in figure 15(a) and for the 3/8-span region in figure 15(b). These factors were calculated for the blades operated at the nominal root stress of 35,000 psi (nominal 3/8-span stress of 27,000 psi) at which the blades were tested.

The results indicate that the stress-ratio factors for the blades with modifications 1, 2, and 3 (blades 15 to 18) are comparable with those of blades 1 to 14 at the same stress level. Modifications 4, 5, and 6 (blades 19 to 26), however, showed a significant decrease in the stress-ratio factor as a consequence of the improved blade life obtained. For regions other than in the base, the factors are approaching 1.0, possibly

because of reduced vibration. A further reduction in the stress-ratio factor for blades of modifications 5 and 6 could be obtained if the tests were extended beyond the selected limit of approximately 50 hours. Additional testing time, as indicated earlier, becomes very large for even small decreases in the magnitude of the stress-ratio factor.

Cooled blades 27 to 30. - Stress-ratio factors for cooled blades are expected to be larger than those for the uncooled blades because of the added effect of the thermal stresses caused by cooling. The stress-ratio factors for the cooled blades tested herein, however, were not evaluated, because the stress-to-rupture data for the shell and strut were not available at the conservative metal test temperatures, and because extended test time would be required to obtain reasonable values of the factor. In order to obtain representative stress-ratio factors for cooled strut blades made of a strategic material and to evaluate the significance of shell failures at high temperatures, it is necessary to endurance-test the blades in an engine or test rig which can operate at higher than current turbine-inlet gas temperatures.

Concluding Remarks

The endurance results presented herein have shown that, of the six modifications tested, the blades having modifications 5 and 6 appear to be the most promising. The shell failures that were encountered throughout the endurance tests may or may not be a serious problem during operation at higher gas temperatures. This can only be determined by further endurance tests in engines capable of operation at higher than current gas-temperature levels. It was shown, however, that the stress-ratio factors for the uncooled blades of modifications 4, 5, and 6 were approaching a value of 1.2 or lower. This is encouraging, considering that the many fabrication processes involved (casting, brazing, etc.) apparently did not have a large effect on the strength properties of the blade materials.

SUMMARY OF RESULTS

Investigations were conducted to determine the durability of air-cooled strut-supported turbine blades with struts cast of high-temperature alloy X-40. Because of the limit of gas temperature in the test engine, most of the blades were tested uncooled in order to obtain metal temperatures of the strut simulating that expected at a turbine-inlet temperature of about 2300° F, a cooling-air to combustion-gas flow ratio of about 0.015, and a blade cooling-air inlet temperature of 500° F. The results of the investigations are as follows:

1. Methods for obtaining satisfactory castings of the finned struts with high-temperature alloy X-40 were developed. The use of the casting

eliminated the somewhat intricate machining of the struts previously required and also reduced the braze penetration into the struts by reducing the number of braze cycles required.

2. Early failures of the uncooled blades at the root region were experienced at the outset of the investigation at the root stress levels of 27,000 and 35,000 psi. Lives of over 100 hours, however, were obtained with the blades at the low stress level (15,000 psi) without a failure.

3. Six modifications of the blades were investigated. Only three of these, however, were successful in eliminating the early blade failures. At a root stress level of 35,000 psi, lives of over 50 hours were obtained without failures on the blades.

4. The four modified blades that were operated cooled completed 50 hours of endurance test time. One of the blades had a shell failure, but this failure was attributed to damage caused during fabrication of the blade. The blades were tested at the stress level of 35,000 psi.

5. The stress-ratio factors (ratios of allowable stress-rupture strengths to calculated average centrifugal stresses) that were obtained for the uncooled blades were as low as 1.2 for the modified blades operating at the stress level of 35,000 psi.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 16, 1956

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TABLE I. - CONSTITUENTS OF MATERIALS USED IN STRUT BLADES

	Material	Chemical composition, percent								
		Co	Ni	Cr	W	Mn	Si	Fe	C	B
Strut and base	X-40	48.40	9.0	23.0	6.0	---	-----	2.0	0.45	----
		to 59.55	to 12.0	to 28.0	to 9.0				to 0.60	
Shell	L-605	46.85	9.0	19.0	14.0	1.0	1.0	2.0	0.15	----
		to 53.85	to 11.0	to 21.0	to 16.0	to 2.0				
Braze	I	-----	72.30	15.0	-----	---	4.50	4.0	0.45	3.75
	II	-----	69.43	19.4	-----	---	10.0	1.14	0.03	----

TABLE II. - ENDURANCE OF UNCOOLED STRUT BLADES 1 TO 14 PRIOR TO BLADE MODIFICATION

Blade	Running time, hr:min		Test conditions		Shell			Number of braze cycles	Blade heat treatment (table III)	Distance from platform to failure, in.	Remarks				
	Total	At test conditions	Centrifugal stress at root (1/8 in. above platform), psi	Strut temp. at blade base, °F	Centrifugal stress at 3/8 span, psi	Strut temp. at 3/8 span, °F	Thickness, Pieces					Leading edge	Trailing edge	Attachment (table I)	
Nominal root stress, 35,000 psi															
1	1:33	1:21	35,700	1275	27,100	1450	0.022	2	(a)	Braze I	Braze I	1	A	1/8	Test terminated after blade damaged by Blade 4
2	1:57	1:51	35,200		26,900		.026						B	3/8	
3	3:36	2:36	35,700		27,100		.022							---	
4	3:36	2:36	35,700		27,100		.022							1/8	
5	1:25	1:25	35,700		27,100		.022							1/8	
6	1:52	1:43	35,200		26,900		.020							1/4	
7	1:13	1:01	35,700		27,100		.022	1	(b)	Braze II Resistance-weld	Braze II Resistance-weld	1	C	1/8	
8	1:30	1:12	35,700		27,100		.022	1		Resistance-weld	Resistance-weld	-	C	0	
9	2:55	2:50	35,200		26,900		.020	2	(b)	Resistance-weld	Resistance-weld	-	B	1/4	
Nominal root stress, 27,000 psi															
10	6:21	6:09	26,900	1230	20,500	1400	0.022	2	(b)	Braze I	Braze I	1	B	3/8	Cracks in shell observed during testing
11	23:35	21:52	26,600		20,300		.020			Braze II	Braze II	1		1/8	
12	50:28	47:15	26,600		20,300		.020			Braze II	Braze II	4		3/8	
Nominal root stress, 15,000 psi															
13	103:35	101:02	15,100	1200	11,500	1400	0.018	2	(b)	Braze II	Braze II	1	B	---	Test terminated; no visual shell or strut failures
14															

^aTrack-welded at three span positions, then brazed along entire length.

^bHellic-welded along entire length.

TABLE III. - HEAT TREATMENTS

Heat treatment	Process
A	<ol style="list-style-type: none">1. Quick heating to 400° or 500° F2. Increase temperature to 1350° F (100° F/hr)3. Age 16 hr at 1350° F4. Raise to 1500° F (100° F/hr)5. Age 4 hr at 1500° F6. Furnace-cool to room temperature
B	As-brazed (12 min at 2100° F, furnace-cool to 1300° F in 20 min, from 1300° F to 500° F in 40 min)
C	Age 50 hr at 1350° F

TABLE IV. - ENDURANCE OF UNCOOLED STRUT BLADES 15 TO 26 AFTER BLADE MODIFICATION

[Nominal root stress, 35,000 psi.]

Blade	Running time, hr:min		Test conditions			Shell				Number of heat treatment cycles (table III)	Distance from platform to failure, in.	Remarks				
	Total at test conditions	psi	Strut temp. at blade base, °F	Centrifugal stress at 3/8 span, psi	Centrifugal stress at 5/8 span, °F	Temp. at span, °F	Thickness, in.	Pieces	Leading edge				Trailing edge	Attachment (table I)		
Modification 1: Hollow tube in leading-edge coolant passage																
15	3:13	2:56	35,100	26,400	1275	1450	0.020	2	(b)	(b)	Braze II	Braze II	1	B	1/8	
Modification 2: Double shell at blade base region																
16	3:20	2:40	29,900	27,100	1275	1450	0.022	2	(a)	(a)	Braze I	Braze I	1	B	1/8	
Modification 3: Elliptical coolant passage in blade base																
17	1:50	1:40	35,700	27,100	1275	1450	0.022	2	(b)	(b)	Braze I	Braze I	1	B	3/8	Opening at junction of fin, shell and base at leading edge not welded
18	3:12	3:00	35,700	27,100	1275	1450	.022	2	(b)	(b)	Braze I	Braze I	1	B	1 1/2	
Modification 4: Extension of shell into blade base																
19	12:45	12:15	35,200	26,900	1275	1450	0.020	2	(b)	(b)	Braze II	Braze II	2	B	1/4	Test discontinued after 53 hr
20	25:57	24:17						1	---	---			5		1/8	
21	55:40	53:00						1	---	---			4		---	
Modification 5: Platform at leading and trailing edges and supporting fin at leading edge																
22	52:10	50:00	33,300	26,000	1275	1450	0.020	1	---	(b)	Braze II	Braze II	1	B	---	Test discontinued after 50 hr
23	59:16	56:01	33,300	26,000	1275	1450	.020	1	---	(b)	Braze II	Braze II	1	B	---	Test discontinued after 66 hr
Modification 6: Cast leading and trailing edges																
24	18:52	18:08	34,800	26,600	1275	1450	0.020	2	(c)	(c)	Braze II	Braze II	2	B	---	Shell failure Test discontinued after 54 hr; crack in shell observed after testing Test discontinued after 54 hr
25	56:53	54:12													---	
26	56:53	54:12													---	

^aTack-welded at three span positions, then brazed along entire length.

^bHelic-welded along entire length.

^cIntegrally cast with strut.

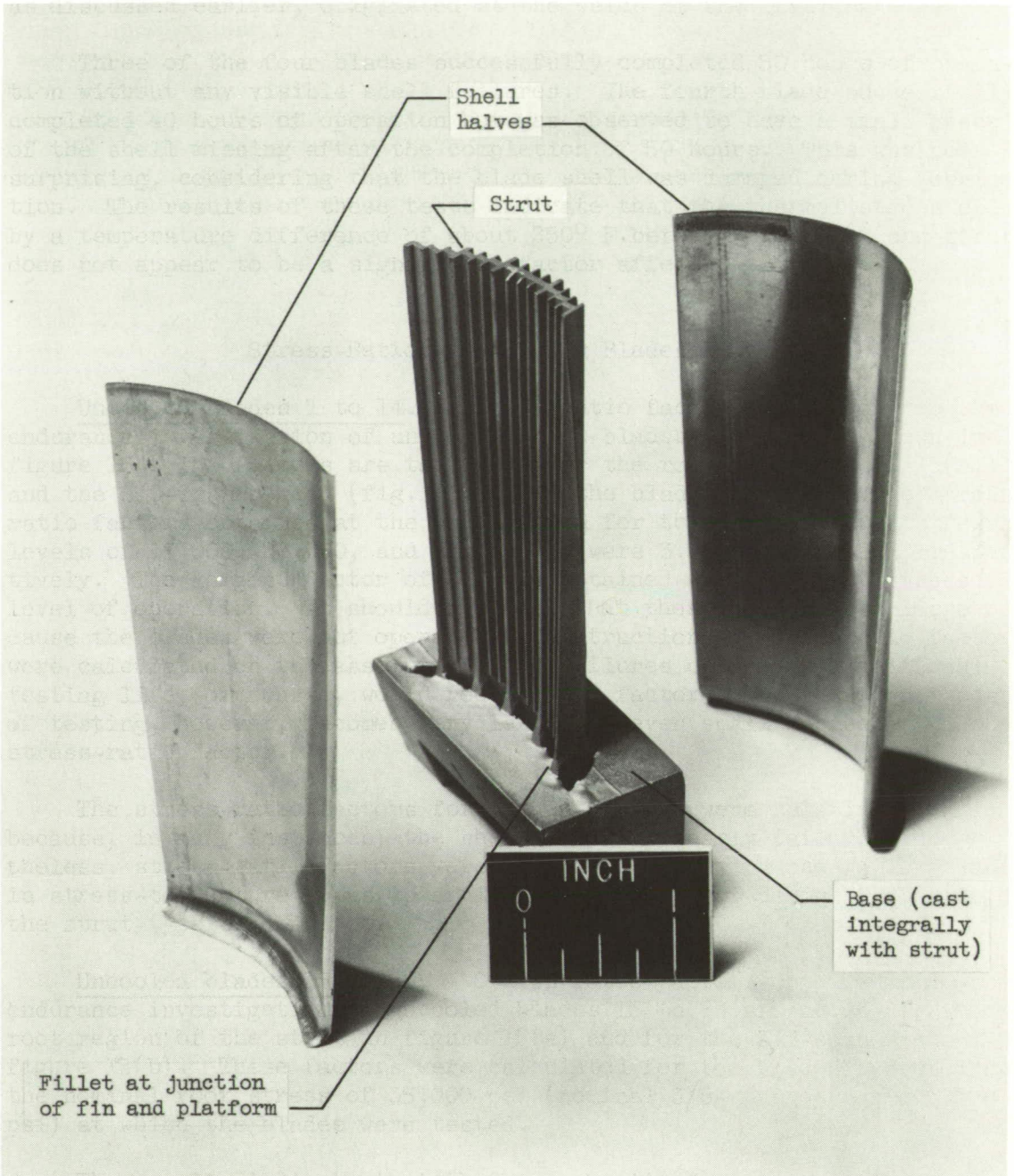


Figure 1. - Strut-blade components.

C-39627

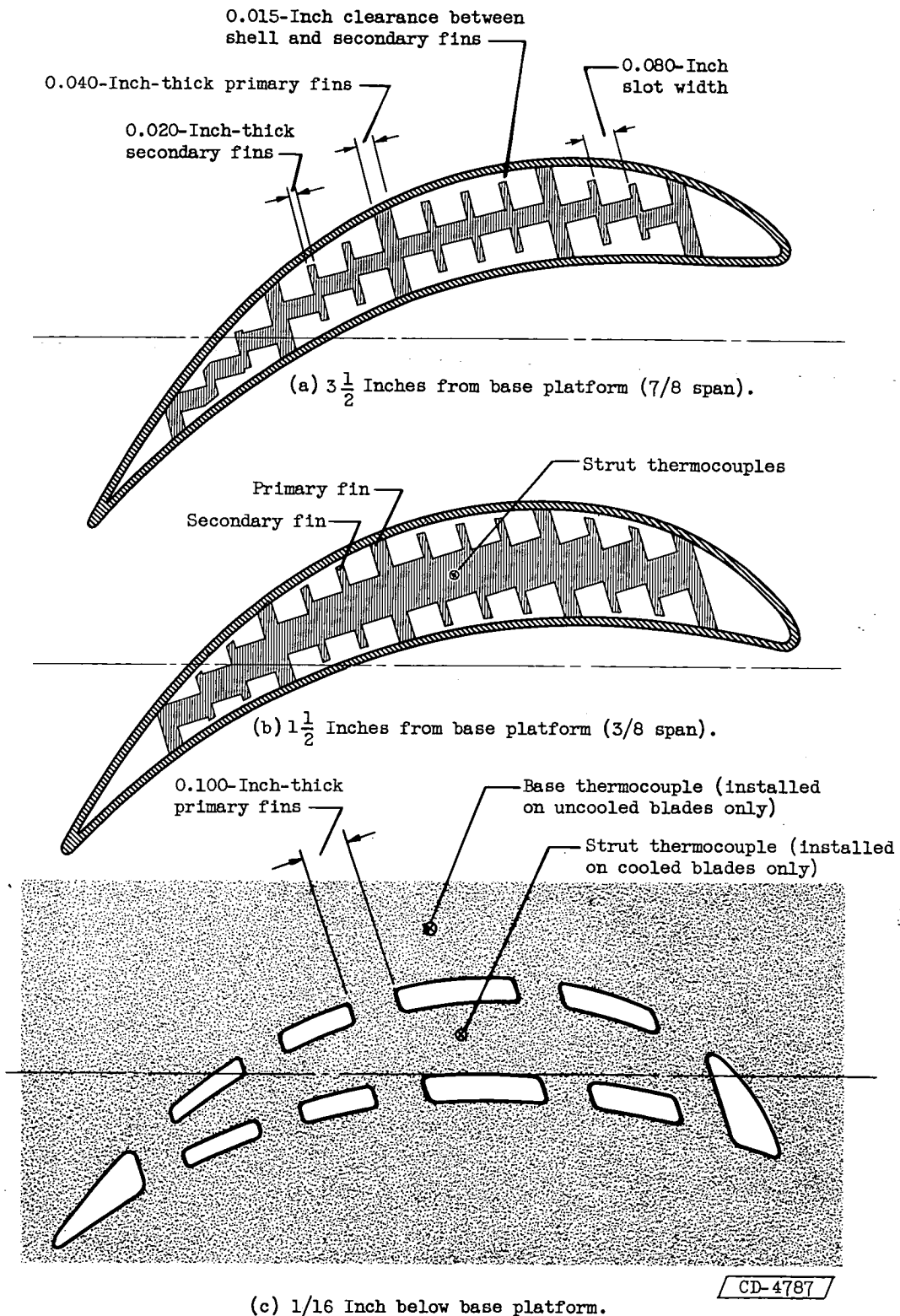
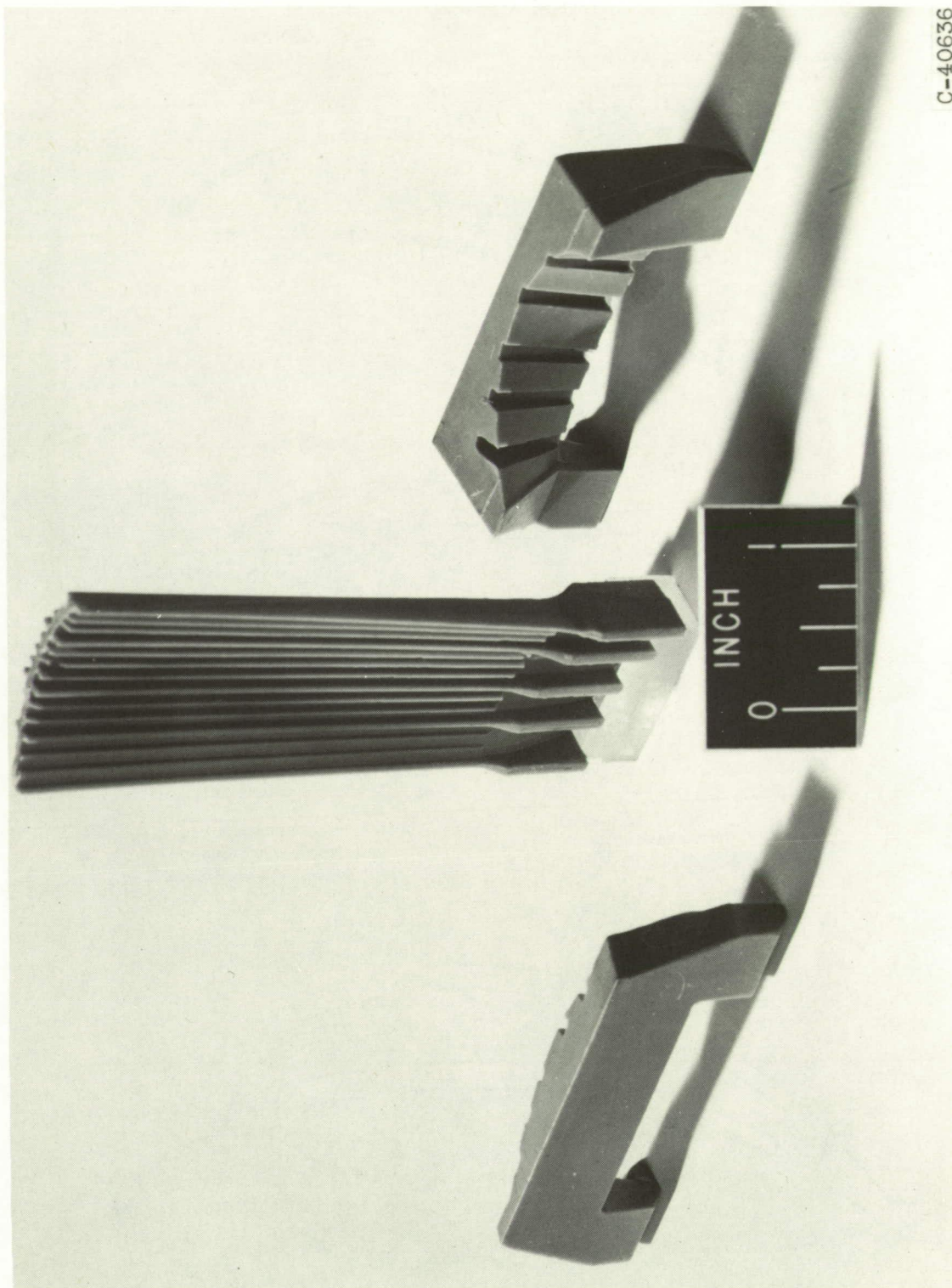
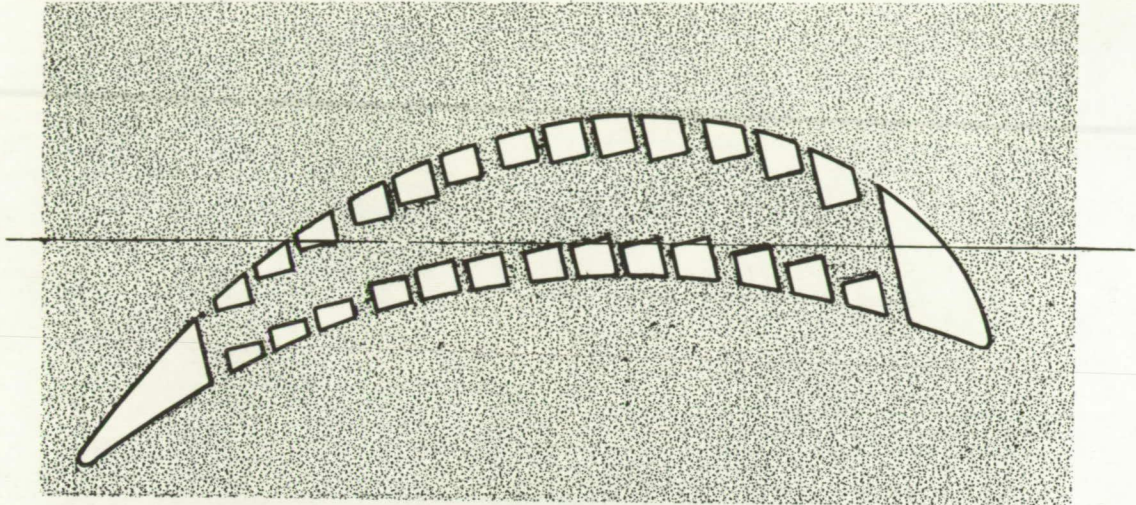


Figure 2. - Cross sections of blade at various spanwise locations, showing locations of thermocouples.

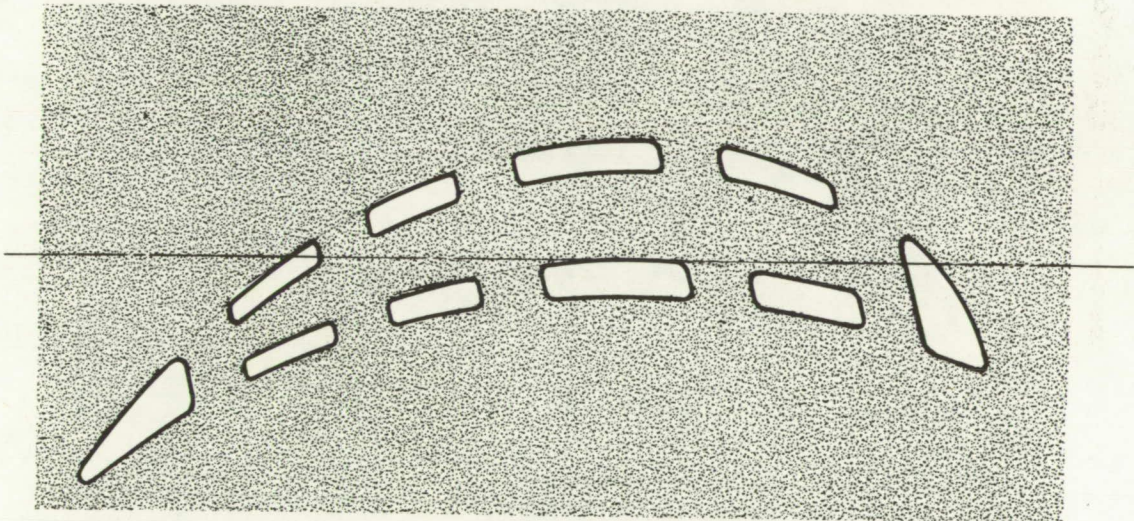


C-40636

Figure 3. - Wax patterns of strut and two-piece base, prior to joining into integral wax structure for casting.



(a) Primary and secondary fins extending into base.



(b) Only primary fins extending into base.

CD-4786

Figure 4. - Comparison of blade cross sections at base (1/16 in. below platform) before and after modification required to eliminate casting difficulty.

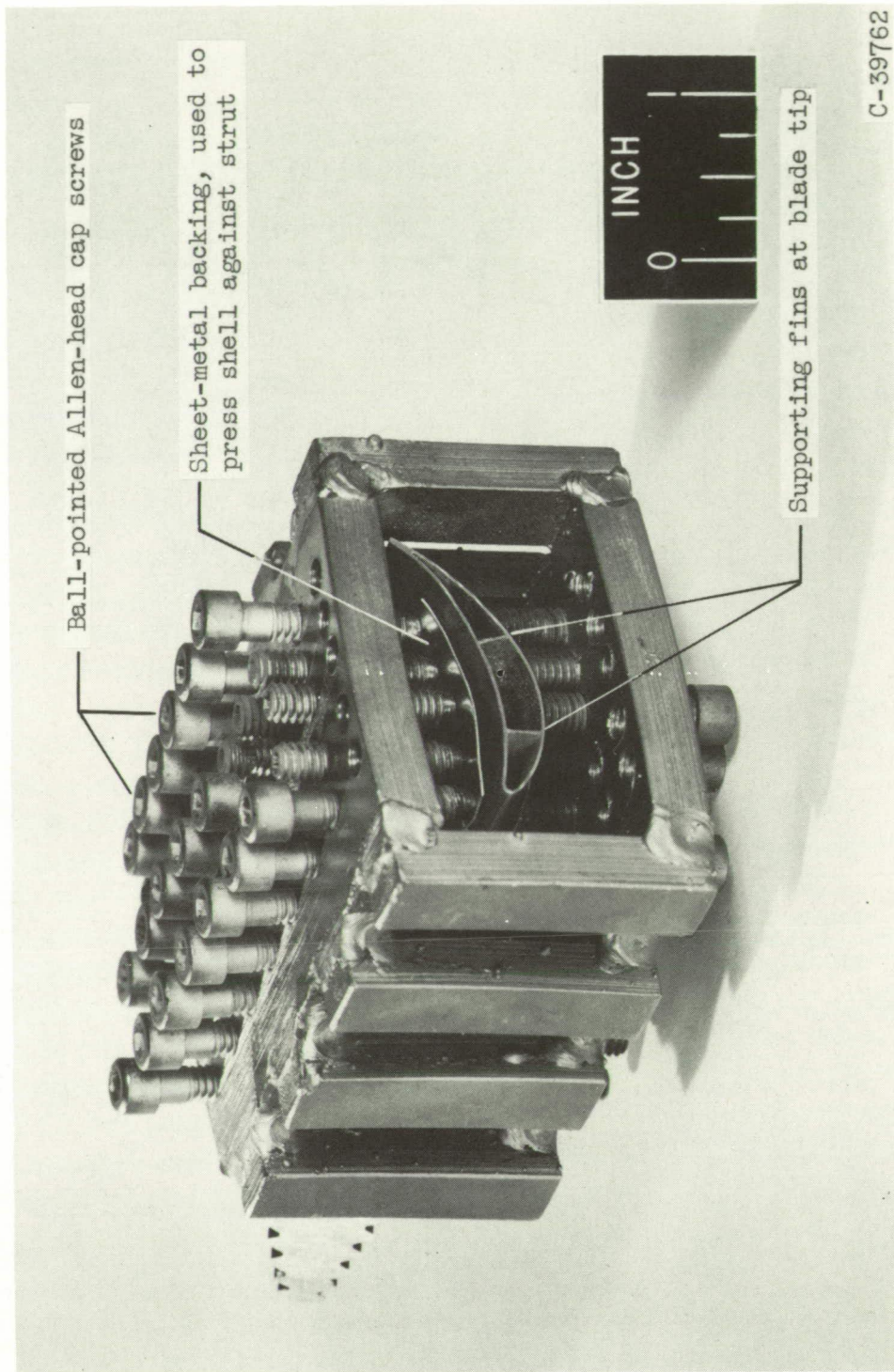


Figure 5. - Strut blade inserted in brazing fixture.

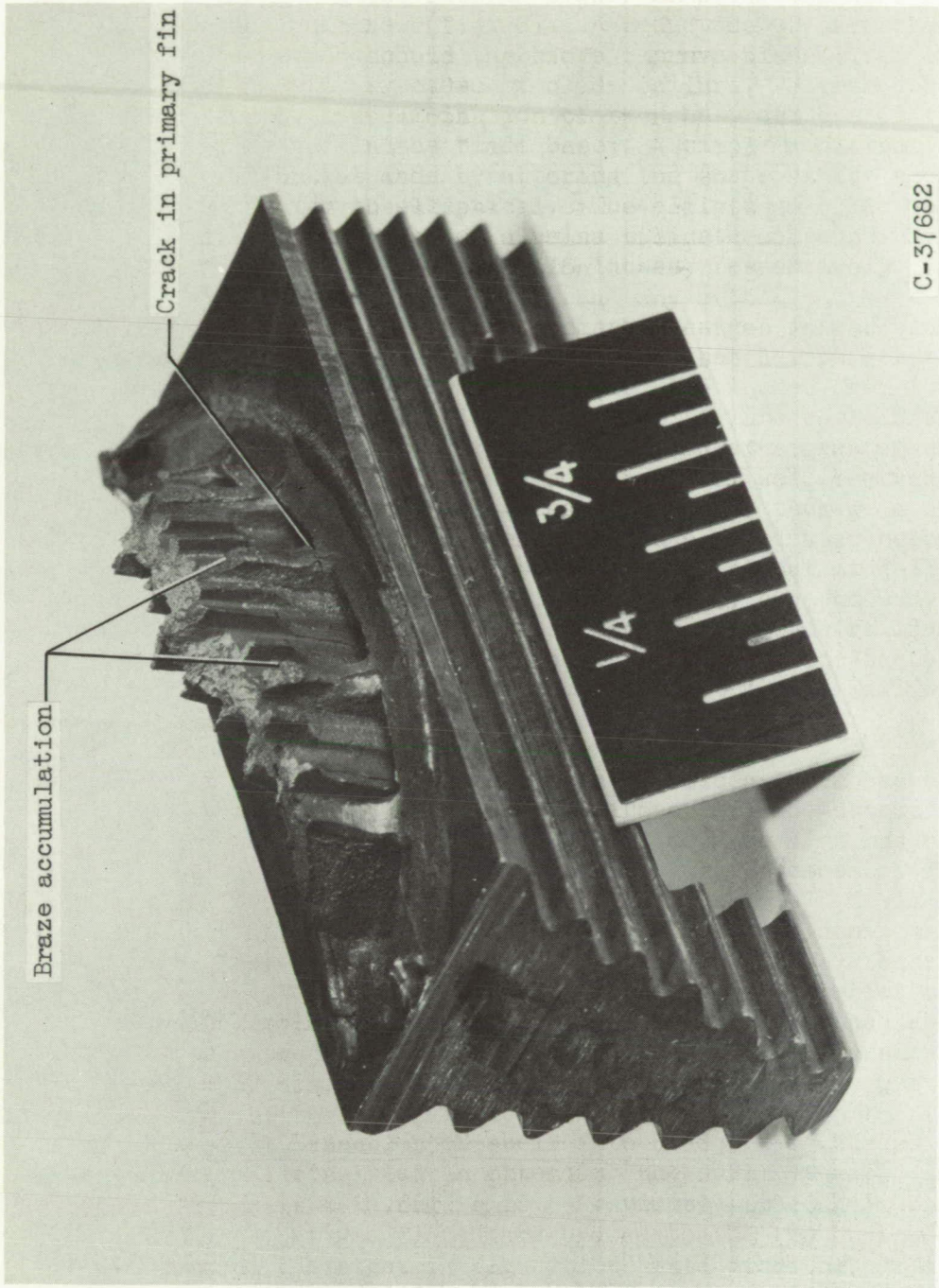
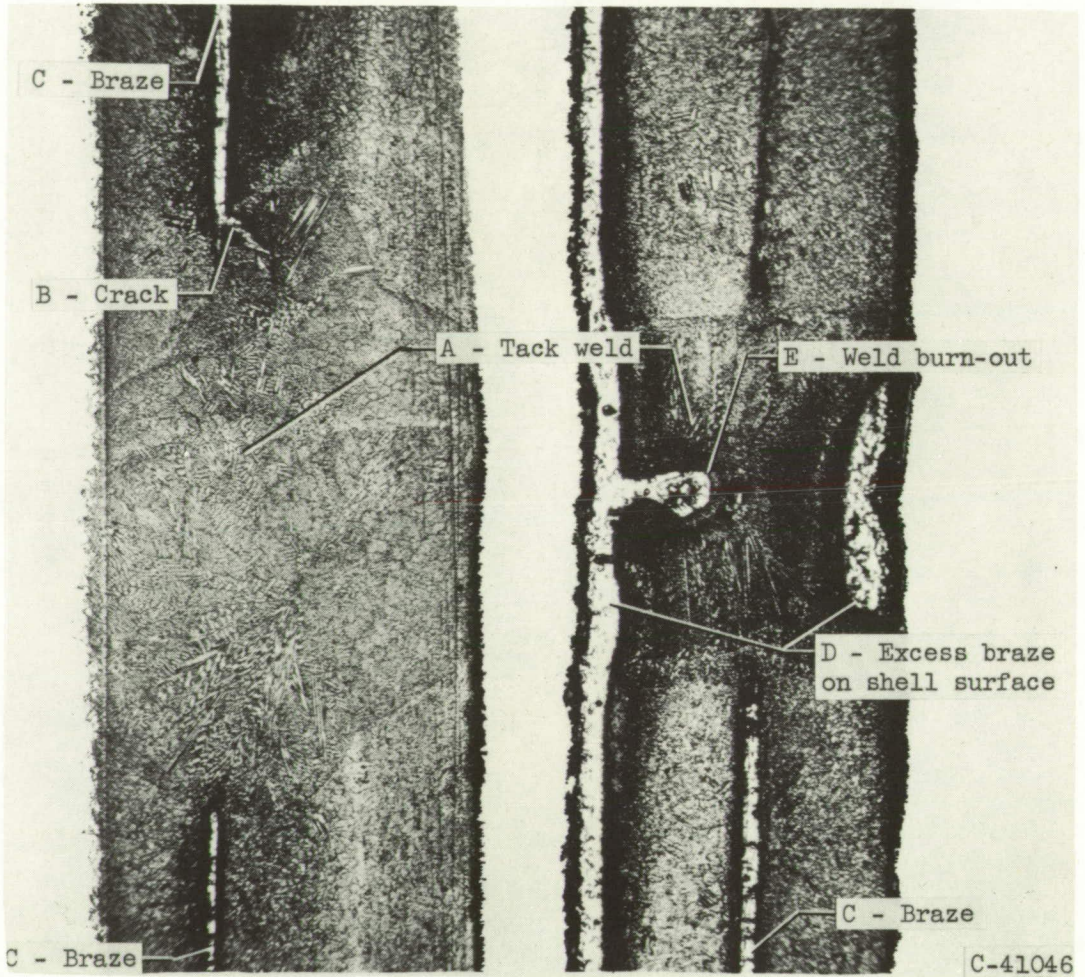
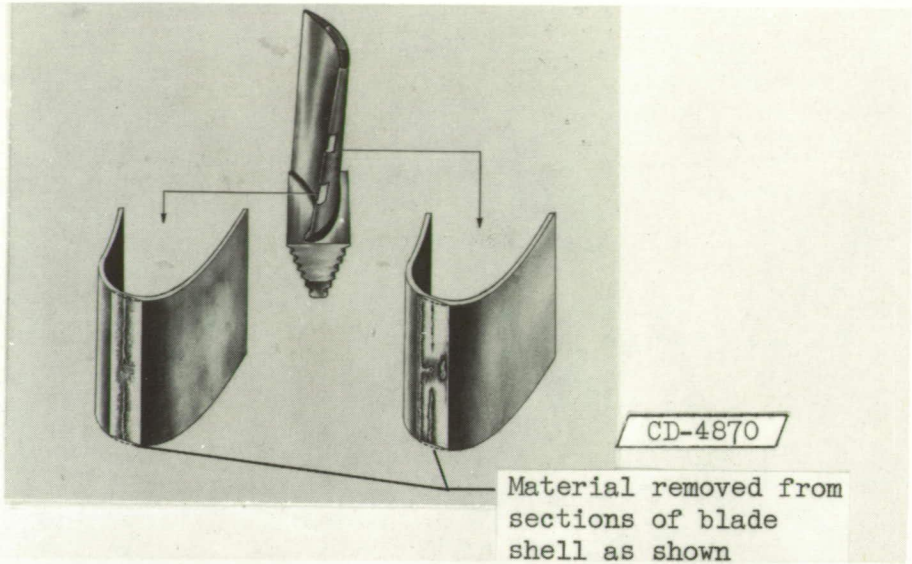


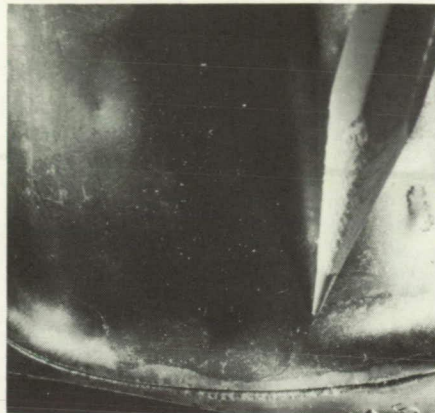
Figure 6. - Typical blade failure (blade 5).



(a) Lower tack weld.

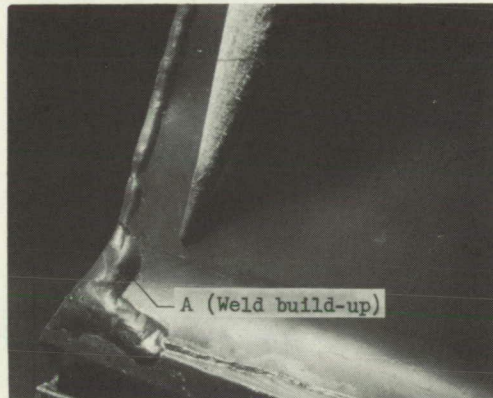
(b) Upper tack weld.

Figure 7. - Photomicrograph (30X) of tack-welded region on shell leading edge.



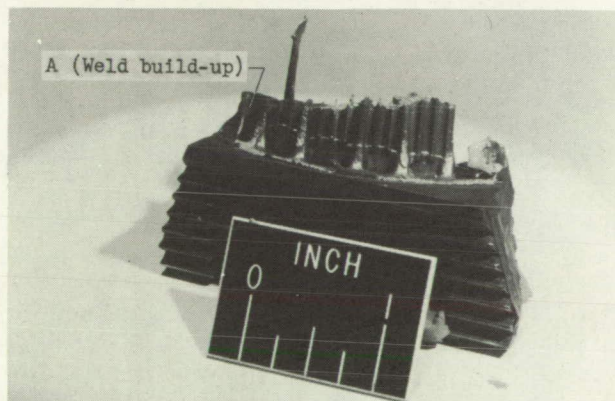
C-38463

(a) Midchord crack in fillet region of shell on suction surface of blade 12 after 12 hours of operation.



C-38649

(b) Trailing-edge crack in fillet region of shell after 22 hours of operation.



C-39431

(c) Strut and shell failure after 47 hours of operation.

Figure 8. - Failure of blade 12.

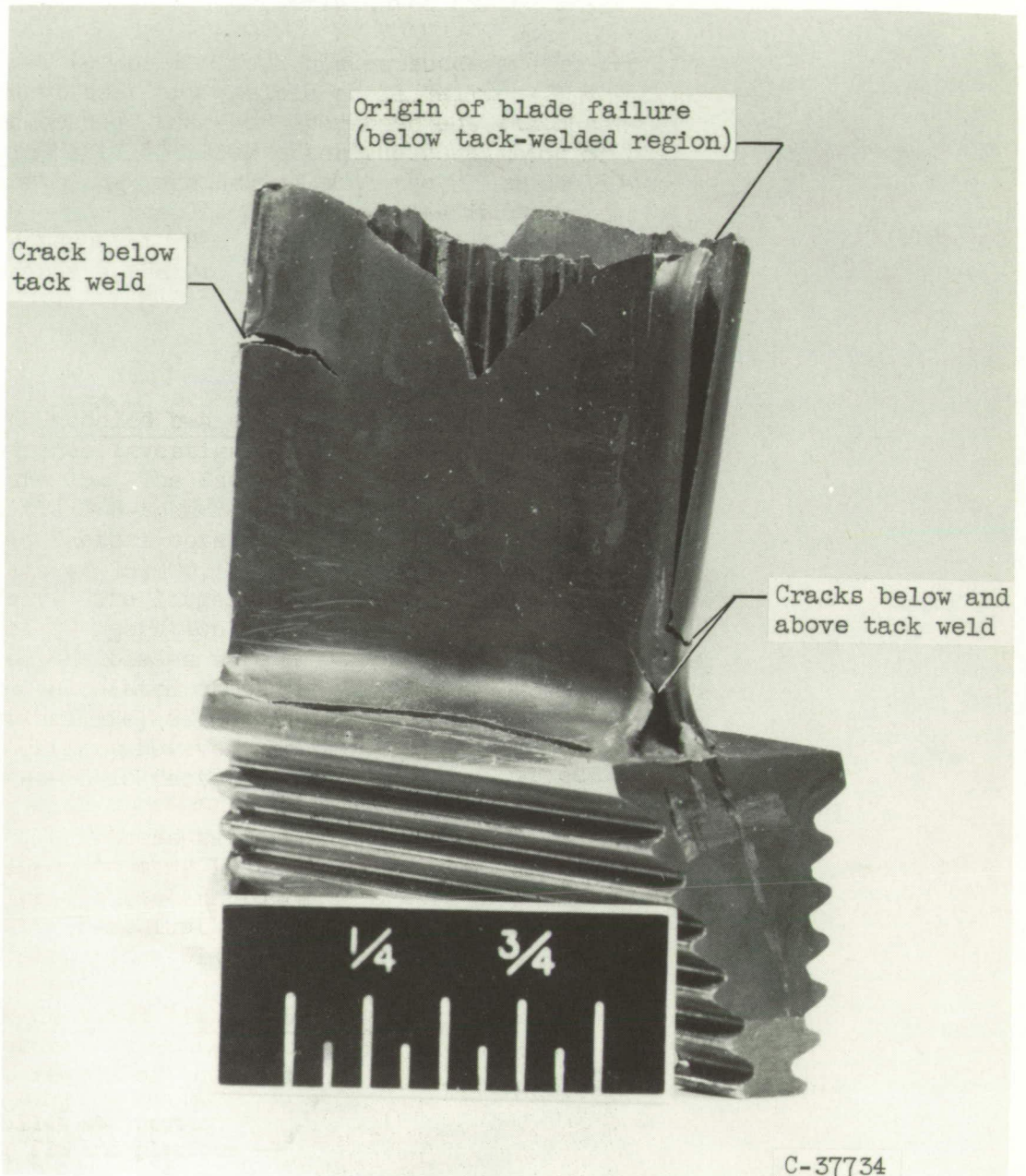


Figure 9. - Failure of blade 18 (modification 3) after 3 hours of operation.

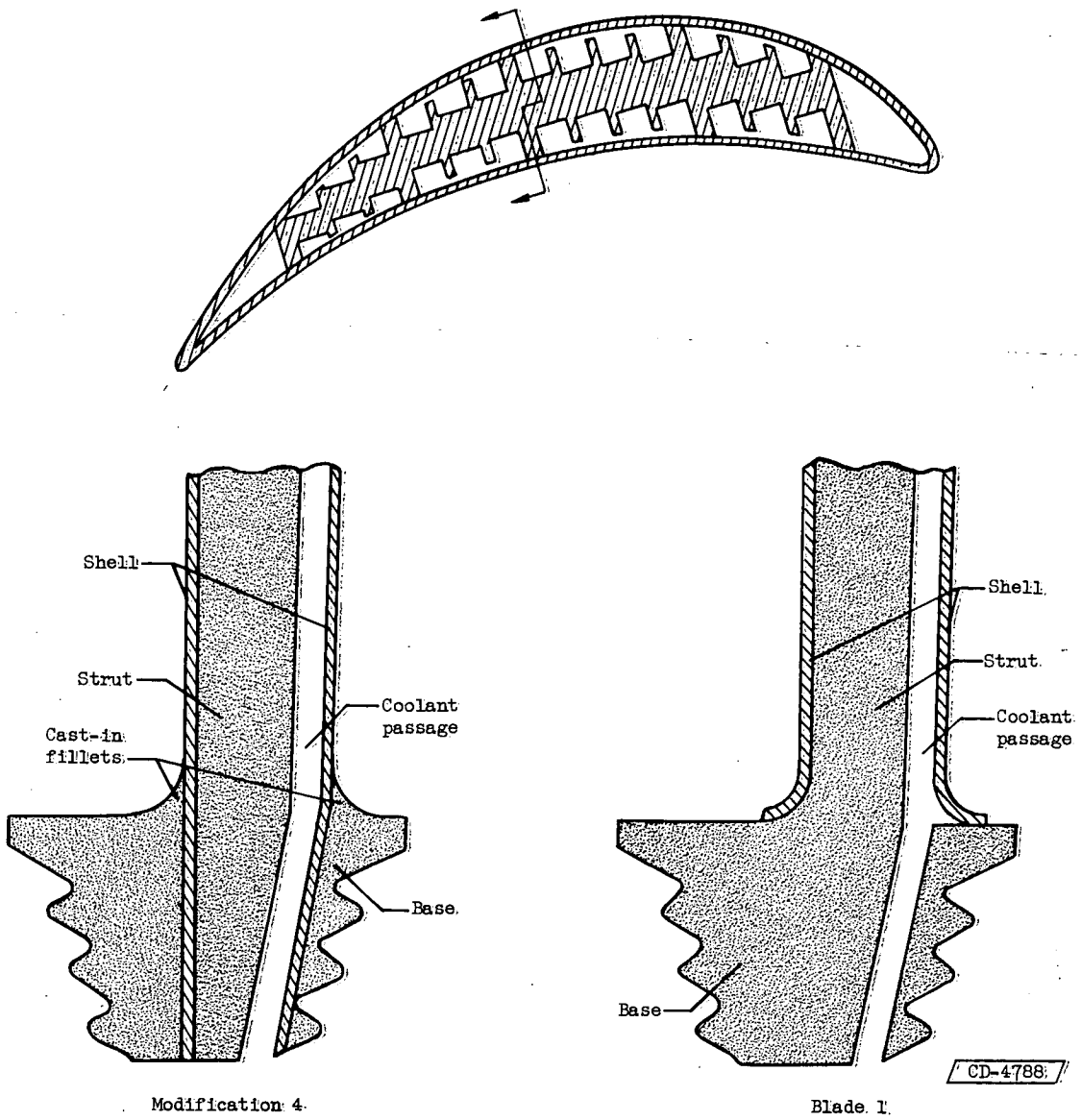
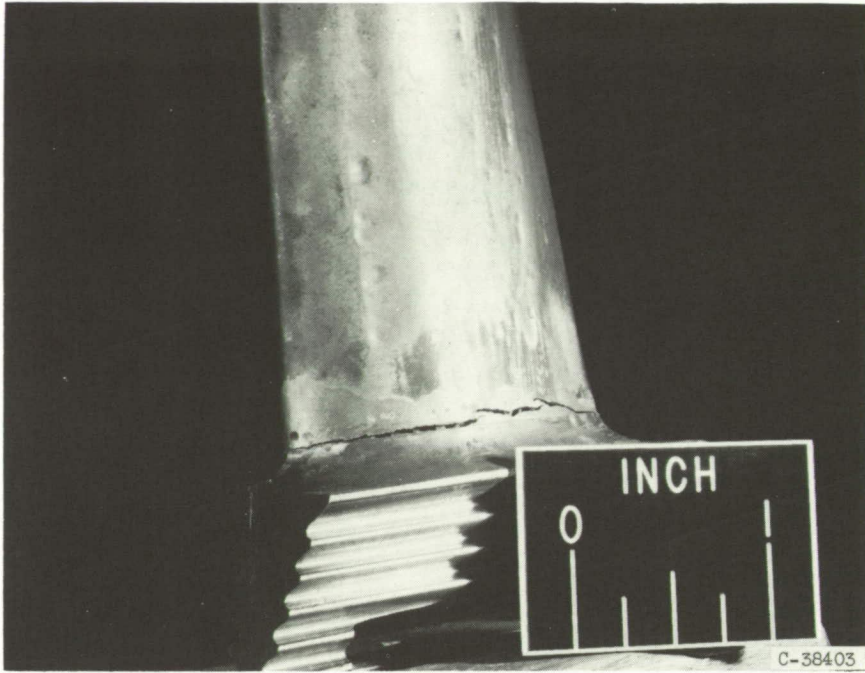


Figure 10. - Comparison of modification 4. (extension of shell into base) with blade 1.



(a) Blade 19, shell failure after 12 hours of operation.



(b) Blade 20, failure after 24 hours.

Figure 11. - Failures of blades with modification 4.

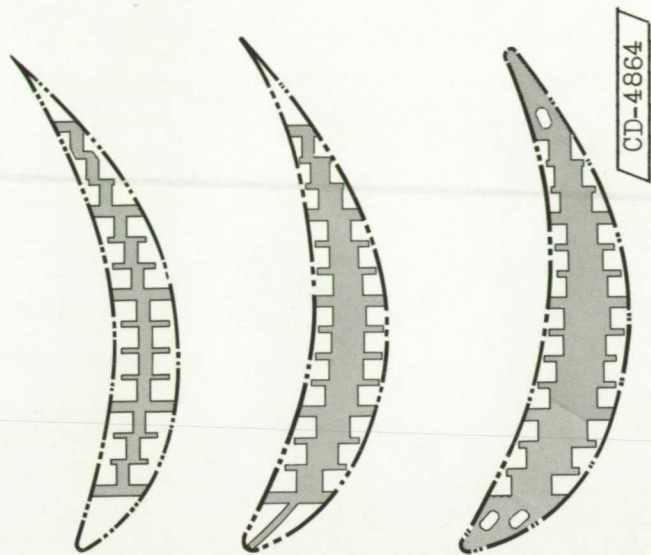
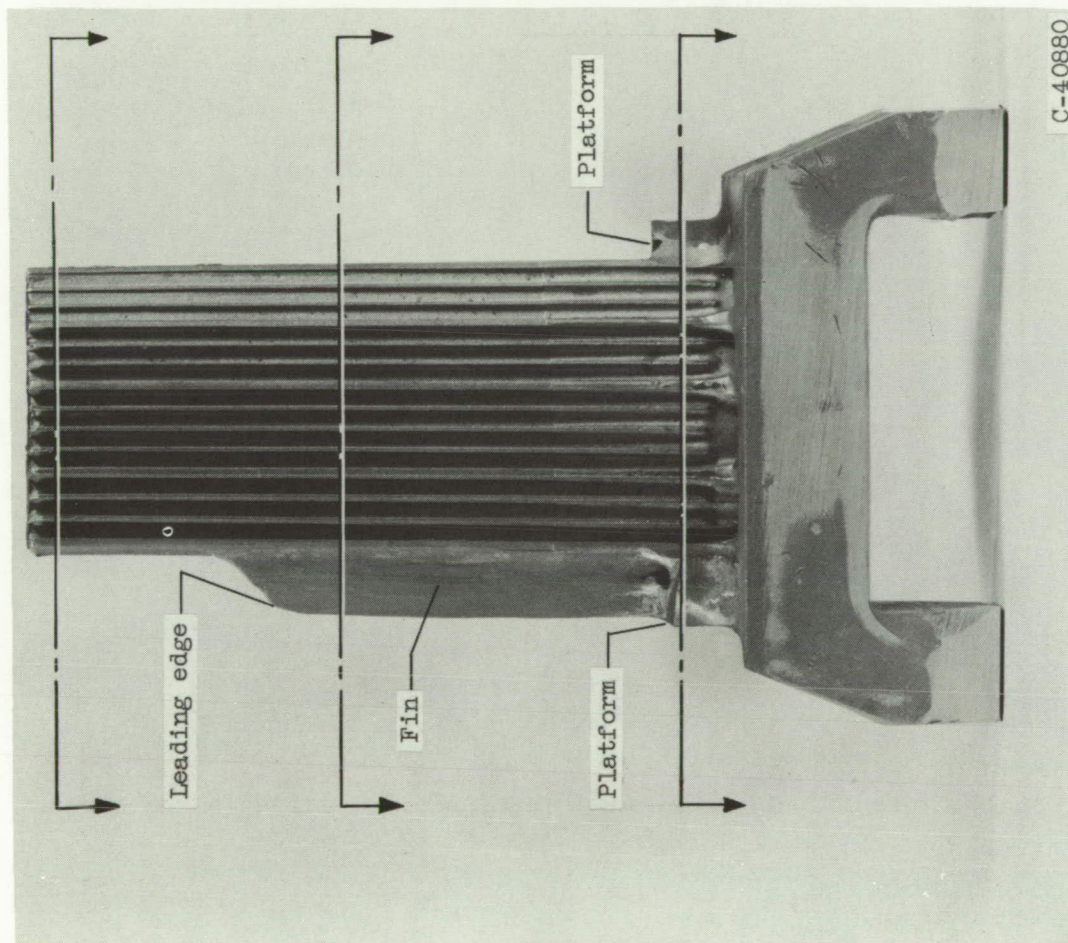


Figure 12. - Modification 5: Platform at strut leading and trailing edges and supporting fin.

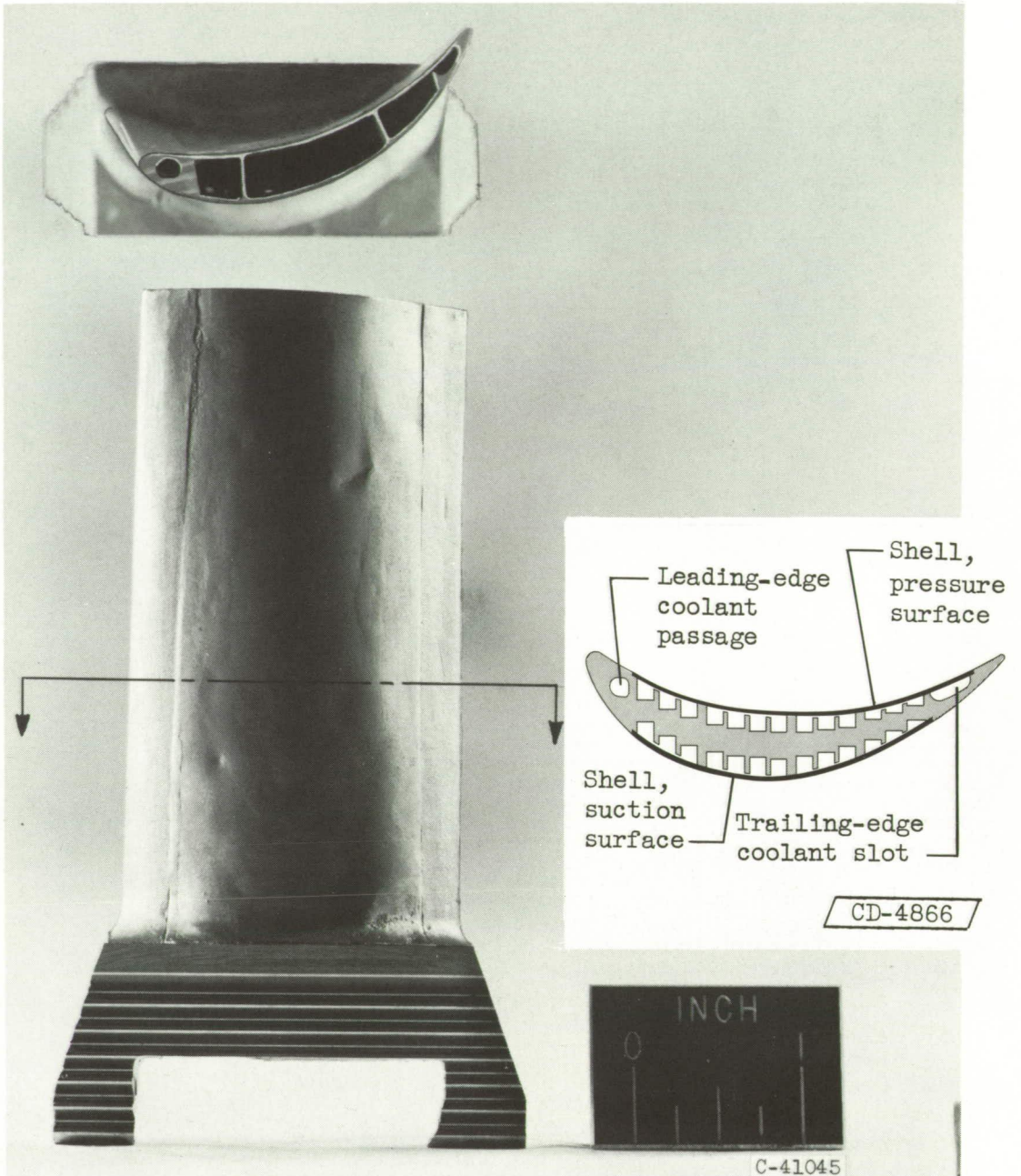


Figure 13. - Modification 6: Cast leading and trailing blade edges.



Figure 14. - Shell failure of blade 24 (modification 6) after 18 hours of operation.

Blades	Nominal root stress level, psi	← Denotes that failure at span location did not occur Numbers beside blocks refer to blade numbers Stress-ratio factor 1 2 3 4
1 to 14	15,000	←□13 ←□14
1 to 14	27,000	□10 □11 □12
1 to 14	35,000	3 ←□01 □07 □04 □02 □05 □06 □08 □09
Modification (blades 15 to 26):	1 35,000	□15
	2 30,000	□16
	3 35,000	□17 ←□18
	4 35,000	20□19 □21
	5 33,000	←□22 ←□23
	6 35,000	25 ←□24 ←□26

(a) Factors at blade root.

Figure 15. - Stress-ratio factors for blades 1 to 14 and for blades having modifications (blades 15 to 26).

Blades	Nominal 3/8-span stress level, psi	← Denotes that failures at span location did not occur Numbers beside blocks refer to blade numbers Stress-ratio factor 1 2 3 4
	12,000	←□13 ←□14
1 to 14	20,000	←□10 ←□11 ←□12
	27,000	3←□1 ←□4←□2 ←□7 ←□6 ←□5 ←□9 ←□8
Modification (blades 15 to 26):	1 26,000	←□15
	2 27,000	←□16
	3 27,000	←□17 □18
	4 27,000	20←□□19 ←□21
	5 26,000	←□22 ←□23
	6 27,000	25←□ ←□24 ←□26

(b) Factors at 3/8 blade span.

Figure 15. - Concluded. Stress-ratio factors for blades 1 to 14 and for blades having modifications (blades 15 to 26).