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EVALUATION OF TRANSPIRATION-COOLED TURBINE BLADES WITH SHELLS OF "POROLOY" WIRE CLOTH

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SUMMARY

An experimental investigation was made to evaluate the durability and permeability of a group of transpiration-cooled, strut-supported turbine blades. The porous shells were formed from a woven-wire material. The blades were fabricated by a contractor for the Bureau of Aeronautics.

The results of permeability tests indicated that the shell material exhibited large random variations in local permeability, which result in excessive coolant flows and very nonuniform cooling. For this reason no heat-transfer evaluations were made because any results would have been inconclusive.

Four blades were investigated for structural soundness in a turbojet engine operating at a turbine-inlet temperature of approximately 1670° F and a turbine tip speed of approximately 1305 feet per second. The maximum temperature of the porous-shell material was approximately 1050° F.

Inspection of the first two blades after 10 minutes of engine operation revealed that the tips of both of the blades had failed. For the second pair of blades, an improved tip cap was provided by the use of built-up weld extending from strut tip to shell. One of these blades was then operated for 33 hours without failure, and was found to be in good condition at the end of this time. The second blade of this second pair failed within the first 10 minutes of operation because of a poor bond between shell and strut lands.

Examination of the shell-to-strut weld attachment by sectioning two other blades revealed that only a very small portion of the shell was properly attached to the strut for either blade.

This rather limited investigation indicated that the shell material may have reasonable potential for application to a transpiration-cooled turbine blade from a structural point of view; however, improved bonding

of the shell to the strut is required. Also, much better control of permeability must be achieved before the material can be seriously considered.

INTRODUCTION

Two general types of materials have been considered for use in shells of transpiration-cooled turbine blades. These are sintered powdered metal (refs. 1 to 3) and woven-wire cloth (refs. 4 and 5). With either type of blade shell an internal strut will be required to serve the dual purpose of supporting the relatively weak porous shell and to compartment the blade in order to meter the air properly to various peripheral locations, as discussed in reference 6. In addition, the permeability must be controlled very carefully if uniform cooling of the blades is to be achieved and if low coolant flow rates are to be obtained. Without proper permeability control the coolant flow requirements may be higher than for the less sophisticated convection-cooled turbine blades. Reference 3 shows that in general random permeability variations should be kept to less than 10 percent.

Design methods for determining required permeability distributions for transpiration-cooled turbine blades are discussed in reference 7. This reference shows ideally that the permeability should vary in a prescribed manner in both chordwise and spanwise directions for greatest economy in cooling. In addition metering orifices are required at the blade base for supplying air at the proper rates to compartments formed by the internal strut. If the ideal permeability distribution cannot be obtained it is possible to utilize shells of constant permeability and to maintain the approximate coolant-flow distribution with the metering orifices, but the coolant flow requirements for this type of blade may be more than three times as great as for the ideal case in order to ensure that no area of the blade shell is overheated.

As a further step in the development of the use of porous wire cloth for transpiration-cooled blades, a cooperative program was initiated between the Bureau of Aeronautics and the NASA Lewis Research Center. The Bureau of Aeronautics placed a contract with a private company to develop methods suitable for mass production of Poroloy porous blade shells and for attachment of these shells to cast supporting struts. The Lewis center supplied the cast bases and integral internal support members of the blades to the contractor for attachment of their porous shells. In addition, the permeability of the blades was specified by the Lewis center using the methods of reference 7. Constant permeability was specified to avoid anticipated difficulties in manufacturing blades with the ideal permeability distribution.

The purpose of this report is to present the results of the Lewis center investigation, which includes permeability measurements on two blades, destructive inspection of two blades to determine the quality of shell to strut attachment, and endurance tests of four blades in a turbojet engine. For the endurance tests the blades were rotated in an engine modified to accommodate several air-cooled turbine blades in an otherwise uncooled turbine at a tip speed of 1305 feet per second (11,500 rpm), a turbine-inlet temperature of approximately 1670° F, and with sufficient cooling airflow to maintain the maximum temperature of the porous shell material at approximately 1050° F.

APPARATUS

Test Blades

The transpiration-cooled turbine blades used in this investigation consisted of woven-wire cloth shells that were attached to supporting struts by resistance welding. The struts of cast S-816 alloy were necessary for two reasons: (1) to provide support for the wire shell and (2) to compartmentalize the volume within the shell in order to control the distribution of cooling air. The following sections summarize the main features of the blades in a rather brief manner.

Strut. - The strut and blade base was an integral precision casting made at the Lewis center by investment casting S-816 alloy material. The strut was designed so that when the porous shell was attached, the outside blade profile coincided with that of the uncooled production blades used in the modified test engine. There were 12 lands or fins on each strut to which the shell was bonded. The width of each land was approximately 0.060 inch. A view of the strut is included in figure 1.

Shell. - The shell was fabricated by the contractor from Haynes Alloy 25 wire with a 0.0031-inch diameter. This wire was used to form shell blanks by winding on a tapered mandrel. The wire was wound on the mandrel under tension and in a certain criss-crossing, overlapping pattern. After a number of layers of wire were wound on the mandrel in this manner, the wire blanks were sintered, removed from the mandrel, rolled, and resintered. The second sintering was followed by a rolling operation, which reduced the wall thickness to a final value of 0.024 to 0.0245 inch. The tubes of porous wire-wound material were then annealed and formed into a preliminary airfoil shape. After a second annealing operation, the porous material was formed into the final airfoil shape. A series of three dies was used in the formation of the airfoil shapes. The permeability of the finished porous material was a function of winding pattern, and the rolling and sintering process. Subsequent forming of the airfoil-shaped blade shell from the original cylindrically shaped tube also changed the permeability. It was through trial-and-error method, in which some or all of the processes were varied, that the desired permeability of the shell material was obtained.

As mentioned in the INTRODUCTION, ideally, the permeability should be systematically varied in both the spanwise and chordwise directions over the blade shell to realize most economical cooling. The difficulty of controlling permeability during fabrication has been inferred in the previous paragraph. It was therefore decided at the outset to simplify the task of the contractor by specifying a constant permeability level over the blade shells. The time of shell fabrication development would thus be shortened.

The shells were attached to the lands on the cast struts by resistance welding. The procedure used consisted of placing the strut and shell assembly between copper die blocks contoured to the specified outer blade profile. The blade and die blocks were then clamped in an electric welding machine and a large current was passed through the assembly. Welding occurred between the shell and the lands on the strut and thus bonded the shell to the strut. Generally, during this welding process, several small holes would appear in the blade shells. These holes were the result of arcing of the electric current. The holes were later filled by the fabricator with a nickel-braze material.

The shells were made to extend approximately 0.150 inch beyond the tip end of the supporting strut. The shell-tip ends were then sealed by compressing this overhang and nickel brazing the joint. The next operation was to weld the base of the shell to the strut by the shielded-arc welding process. The latter process caused shrinkage cracks in the porous shell, which were filled with nickel-braze material. Figure 1 includes a photograph of a typical blade as completed by the fabricator. A total of 12 blades (bearing identification numbers 1 through 12) were shipped to the Lewis center. In the remainder of this report, identification of individual blades will be made by referring to the blade numbers.

Blade serrations. - The blades as received had bases in the rough-cast condition, as shown in figure 1. Base serrations were ground by the Lewis center and special care was exercised to prevent contamination of the permeable shell with grinding dust and cutting oil.

Test Facility

Permeability apparatus. - Measurement of the local shell-permeability variations was accomplished with apparatus similar to that described in reference 2. Briefly, this equipment allowed metering of issuing air for small areas on the airfoil while a constant, measured pressure difference was imposed across the blade shell. The method of sampling the flow of cooling air from small areas was designed to minimize disturbance of issuing air to obtain a fair measure of the local flow (or permeability).

Endurance apparatus. - The transpiration-cooled blades were investigated for durability in a commercial turbojet engine that was modified to accommodate two air-cooled turbine blades. The cooled turbine blades were located 180° apart in the turbine rotor. Cooling air for the blades was provided by an air-supply system that was external to the engine. A detailed description of the engine modification that was necessary to utilize a commercial engine for air-cooled blade studies is given in reference 8. The engine used in the present investigation was essentially the same as that described in reference 8 except that, for the present investigation, an improved method of transferring cooling air from stationary to rotating parts was used. The improved method consisted of the employment of a balanced-pressure sliding seal between the stationary and rotating components of the cooling-air system, such as described in reference 9.

Instrumentation

It would have been desirable to provide a number of thermocouples in the porous blade shell so that shell temperature data could be obtained easily during operation of the test engine. However, the use of any suitable thermocouple system to measure shell temperatures would have required grooves to be made in the porous shell (for examples of thermocouple installations in air-cooled turbine blades see refs. 8 and 10). It was felt that the grooving of the wire shell might possibly weaken the shell to such an extent that erroneous endurance results might be obtained. Also, the permeability of the shell would be affected by the thermocouple installation. As a consequence, only temperature-indicating paints were used for measurement of shell temperatures during engine operation. Light coatings of a type of paint that was color sensitive to temperature were employed. A discussion of the use of temperature-indicating paints can be found in reference 10.

On blades 9 and 10, temperature-indicating paint that changed color (from red-orange to yellow) at a temperature of 1040° F was lightly sprayed over the entire surface of the shell. A brief calibration test to determine whether the presence of the paint would affect the over-all permeability of the shell indicated that there was a decrease of about 20 percent. It was decided to use the paint in spite of this difficulty, since it was important to locate any local hot areas resulting from the variation in local permeability over the surface of the airfoil. In addition, as will be explained in the RESULTS AND DISCUSSION, the measured permeabilities were so variable and so far from the design values that this permeability decrease due to the paint had no significant effects on the results.

PROCEDURE

From the 12 blades with Poroloy shells that were submitted to the Lewis center, a total of six were used for investigative purposes.

Blades 11 and 12 were arbitrarily selected for making investigations of the local permeability in the wire-cloth material. The permeability investigations made herein were not extensive and were made only to obtain some idea of the permeability level and variation within the porous blade shells.

Blades 8, 9, 10, and 11 were chosen for operation in the test engine. The selection of these blades was somewhat arbitrary, but was based partly on a visual inspection of the blade shells. The blades selected were those that seemed to have the fewest repaired areas in the shells. These repaired areas are those that were burned through during the electric welding procedure for attaching the shell to the strut lands, and subsequently were repaired by the use of braze material, as mentioned previously.

The test engine could only accommodate two air-cooled turbine blades at a time. As a consequence the blades were investigated in pairs. Blades 9 and 10 were investigated first and blades 8 and 11 were the second pair tested. Prior to installation in the engine, the airfoil section of each test blade was sprayed lightly with a temperature-indicating paint that exhibited a color change at 1040° F, as explained previously.

The engine operating procedure was as follows: The first time a pair of blades was operated in the engine, cooling air in an amount thought to be somewhat in excess of that required to cool the test blades adequately was supplied to the blades from the external cooling-air-supply system. This cooling air was admitted to the blades prior to starting the engine. After engine start, the desired engine operating conditions were set, which consisted of an engine speed of 11,500 rpm (rated engine speed) and a turbine-inlet temperature of about 1670° F. An engine speed of 11,500 rpm results in a turbine blade tip speed of 1305 feet per second. After 10 minutes of operation at this condition the engine was shut down and the test blades were inspected to determine whether the temperature-indicating paints indicated that any portion of the blade shell was operating above 1040° F. If portions of the blade shell, except the extreme leading- and trailing-edge regions, exhibited temperatures above 1040° F the coolant flow was increased and the process repeated until a suitable coolant flow was established. Once a suitable quantity of cooling air was known, operation of the blades was continued with the established coolant flow. The blades were then operated continuously with the exception of shutdowns required for periodic blade inspections, blade failure, servicing of the test engine, or conclusion of the work day. Whenever an engine start was made, coolant was flowing through the test blades before the engine was operated.

Blades 4 and 12 were cross-sectioned to obtain some insight into the quality of the weld where the shell was attached to the lands of the strut. The cross sectioning was made in a spanwise direction at two chordwise locations after several chordwise sections had been cut from the tip area.

RESULTS AND DISCUSSION

Permeability Investigation

Measurements of shell permeability were made on two of the blades received. The results indicated that the permeability-to-thickness ratio varied randomly from approximately 2.5×10^{-9} to 13.5×10^{-9} inch on blade 11 and from 8.0×10^{-9} to approximately 30×10^{-9} inch on blade 12. A discussion of permeability coefficients is given in reference 3. The permeability-to-thickness ratio desired was a uniform 7.2×10^{-9} inch. The variation of permeability ranged from 300 percent more to 65 percent less than the 7.2×10^{-9} value specified.

Random permeability variations such as these on individual airfoils as well as between airfoils are very undesirable because large variations in local blade wall temperature will result. Reference 3 indicates that in order to keep temperature variations to less than $\pm100^{\circ}$ F for a specified blade temperature of 1000° F, a permeability variation not over ±10 percent for a turbine-inlet temperature of 1600° F can be allowed. The addition of cooling-air orifices to meter air to the various blade compartments will not reduce temperature variations caused by random variation in permeability in a spanwise direction. Orifices would aid in chordwise control, but only where the level of permeability was not already too low.

In addition to large variations in local temperatures, random variations in permeability will also result in unequal air distribution to individual blades. For example, at the same condition of cooling-air pressure difference across the porous shells of the two blades, the measured flow for blade 11 was 105 pounds per hour while for blade 12 the flow was 187 pounds per hour.

Endurance Evaluation

Blades 9 and 10. - After 10 minutes of preliminary operation at rated engine conditions, which was primarily to observe the shell temperature distribution by means of the temperature-sensitive paint, it was discovered that the tips of the shells of both blades had failed (fig. 2). The cause was probably the parting of the brazed junction at the blade tips with the resulting vibration of the unsupported surfaces leading to failure of the shell material.

In order to circumvent this difficulty on subsequent blades, the shell material was cut off even with the tip of the strut and a method of welding the tips closed by bridging from the tip of the strut outward to the wire shell was followed.

Blades 8 and 11. - Operation of blades 8 and 11 for their initial 10-minute period at rated engine conditions revealed that blade 8 had failed but blade 11 appeared to be undamaged. The failure of blade 8 is shown in figure 3. Most of the shell between the base and tip areas of the blade had broken away from the strut lands. Visual inspection of the lands in the areas where the blade shell no longer existed indicated there was little or no bond between the shell and the strut. Inspection of the shell that remained on the blade also revealed that there was poor bonding between the shell and the strut. The porous shell material at the root of the blades was apparently retained primarily by the weld at the blade platform. The shell at the tip was retained by the weld between the shell and strut at the extreme tip of the blade.

Inasmuch as the failure of blade 8 did not damage blade 11, operation of this latter blade was continued successfully for 33 hours, including 10 engine starts. The investigation was arbitrarily stopped at this time. The ratio of cooling-air flow to gas mass flow for blade 11 was maintained at approximately 0.11 for the endurance operation. If the permeability of the blade had been within the design limits, the ratio should have been 0.065. For a blade designed with the ideal permeability distribution, the required coolant flow would be only 0.02 for the conditions of this test. Figure 4 shows the condition of the blade at the conclusion of the tests.

The blackened areas are deposited carbon and a scorching effect that is caused by extended periods of operation on the temperature-indicating paint. The flow of cooling-air remained constant for a given pressure with blade operating time. This indicated that the carbon deposition and other foreign particles that might have been in the cooling-air or combustion gas did not affect the over-all permeability of the blade appreciably.

From this rather limited operation, the investigation of blade 11 seemed to indicate that the shell material may have reasonable potential for application to a transpiration-cooled turbine blade from a structural point of view. However, before the material can be seriously considered for cooled blades, much better control of the local permeability must be achieved and also a more dependable method of attachment of the shell. Variations of permeability, such as mentioned previously, would force overcooling of the whole blade in order to be certain that no small area of the shell exceeded the maximum allowable temperature. Thus, the efficient nature of the cooling method is nullified by the demand for excessive coolant supply.

Investigation of Bonding of Shell to Strut

In view of the manner of failure of blade 8, it was decided that two blades that had not been operated previously should be cross sectioned to examine the bond between the airfoil shell and strut lands. Neither of these blades had well-bonded welds. A typical example was blade 4 shown in figures 5 and 6. The blade was sectioned in a spanwise direction as shown in figure 5. Figure 6 is an enlarged view of the center section in figure 5. Observation of the enlarged area shows no weld contact over the outer four-fifths of the span on either surface of the strut. The shell sections were separated by slight finger pressure to the position shown. The right-hand section in figure 5 is the blade leading-edge region. Again the shell was spread away from the supporting strut to indicate no contact from a point approximately 50 percent span outward. Although it is not clear from the figure, examination of the actual blade indicated only sporadic contact between any of the strut lands and the adjacent shell.

Two primary difficulties arise from lack of good bond between shell and strut: (1) the resultant lack of shell support and (2) less obvious, the defeat of the idea of compartmentalizing the cooling-air-supply volume. Because of the differences of pressure between adjacent compartments, flow between compartments would be altered from that intended, adversely affecting the cooling of the shell.

SUMMARY OF RESULTS

The results of a durability evaluation of representative transpiration-cooled, strut-supported turbine blades having shells fabricated of woven-wire cloth are summarized as follows:

1. The permeability of two blades selected at random was found to vary excessively on individual airfoils as well as between each airfoil. The variation ranged from 300 percent more to 65 percent less than the value specified. A variation of ±10 percent is probably acceptable.

2. The first two blades selected for endurance trials in an operating jet engine, failed at the tips after approximately 10 minutes of operation. These failures appeared to be due to the method of closing the airfoil tip by crimping and brazing the suction and pressure surfaces together.

3. Operation of two more blades (8 and 11) with improved tip welding procedures gave widely differing results. One blade (8) lost most of the porous airfoil within the first 10 minutes of operation. Examination of the surface of the supporting strut indicated lack of satisfactory weld between the shell and the lands of the strut. The second blade (11) operated satisfactorily for 33 hours at rated engine conditions (including 10 engine starts), with a ratio of coolant-to-gas flow of 0.11.

4. The mode of failure of blade 8 suggested further investigation of shell-to-strut weld bonding. Two blades that had not been operated in an engine were sectioned revealing very few satisfactory welds.

5. Tests on one blade indicated that wire-cloth blades would probably be feasible if suitable shell-to-strut attachment methods are developed and if methods of permeability control are developed that are much better than indicated in the blades obtained.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 4, 1958

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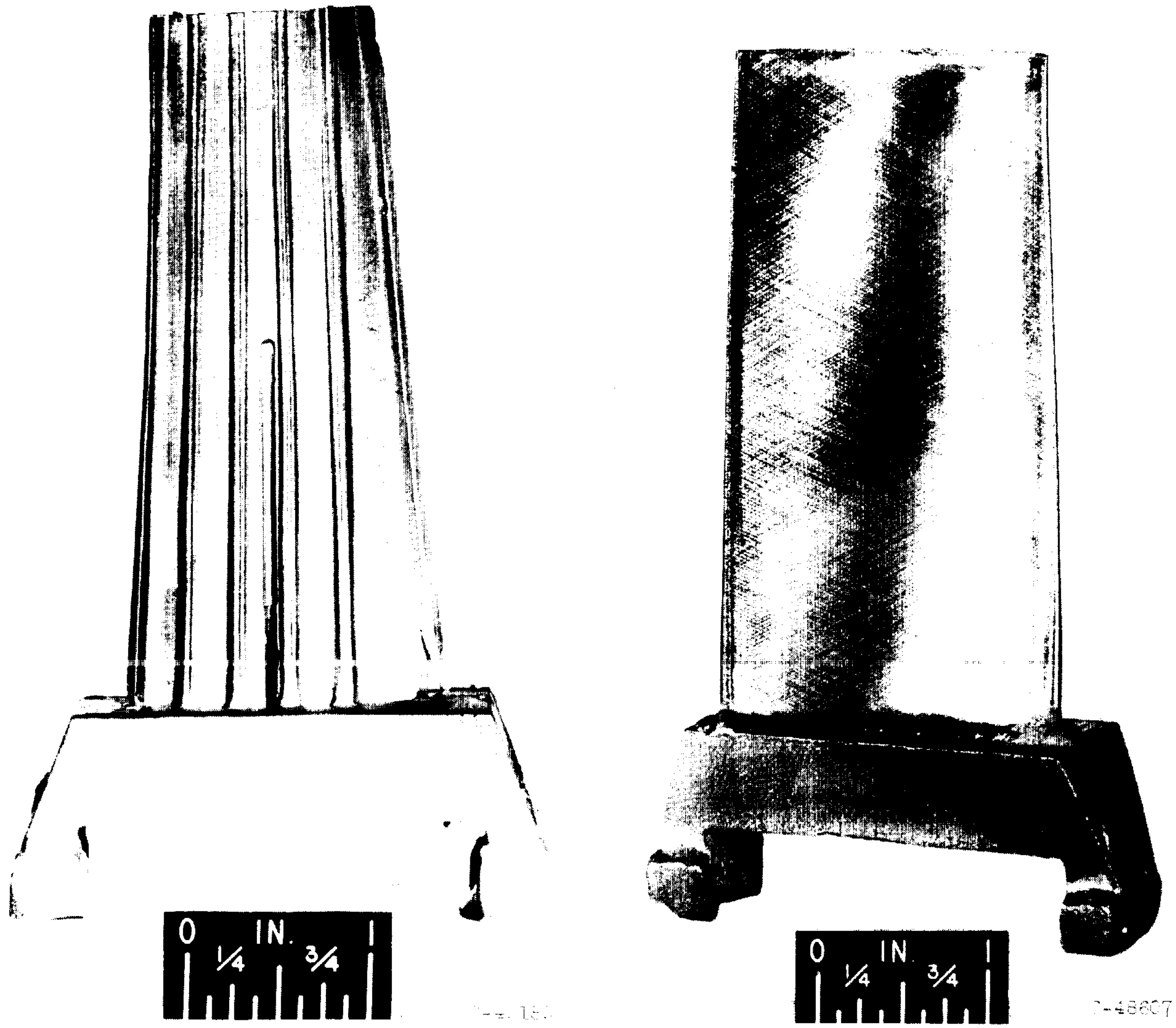


Strut

Turbine blade

Figure 1. - One of 12 transpiration-cooled turbine blades as received from the contractor.

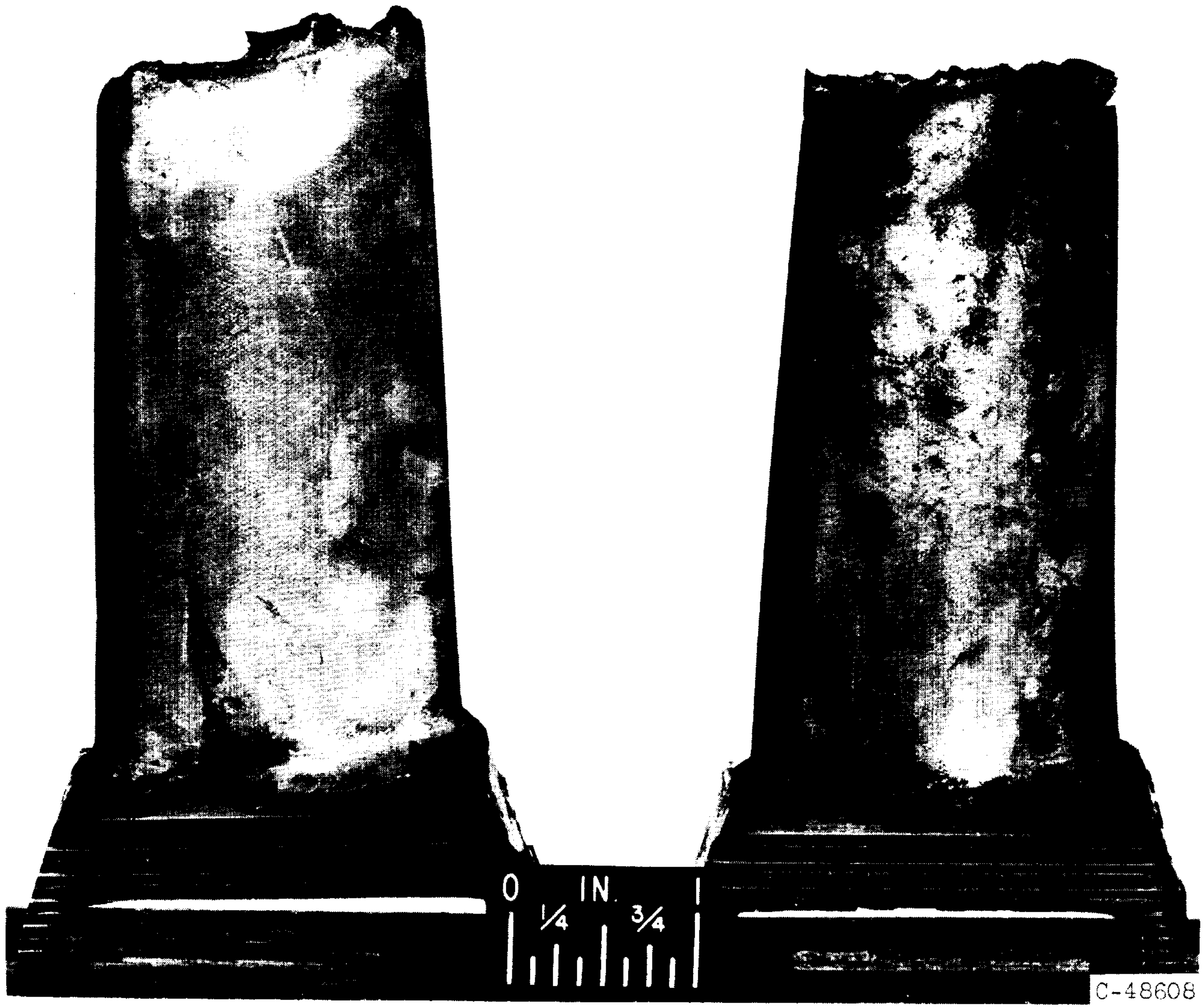
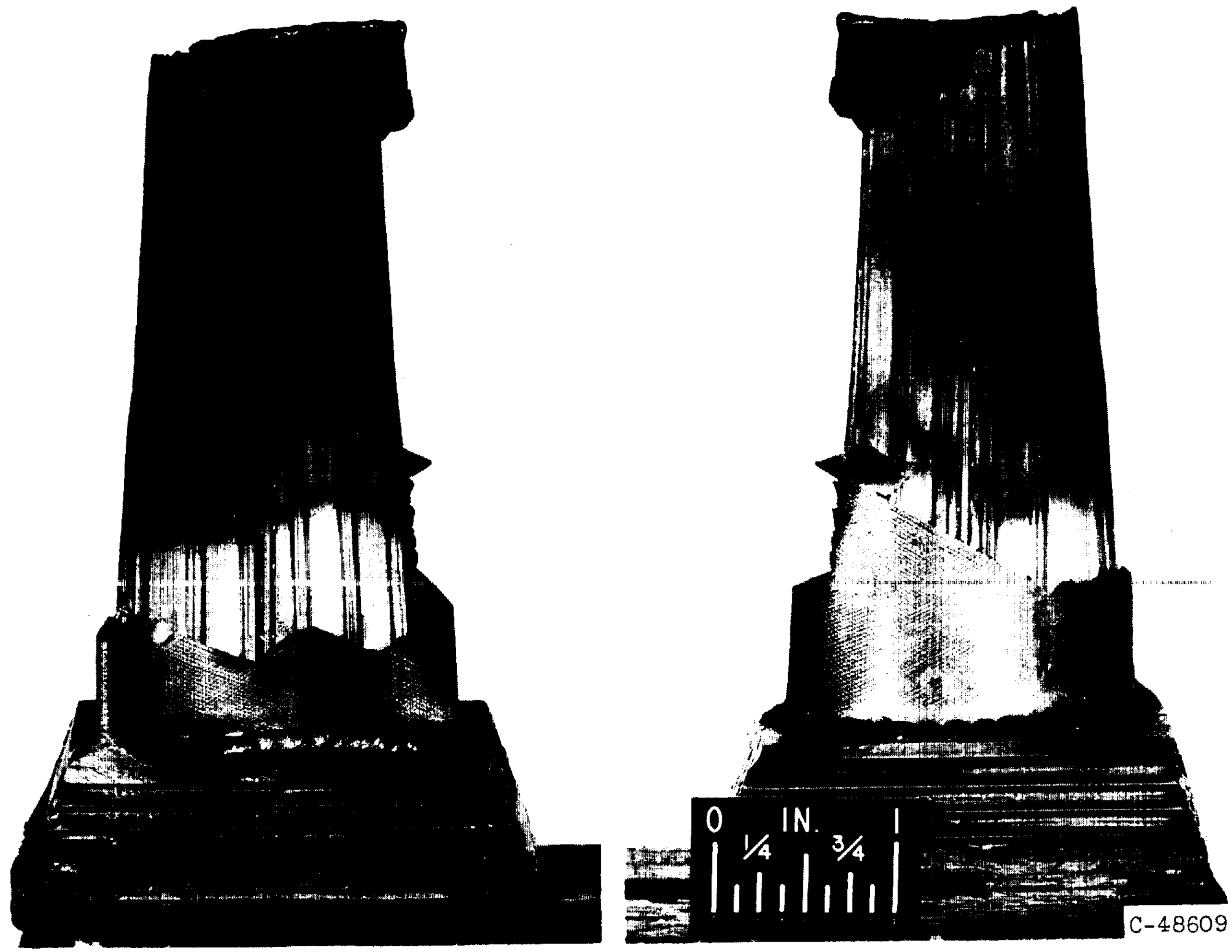


Figure 2. - View of failure of tips of blades 9 and 10 after 10 minutes of engine operation.



Pressure surface

Suction surface

Figure 3. - Failure of blade 8 after 10 minutes due to weld failure.

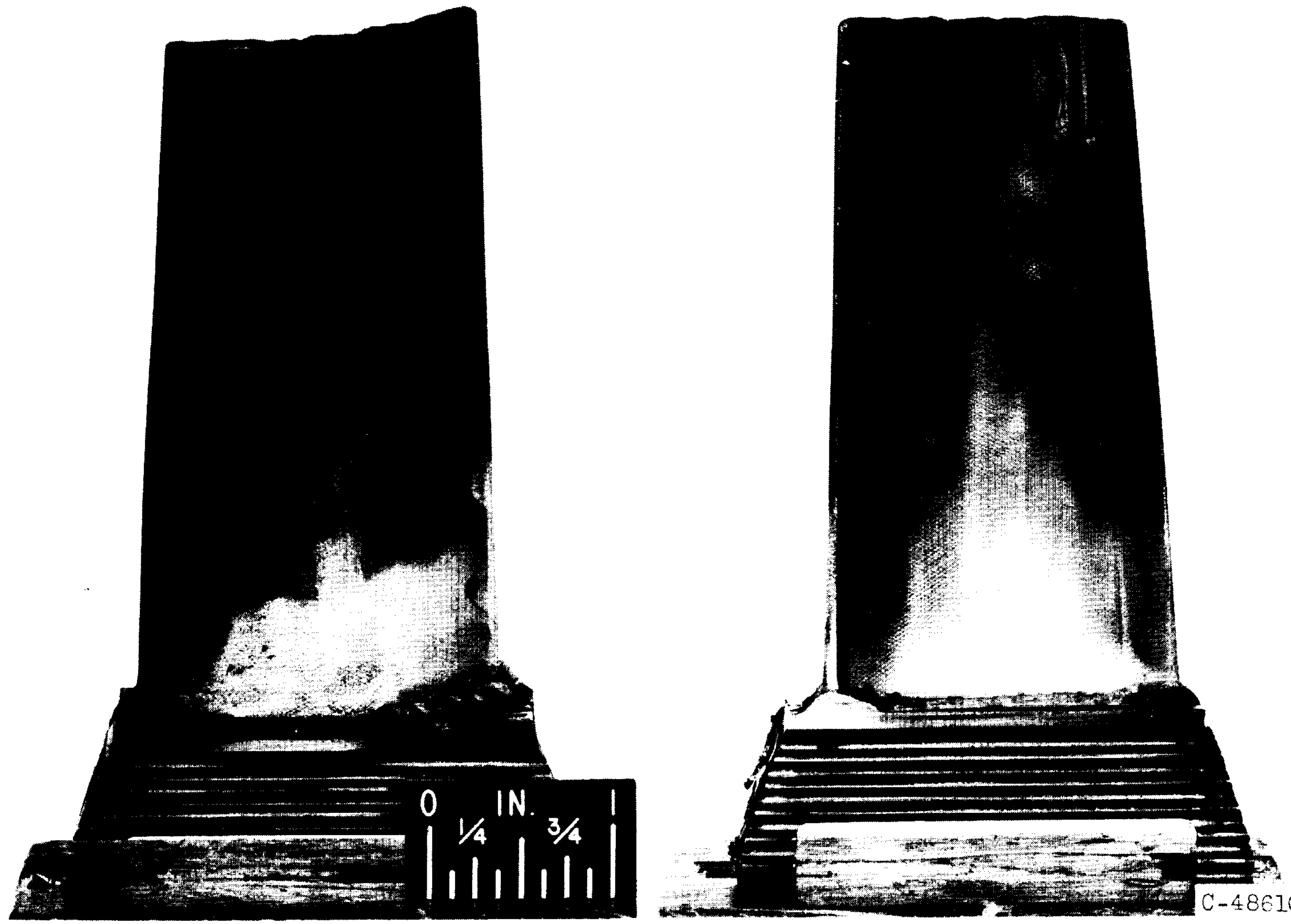


Figure 4. - Blade 11 after 33 hours of engine operation.

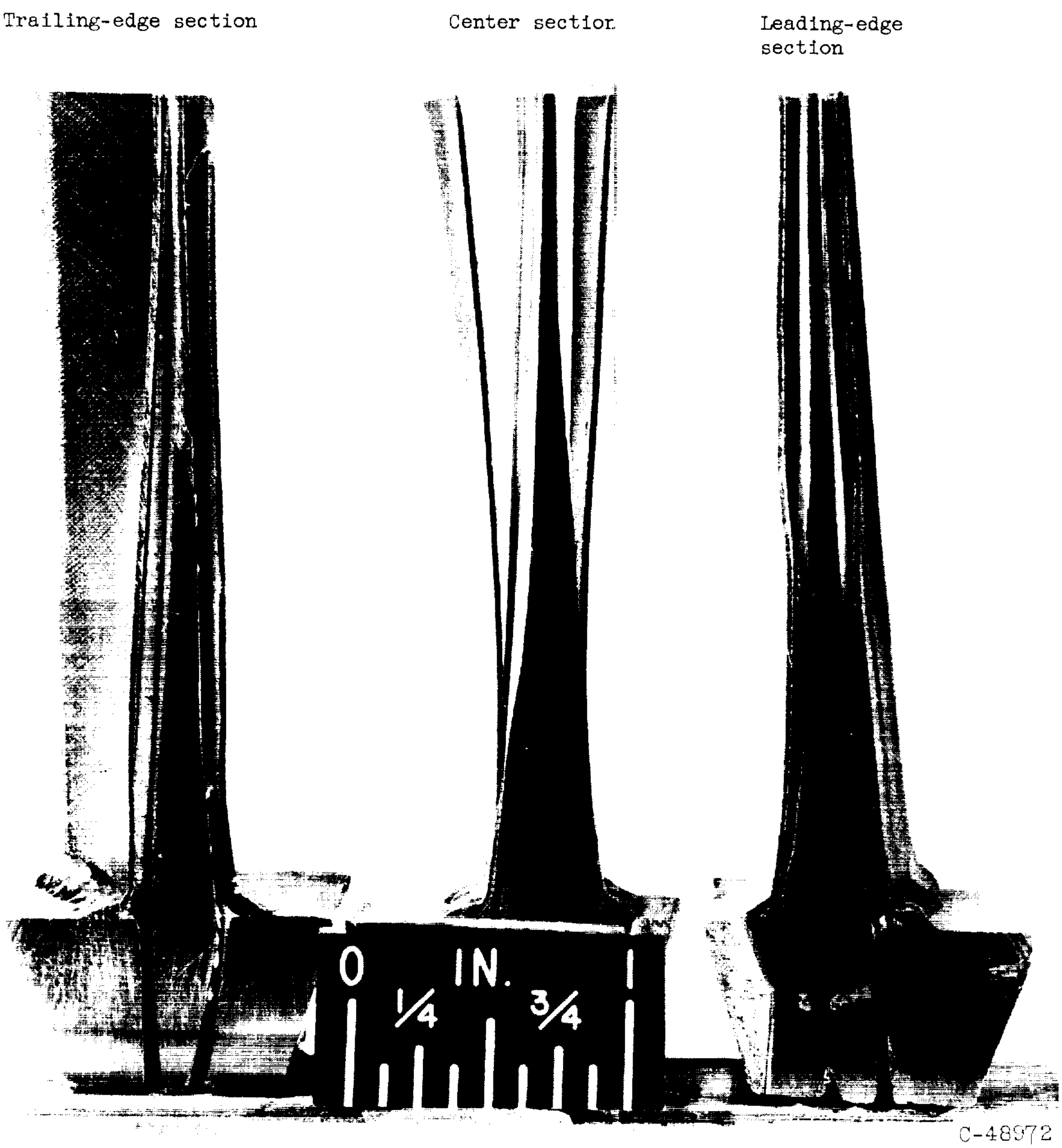


Figure 5. - Blade 4 after being sectioned at two chordwise locations showing the poor shell-to-strut bond.

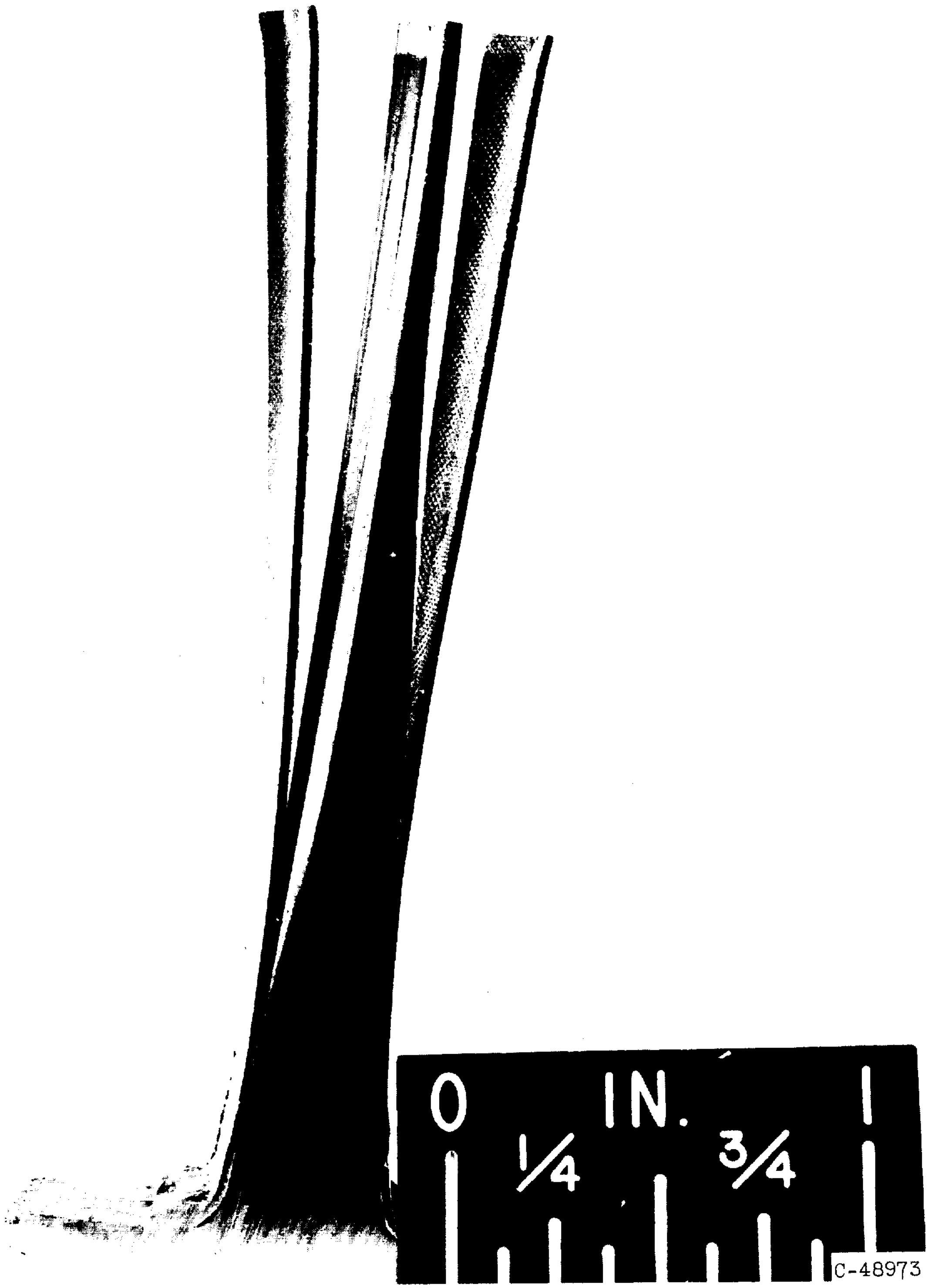


Figure 6. - Enlarged view of the center section of blade 4 indicating lack of bond between shell and strut