Demonstration of a Cooled Laminated Integral Axial Turbine

R. W. Vershure Jr.* and H. R. Fisk†
AiResearch Manufacturing Co. of Arizona, Phoenix, Ariz.
and
J. A. Vonada‡
Wright-Patterson AFB, Dayton, Ohio

A low-cost, high-temperature axial turbine has been developed that demonstrates the feasibility of constructing a small, integral, cooled turbine using photoetched laminates bonded together to form a complete wheel. A turbine design was established utilizing a cooling scheme suitable for operation at 2600°F. The photoetch and bond-process parameters were optimized utilizing small bonding stacks. A full-size wheel blank was bonded, and the laminated wheel mechanical integrity was established by operation in a whirlpit test at 115% design speed.

I. Introduction

IN the past decade, there has been a sharp increase in the demand for small, low-cost, high-performance gas turbine engines in both military applications—such as expendable missiles and RPV's—and various commercial applications. Maximum economic payoff can be achieved by savings realized in the manufacturing process and through the use of high-temperature, high-performance turbines.

In small turbine engines, the major technical manufacturing problem that limits the achievement of high operating temperatures has been the difficulty of producing turbine blades/wheels in either uncooled configurations made of advanced materials or cooled configurations with complex internal cooling passages, without incurring high production costs.

The laminate manufacturing process being developed by AiResearch has the potential for low cost without sacrificing the important performance objective of high cooling effectiveness. This process permits utilization of combined impingement, convective, and film-cooling techniques in small turbines of either radial or axial configurations. The cooled laminated turbine is produced from numerous thin sheet laminates that are bonded together. Complex internal passages are formed from a combination of laminate configurations that are initially photoetched from sheet material. When properly stacked and bonded, the resulting component is finish-machined to the desired aerodynamic and structural contours. The process is applicable to turbine stators, shrouds, and rotors (either axial or radial). Axial rotors can be produced with either integrally cooled blades or inserted blades.

In 1970, the feasibility of producing turbine rotors by the laminate process was verified at AiResearch through the manufacture of a radial inflow turbine rotor from Waspaloy sheet material. This wheel was successfully whirlpit tested at room temperature and speeds up to 70,200 rpm (a tip speed of 1900 fps).

Although the laminate process was proven feasible and possessed many potential benefits, extensive development efforts were required to optimize the photoetching methods, the bonding parameters, and the finish machining procedures before an air-cooled laminated turbine rotor could be manufactured in production quantities.

In 1974, a program was initiated with the United States Air Force, Aero Propulsion Laboratory[1] to extend the feasibility of manufacturing a cooled integral axial turbine rotor using the laminate process. This paper describes the initial design, development, and metallurgical process work that led to the manufacture and testing of the first integral axial turbine, as shown in Fig. 1. A subsequent program with the United States Air Force Materials Laboratory[2] is also described that extends the laminate process for higher temperature turbine applications.

II. Design and Development

Design, development, and manufacturing programs were undertaken to prove the feasibility of manufacturing a small, integrally cooled, axial turbine wheel using the laminate process. The Air Force selected an axial wheel for development with future applications intended for remotely piloted vehicle propulsion (RPV's) with a design life goal of 20 hours. Additional objectives of the program were:

1) Utilize a complex cooling design that will be compatible with operation up to 2600°F.

2) Further develop the photoetching, bonding parameters, and finish machining procedures to permit manufacture of a laminated axial turbine wheel.

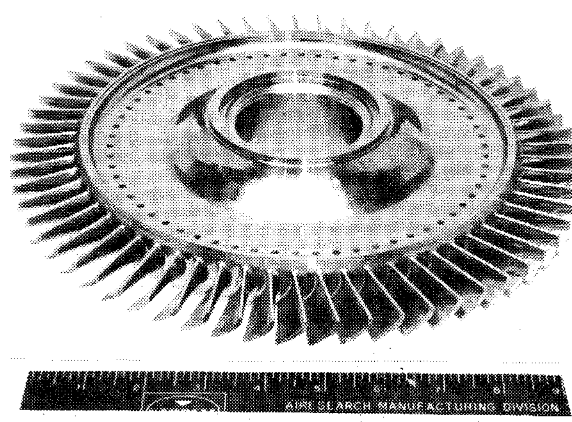


Fig. 1 Fully machined laminated axial turbine wheel.

Received June 20, 1977; presented at Paper 77-949 at the AIAA/SAE 13th Propulsion Conference, Orlando, Fla., July 11-13, 1977; revision received June 30, 1978.

Index categories: Powerplant Design; Airbreathing Propulsion; Materials, Properties of.

*Development Specialist, Advanced Technology Propulsion Engines.

†Supervisor, Manufacturing Process Technology.

‡Captain, USAFPL/TBC.

3) Design and manufacture a laminated turbine wheel using the developed process.

4) Evaluate the bond-joint characteristics and the wheel material properties for several candidate nickel-base sheet materials.

5) Compare the manufacturing cost of the integral wheel produced by the laminate process to a conventional inserted-blade configuration.

6) Demonstrate the wheel mechanical integrity utilizing overspeed test procedures.

Baseline Turbine Wheel Design

The baseline axial-flow turbine design chosen for the demonstration program was the Model TFE731-3 engine high-pressure turbine rotor. This is a conventional design consisting of 62 separately cast air-cooled blades attached to a forged disk. The blades are quite small (1.3 in. span, 0.8 in. chord, and 0.025 in. trailing-edge thickness). The rotor is 11.13 in. in diameter and has a design speed of 29,692 rpm. The high-pressure rotor and secondary cooling system are illustrated in Fig. 2. Blade cooling air is introduced to the rotor by inlet orifices at each blade shank. The front seal plate provides for axial retention of the blades and forms a pumping cavity for the cooling air to the blade shank. For simplicity, the same seal plate system was selected for the laminated turbine design.

Laminated Turbine Design

The laminated turbine design that met the overall program objectives was subjected to a series of design iterations. The design posed a great challenge to the designer for a number of reasons.

First, the extreme flexibility of the photoetch process makes it possible to produce accurate and complex passage geometry. In fact, practically any geometrically shaped passage that can be visualized and drawn can be etched. Dimensional tolerances in the range of ±0.002 in. are also possible. However, tolerance standards and minimum passage size limitations for superalloy sheet materials were unknown when utilizing the photoetch process, and these limitations had to be experimentally determined. The following two general design rules were adopted as a result of this testing:

1) The smallest passage in a given design etches more consistently if the narrowest passage dimension is equal to or greater than the sheet thickness and the longest dimension is equal to three times the thickness.

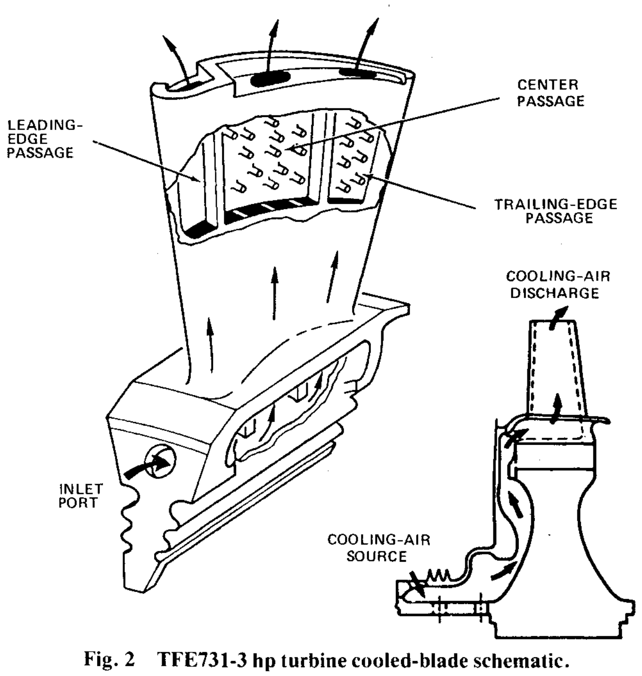


Fig. 2 TFE731-3 hp turbine cooled-blade schematic.

2) The line width, which is the exposed etching surface, on any single lamination must be constant for a given material and thickness.

Second, the dimensional tolerances that may be achieved with use of conventional drafting and photographic tooling methods are ±0.007 in. This was considered unacceptable for the laminate wheel design because of wall thickness variations in the blades. With the conventional method, a given blade passage is scribed 10-times-size on mylar, and through subsequent photographic reductions and step-and-repeat operations, a 1:1 photoetch tooling master is produced. Full-scale laminates produced with this method revealed ±0.0017 in. circumferential and ±0.0034 in. radial variations. As a result of this effort, a new detail design method was initiated to reduce tolerances to acceptable limits. This method utilizes computer-aided design techniques and defines the cooling passages by straight-line elements using an X/Y digitized-coordinate system at each Z section. The coordinates were fed into an Auto-Trol minicomputer, and reproduced graphically as a final check prior to tape input into a Gerber automatic plotting table with an optical exposure head. The final 1:1 size Z-section tooling master is automatically plotted on a photosensitive glass plate to a tolerance of less than ±0.001 in. Mylar photopositives are made of the final tooling for each of the laminates. The benefits of this design method are:

1) Substantially increased accuracy.

2) More consistent photoetching, since the optically generated line width is precise (less than ±0.0005 in.) as compared to a hand-drawn line photoreduced to size.

3) Faster turnaround in the design and development cycle that permits rapid modification of the cooling passage flow areas in a given laminate tool. This is accomplished by merely changing several of the coordinates.

Third, in a laminated integral wheel design, the laminates must be stacked normal to the centerline. This provides a structurally sound disk with the tangential bore stresses oriented longitudinally or parallel to the laminates. However, to achieve a balanced design in the blade trailing-edge region, thinner laminates are required due to the blade angle. A view of the cross section of the laminated blade is presented in Fig. 3. In the trailing-edge region, 0.010-in. laminates are required to provide sufficient flow area and wall thickness. The reason for this becomes obvious after consideration is given to the basic etching process which only generates passages normal to the laminate surface.

Fourth, precise control of the laminate sheet thickness, surface quality, and sheet material properties is necessary to achieve a balanced design. Obviously, the selection of the laminate sheet thickness has a major effect on the final design, and this parameter becomes of major importance. The designer must geometrically balance sheet thickness with cooling flow areas and minimum wall thickness to achieve acceptable metal temperatures and stress levels.

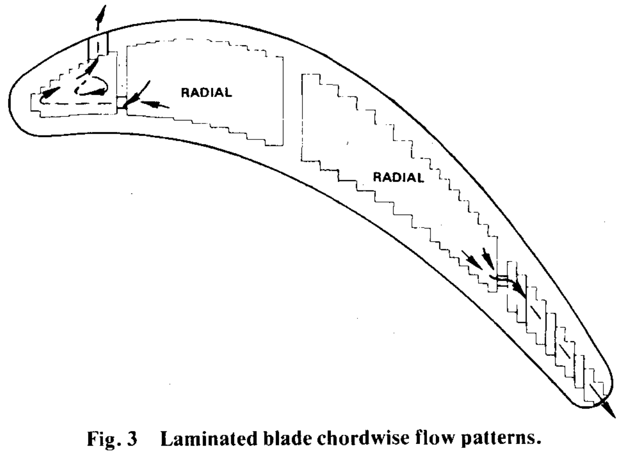


Fig. 3 Laminated blade chordwise flow patterns.

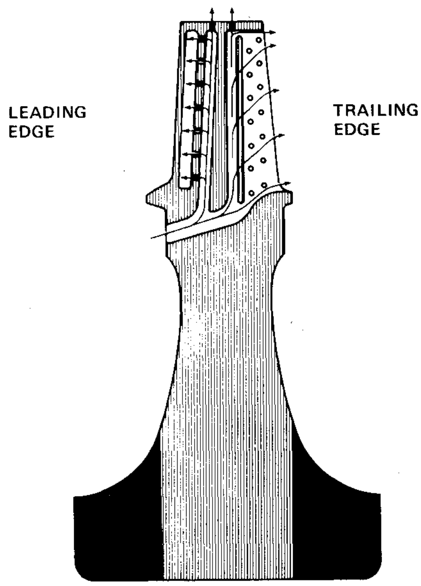


Fig. 4 Cooling concept selected.

The selected tooling concept, as seen in Fig. 4, utilizes impingement cooling of the leading edge with suction-side film-discharge slots, convective cooling of a two-passage center section, and convection cooling with center discharge in the trailing-edge section. Figures 3 and 5 will aid in visualizing the cooling flow patterns, the flow split, and the radial distribution.

Note the pin-fin-array appears square in cross section as an etched laminate is actually produced. The final design utilizes a total of 62 Waspaloy laminates—24 are of 0.020-in. sheet stock and 38 are of 0.010-in. sheet stock. Each of these laminates has a different photoetched cooling passage definition to provide the desired blade and disk internal cooling passage arrangement in the final assembly. The laminates are sandwiched between two solid end plates of Waspaloy that form the remainder of the turbine disk. The external blade shape is designed to be machined after bonding of the wheel elements. Furthermore, with laminate construction, the chordwise flow in the trailing-edge region follows a rough stair-step inner wall, which is a desirable heat-transfer cooling surface. Also, note that the trailing-edge thickness was increased to 0.060 in. to maintain adequate slot area. This was accomplished by cutting back the chord length, which required rotating the blade row closed 1.5 deg in order to maintain the turbine vector diagram and the desired throat area.

Table 1 Two-percent creep life vs average turbine inlet temperature

Turbine material	Turbine inlet temperature, °F	Life at temperature, h
Waspaloy	2320	20
Astroloy	2530	20
AF2-1DA	2600	29

Table 2 Calculated disk stresses at 100% rated speed

Average tangential stress	60.9 ksi
Maximum tangential bore stress	94.0 ksi
Maximum radial stress at web	45.3 ksi
Maximum shear stress	23.5 ksi
Minimum burst speed (cold)	136% (rated speed)

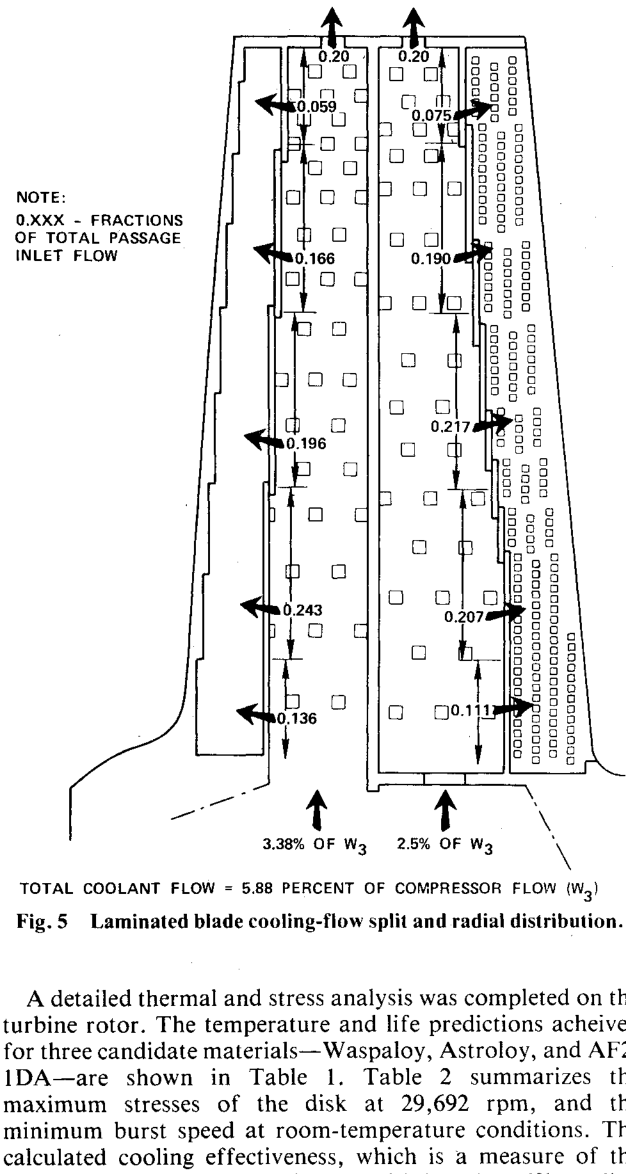


Fig. 5 Laminated blade cooling-flow split and radial distribution.

A detailed thermal and stress analysis was completed on the turbine rotor. The temperature and life predictions acheived for three candidate materials—Waspaloy, Astroloy, and AF2-1DA—are shown in Table 1. Table 2 summarizes the maximum stresses of the disk at 29,692 rpm, and the minimum burst speed at room-temperature conditions. The calculated cooling effectiveness, which is a measure of the heat transfer performance, is 0.58 with less than 6% cooling flow. This very high effectiveness is comparable to that achieved by advanced inserted-blade cooling methods.

III. Process Development

In the fabrication of a laminated turbine wheel, the major areas of processing that require definition and control are: the base-metal sheet quality and sheet thickness dimensional control; the chemical machining process for accurate photoetching of design configurations; the bond-alloy and method of application; the assembly tooling and bonding parameters; and the bond-joint quality verification. Figure 6 illustrates the flow diagram of the manufacturing process operations in the fabrication of a laminated cooled axial turbine wheel.

Laminate Sheet Material

The process feasibility study was initiated with the 0.020- and 0.010-in. Waspaloy sheet then available. Due to the thickness tolerance permitted, the 12×12 in. laminates utilized for processing had to be selectively identified. This was done to permit satisfactory photoetching with a constant etch-rate factor and to prevent exceeding the stack height tolerance requirements. To eliminate these time-consuming operations and to permit utilization of more advanced bonding systems, the parameters for cold rolling 0.030 in. Waspaloy sheet to the required thickness with a ±1% tolerance across a 12 in. width were established. This activity

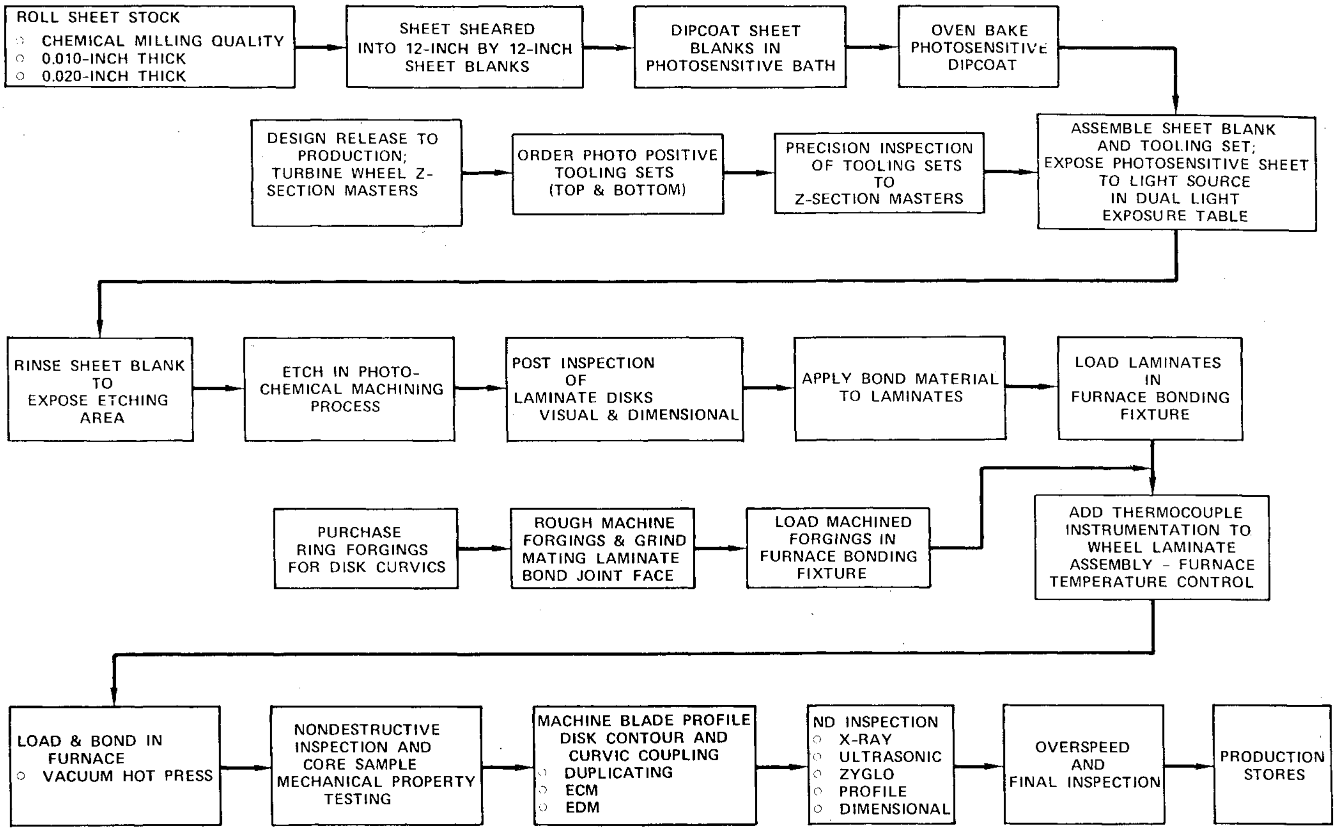


Fig. 6 Flow diagram of the manufacturing process operations in the fabrication of cooled axial turbine wheel.

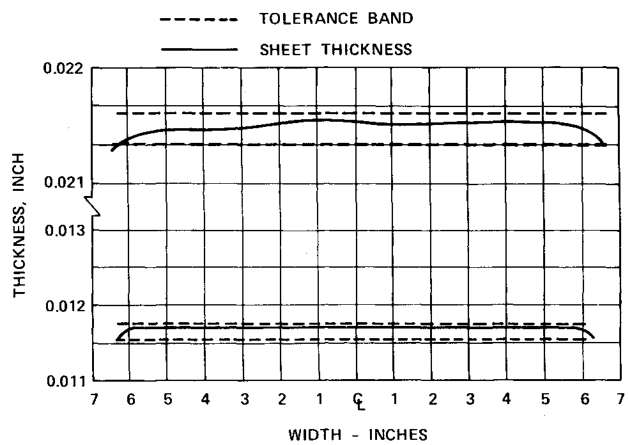


Fig. 7 Profile of rolled Waspaloy sheet.

was satisfactorily completed and Fig. 7 illustrates the typical results of thickness tolerance control across the 12 in. width obtained in the initial rolling operation.

Photoetching Process

The two main areas of concern in the photoetching process are photoresist adhesion to the laminates and reproducible chemical-etching rates. Lack of complete photoresist adhesion can cause pitting or thinning of the laminate sheet adjacent to the cooling passages. Process results showed that improved adhesion consistency was obtained with the use of a single dipcoat approximately 0.0005 in. thick followed by quartz lamp curing to 230°F for 3 min.

The results of the initial photoetching operations on Waspaloy laminates were inconsistent. Consequently, a laboratory investigation was conducted to improve the consistency of the photoetching solutions. This resulted in a consistent etch-rate factor of 1.1 mils/min. Machine speeds were set to photoetch Waspaloy laminates in two cycles with each laminate being turned over and rotated 90 deg after the first cycle. Typical photoetched laminate configurations are shown in Fig. 8. Dimensional inspection, previously established by optical comparator measurements, were correlated to the 2 in. center bore diameter when using a given etch-rate factor.

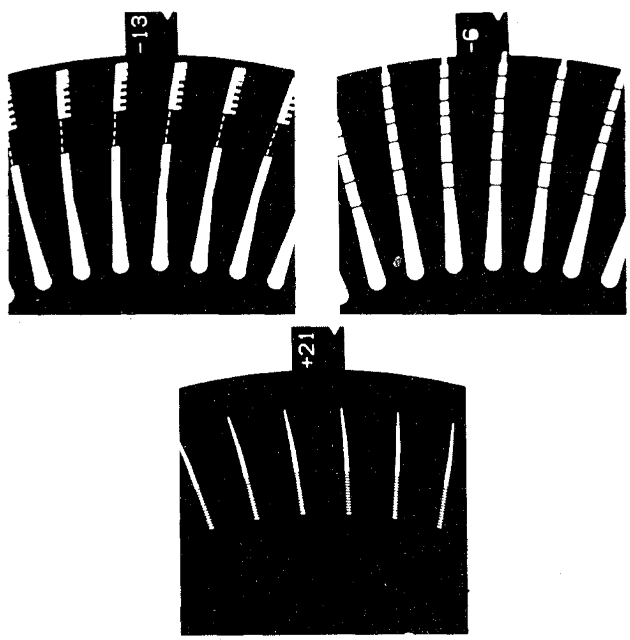


Fig. 8 Three typical laminate sheets.

Bond-Alloy Selection and Application

Based on earlier laboratory bond-joint property studies with Waspaloy laminates, the nickel-base bond-alloy AMI

915 was selected for the initial turbine wheel fabrication. For consistency of application, the bond-alloy powder was processed with an acrylic binder to produce a 0.002 in. thick tape form with an acrylic content of less than 5% by weight. The tape was applied to one side of each photoetched laminate, followed by a vacuum outgassing cycle of 50 h at 450°F to remove approximately 75% of the acrylic binder. The photoetched channels were cleared by the application of filtered, compressed air to the degassed tape covering the passages and center bore diameter.

To eliminate this time-consuming method of bond-alloy application and the inherent contamination problem caused by outgassing of the acrylic binder, alternate bond-alloy systems and application techniques were investigated during the advanced fabrication process program. These methods included sputtering of boron-modified base metal, electroless nickel-boron plating, and direct boriding of the laminate surface by the Borofuse process. Borofuse is a proprietary process of diffusing boron into the base metal surface under controlled conditions to obtain the desired boride density that reduces the melting point temperature at the bond interface. The Borofuse process was applied to both sides of every other laminate. This provided consistent chemistry control, simplification of the wheel stack assembly, consistent bond-joint quality, improved bond-joint properties, and bond-joint flow control to prevent clogging of internal cooling passages.

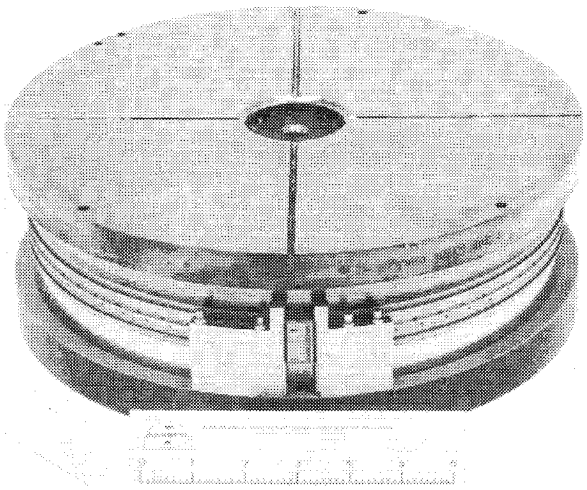


Fig. 9 Laminated stack assembled in bonding fixture.

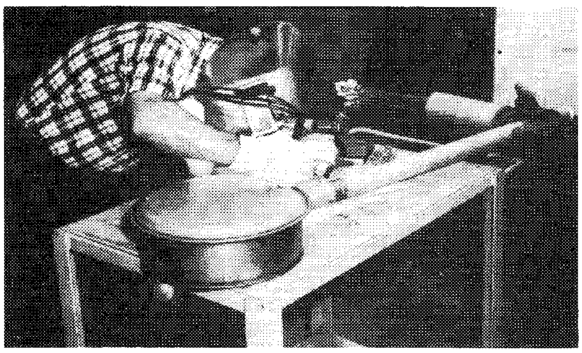


Fig. 10 Laminated wheel blank retort being welded after backfilling with argon.

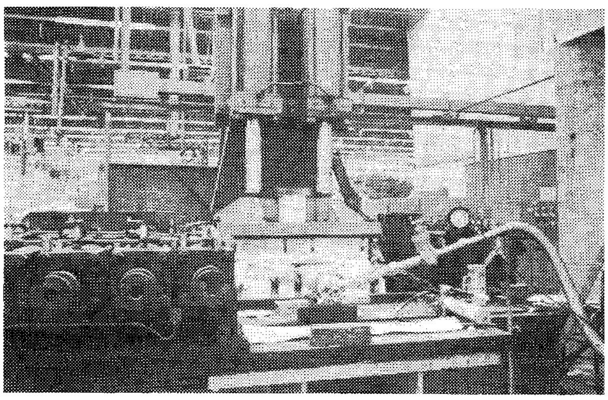


Fig. 11 Hot press for bonding the wheel blank.

Assembly and Bonding

The initial wheel blank assembly was composed of 62 Waspaloy laminates—twenty-four 0.020 in. and thirty-eight 0.010 in., plus two 0.075 in. thick Waspaloy end plates—which were bonded with AMI 915 tape.

The tooling for bonding this assembly was composed of a top and bottom baseplate of 1-in. thick Waspaloy, with center holes machined to accept a locating post for central alignment of the laminates and the end plates. The bottom baseplate had two locating posts at the periphery to accept the numbered tab of each laminate for correct sequential alignment during assembly (see Fig. 9). The baseplates were plasma-arc coated with alumina at the interface to the wheel to prevent adherence during the bonding operation. The alumina coating was ground to 0.001 in. for flatness and parallelism. This was followed by degreasing of the tooling, and a vacuum outgassing operation at 450°F. The end plates and laminates were then sequentially assembled on the bond fixture. Twelve thermocouples were installed for monitoring the temperature profile at the center bore, and three peripheral locations on the laminate stack and end plates. The wheel blank was placed in a vacuum bonding retort, as shown in Fig. 10, thermocouple leads and vacuum feedthrough were installed, and the assembly was backfilled with argon and welded. The bonding was performed with a hot press in a vacuum utilizing resistance-heated ceramic platens on the top and bottom surfaces of the wheel blank assembly (see Fig. 11). The heating rate was 11°F/min.

In addition to use of the Borofuse bonding process, several further processing changes were incorporated in the advanced rotor to improve 1) the bond-process control, 2) the nondestructive inspection sensitivity, and 3) the production of a more net-shape wheel blank unit. The mass of the laminate wheel stack during laminate bonding was reduced approximately 60% by removing both 11 in. diameter by 0.75 in. Waspaloy end plates, and increasing the number of lamintes

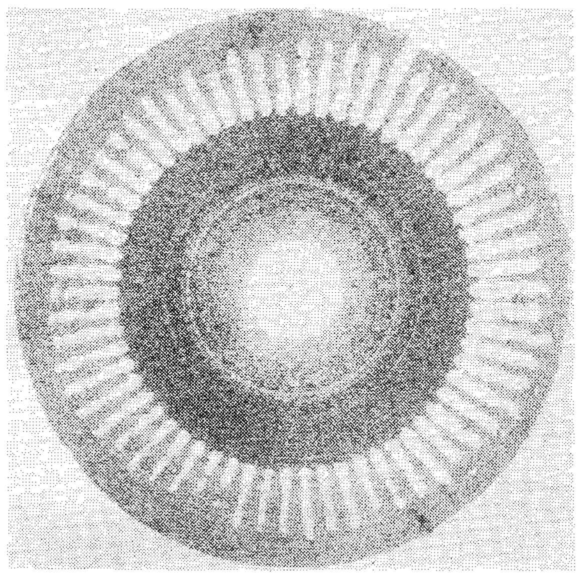
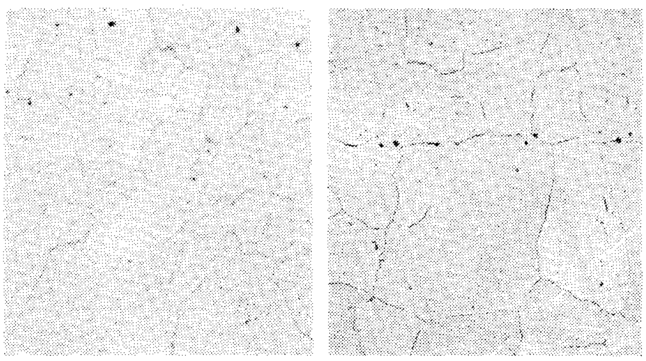


Fig. 12 Ultrasonic inspection results.

from 62 to 75, which provided machining stock for the blade platforms. Reduction of the mass permitted increased heating rates with improved control of the temperature profile during heating and bonding. Nondestructive inspection of laminate bond joints by ultrasonic techniques was improved, and as a further NDI procedure, gas-flow checks of the cooling passages were performed prior to final machining. The Waspaloy end plates were subsequently reduced (5 in. in diameter by 0.5 in. thick) and bonded to the laminate stack during the heat-treatment cycle.

Bonding Results

Ultrasonic inspection of the initial bonded wheel blank showed complete bonding within the hub area (see Fig. 12). Specimens removed from the bore section of the wheel for metallographic examination showed complete homogenization across the bond joints, as shown in Fig. 13. Metallographic examination of the outside diameter showed evidence of bond-alloy liquid flow in several cooling passages, as can be seen in Fig. 14. The advanced bond process that incorporated a thin boride film to replace the AMI 915 tape has permitted improved bond-alloy flow control during the bonding cycle, and eliminated the cooling passage clogging problem, as shown in Fig. 15. Figure 16 shows a metallographic cross section of a typical Waspaloy laminate bond joint. Figure 17 presents the comparative Waspaloy laminate bond-joint strengths utilizing AMI 915 bond-alloy tape, and the advanced process program utilizing the borided bond alloy. Transverse specimens are shown which have the test axis normal to the bond joint, while longitudinal specimens have the test axis parallel to the bond joint. Figure 18 presents stress-rupture bond-joint properties of the two bonding methods compared with the unbonded heat-treated Waspaloy laminate sheet.



a) b)

Fig. 13 Interfaces of laminate bond joints from the bore specimen. (mag. = 50X): a) interface of end plate to first 0.020-in. laminate; b) interface of 0.020-in. to 0.010-in. laminate.

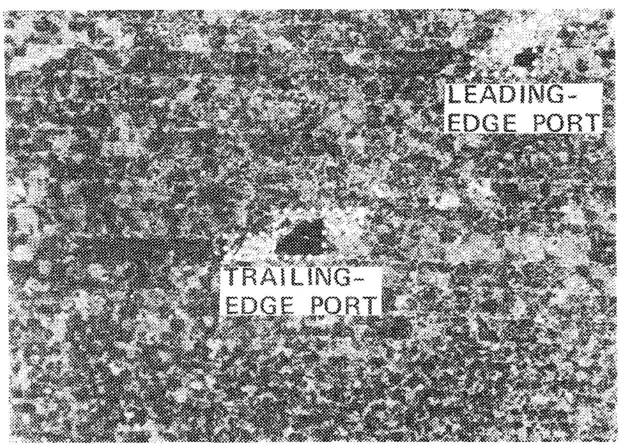


Fig. 14 Surface of the wheel blank outside diameter indicating flow of bond alloy liquid into the tip passages. Dotted lines show approximate passage size (mag. = 9X).

Fabrication of laminated axial turbine wheels utilizing the more advanced superalloy Astroloy with the boride bonding process will provide an additional 200°F operating temperature capability above Waspaloy. The tensile and stress-rupture properties of borided Astroloy bond joints are compared with unbonded Astroloy sheets in Figs. 19 and 20.

IV. Mechanical Integrity Testing

The mechanical integrity testing and evaluation of the first axial-laminated turbine wheel consisted of a series of whirlpit tests that included Stresscoat, growth, and overspeed tests, and final nondestructive inspections.

Stresscoat Test

The purpose of the Stresscoat test was to assess possible areas of stress concentration in the rotor. The test was conducted in the whirlpit test facility under carefully controlled temperature and humidity conditions to insure stabilization of the Stresscoat. The locations of the stress zones are shown in Fig. 21 on the leading-edge side of the wheel after Stresscoat testing. The locations of high stress areas or stress zones compare very well with the locations of stress concentration zones predicted by the analytical stress model performed on the wheel. Also, no unexpected areas of stress concentration were discovered during the test.

Growth and Overspeed Test

The laminated wheel was growth tested in order to determine the response of the wheel structure to overspeed conditions and to verify the wheel mechanical integrity. In addition, it was desirable to determine the effect of laminate construction on ductility, and its ability to yield and redistribute loading in regions of stress concentration. The results of the growth testing are presented in Figs. 22 and 23, where total growth has been plotted as a function of speed. A maximum total growth of 0.001 in. occurred in the center of

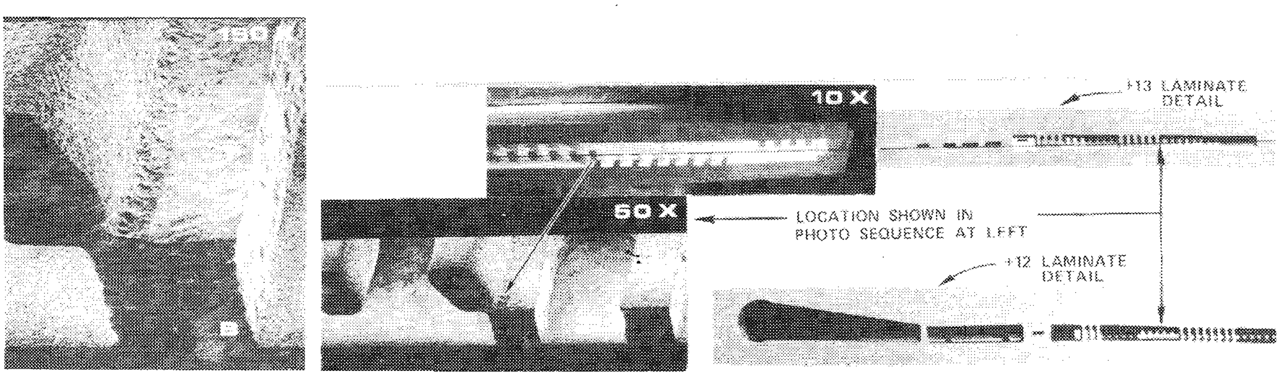


Fig. 15 Laminate bond joint with improved bond-alloy flow control. As-printed magnifications are 80% of value shown.

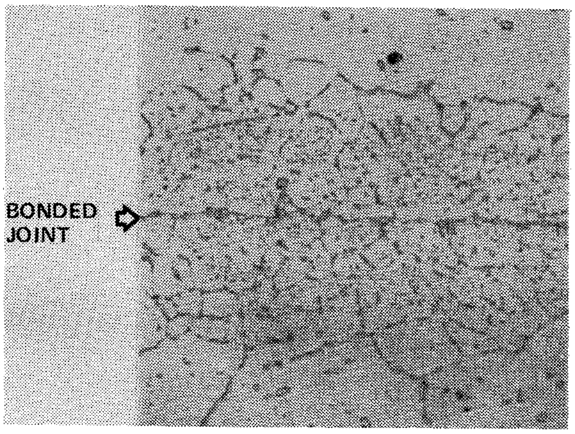


Fig. 16 Micrograph of Waspaloy laminate bond joint with boride coating (mag. = 300X).

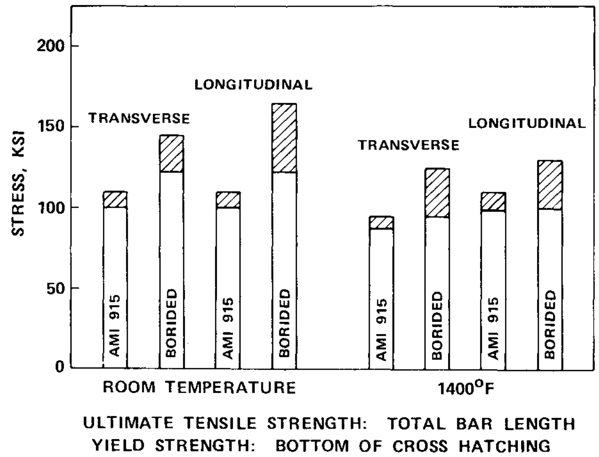


Fig. 17 Comparative Waspaloy-bonded tensile properties.

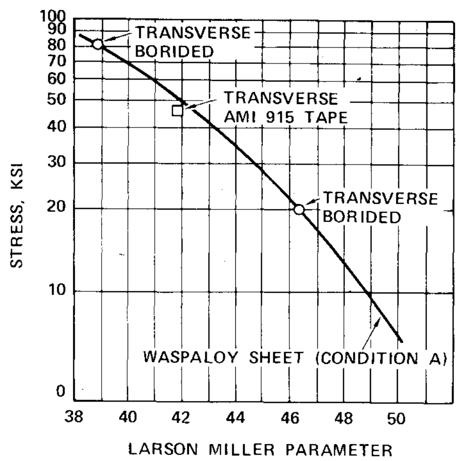


Fig. 18 Average stress-rupture properties of bonded laminate methods compared to Waspaloy laminate sheet (condition A).

the bore, with less than 0.001 in. growth over the wheel tip diameter. The maximum operating speed was 34,100 rpm, 115% of the design speed. The maximum bore growth amounted to a total change of 0.042% of the bore diameter, which is less than another AiResearch integrally cast wheel that is in production for long-life commercial and military applications.

Nondestructive Inspection

At the completion of the overspeed testing, a Zyglo inspection was performed. No delaminations or joint cracks

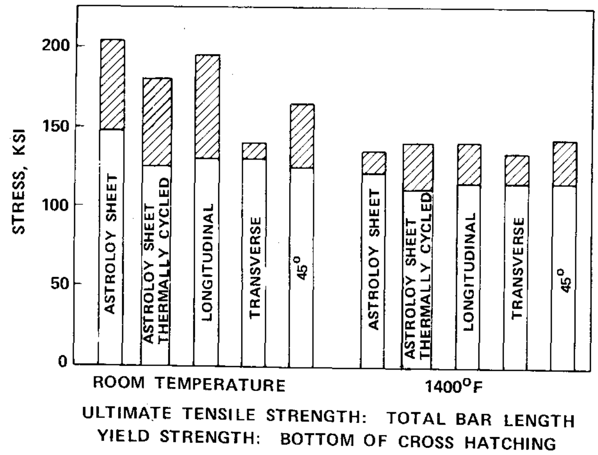


Fig. 19 Comparison of average tensile strength properties for boride-bonded 0.020-in. Astroloy.

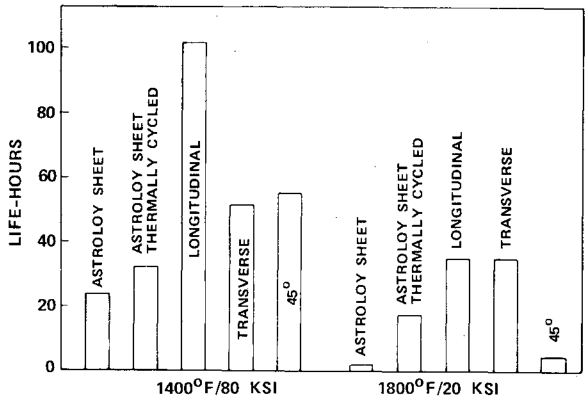


Fig. 20 Comparison of stress-rupture strength for boride-bonded 0.020-in. Astroloy.

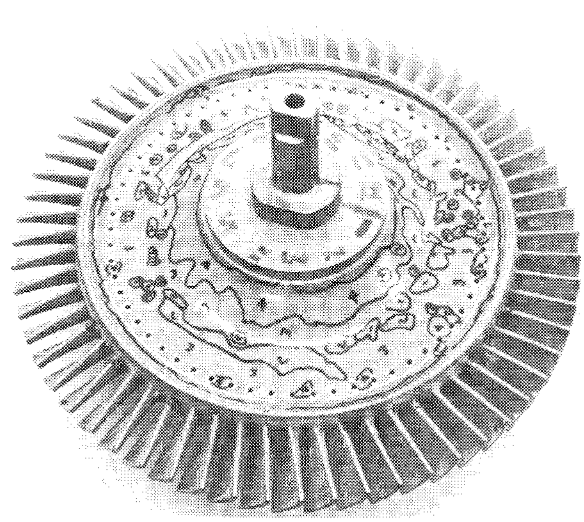


Fig. 21 Laminated turbine wheel leading-edge side after Stresscoat testing.

were noted in either the blades or in the bore area. A post-test ultrasonic inspection was conducted and compared to the ultrasonic inspection prior to the test. No unbonding occurred in the disk section as a result of growth and overspeed testing.

Therefore, it was concluded that the mechanical integrity for the first laminated axial turbine rotor had been established.

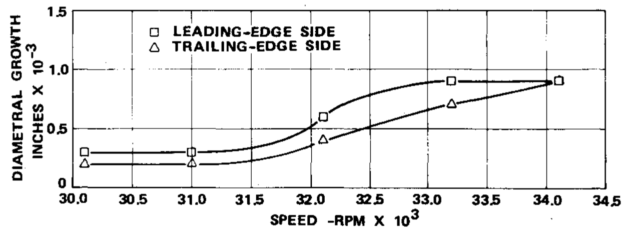


Fig. 22 Laminated turbine wheel tip growth.

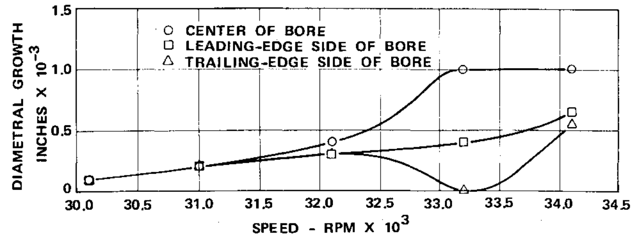


Fig. 23 Laminated turbine wheel bore growth.

V. Conclusions

The program has demonstrated the feasibility of constructing a small, cooled, turbine wheel incorporating complex cooling passages using the laminate process. It has also proven, by test, that the turbine wheel possessed good mechanical integrity. Furthermore, the advanced design methods and laminate process has led the way to a new level of performance for small turbine engines capable of operation at 2600°F or higher. Also, preliminary production cost estimates of the laminate process indicate that the axial rotor could be produced for one-half that of a conventional inserted blade turbine.

Acknowledgments

This work was performed under U.S. Air Force Contracts F33615-74-C-2034 and F33615-75-C-5211.

References

[1]Vershure, R. W., Furst, D. G., Pyne, J. A., and Clarke, J. J. "Integral, Low-Cost, High-Temperature Turbine Feasibility Demonstrator" (Small Laminated Axial Turbine Program), USAFAPL, TR-77-2, Feb. 1977.

[2]"Manufacturing Methods of Fabrication of Cooled Laminated Axial Turbine Wheels," USAF Material Laboratory, AFSC, Contract F33615-75-C-5211.