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ENERGY EFFICIENT ENGINE
SHROUDLESS, HOLLOW FAN BLADE TECHNOLOGY REPORT

Prepared
by

C. J. Michael, et al.

PERSONAL COPY

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Products Division

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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Lewis Research Center
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Cleveland, Ohio 44135

Attention: Mr. Carl C. Ciepluch, Mail Stop 301-4

Subject: Submittal of the Energy Efficient Engine Shroudless, Hollow Fan Blade Technology Report, NASA CR-165586 (PWA-5594-199)

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(b) Letter, J.W. Schaefer to W.B. Gardner, 'Contract NAS3-20646 - Approval of Shroudless, Hollow Fan Blade Technology Report (WBS 4.2.1.2.2),' dated January 28, 1982, ref. 2321

Enclosures: Twenty copies of the subject report

In accordance with the requirements of references (a) and (b), we are pleased to submit twenty copies of the subject report, which includes all revisions to the draft accompanying the reference (b) letter.

Distribution is being made in accordance with the reference (b) letter.

Sincerely yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Aircraft Group
Commercial Products Division

W B Gardner

W.B. Gardner
Program Manager

cc: Administrative Contracting Officer
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16. ABSTRACT

The Shroudless, Hollow Fan Blade Technology program was structured to support the design, fabrication, and subsequent evaluation of advanced hollow and shroudless blades for the Energy Efficient Engine fan component. Fabrication of hollow fan blade test specimens was performed by two subcontractors, each employing a different manufacturing technique.

Rockwell International was initially selected to produce hollow airfoil specimens employing the superplastic forming/diffusion bonding (SPF/DB) fabrication technique. Rockwell demonstrated that a titanium hollow structure could be fabricated utilizing SPF/DB manufacturing methods. However, some problems such as sharp internal cavity radii and unsatisfactory secondary bonding of the edge and root details prevented production of the required quantity of fatigue test specimens. Subsequently, TRW was selected to (1) produce hollow airfoil test specimens utilizing a laminate-core/hot isostatic press/diffusion bond approach, and (2) manufacture full-size hollow prototype fan blades utilizing the technology that evolved from the specimen fabrication effort. TRW established elements of blade design and defined laminate-core/hot isostatic press/diffusion bonding fabrication techniques to produce test specimens. This fabrication technology was utilized to produce full size hollow fan blades in which the HIP'ed parts were cambered/twisted/isothermally forged, finish machined, and delivered to Pratt & Whitney Aircraft and NASA for further evaluation.

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FOREWORD

The Energy Efficient Engine Component Development and Integration Program is being conducted under parallel National Aeronautics and Space Administration contracts with Pratt & Whitney Aircraft Group and General Electric Company. The overall project is under the direction of Mr. Carl C. Ciepluch with Mr. John W. Schaefer serving as NASA's assistant project manager for the Pratt & Whitney Aircraft effort under NASA contract NAS3-20646. Mr. Frank Berkopec is the NASA project engineer responsible for the portion of the project described in this report. Mr. William B. Gardner is manager of the Energy Efficient Engine program at Pratt & Whitney Aircraft Group.

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SECTION 1.0 SUMMARY

The Shroudless, Hollow Fan Blade Technology program was structured to support the design, fabrication and subsequent evaluation of advanced hollow, shroudless blades for incorporation into the Energy Efficient Engine fan component. To manufacture these blades, as designed, required an evolutionary extension of current fabrication technology. After determining potential fabrication requirements, a screening of candidate fabrication techniques was conducted. From this screening process, two candidate manufacturing methods were selected for evaluation.

- Superplastic Forming/Diffusion Bonding Process (SPF/DB)
- Laminate-Core-Hot Isostatic Press/Diffusion Bonding and Isothermal Forging Process

The Superplastic Forming/Diffusion Bonding (SPF/DB) fabrication process was initially selected. Rockwell International was the subcontractor chosen to fabricate the part employing this manufacturing methodology. Selection of the SPF/DB process was based on previously successful applications of this fabrication technique in producing various other unique hollow structures and favorable production costs as compared to conventional methods of fabrication. Some of these advantages are the use of inexpensive titanium sheet metal compared to costly machined forgings, reduced post-form machining and the number of additional details required, and good dimensional control. However, some major problems such as (1) sharp internal cavity radii, and (2) unsatisfactory secondary bonding of the edge and root details were identified early in the Rockwell subcontract effort and prevented production of the required quantity of fatigue test specimens within the funding budgeted.

Subsequently, work was subcontracted to TRW for fabrication of test specimens and blades using the laminate/core hot isostatic press/diffusion bonding and isothermal forging process. This fabrication method, like Rockwell's superplastic forming/diffusion bonding process, takes advantage of the forming and bonding properties of titanium to form an airfoil using sheet titanium and leachable steel cores. A two-task effort was defined to accomplish the TRW program objectives established in the contract. Under Task 1, the elements of blade design were defined along with fabrication processing techniques to successfully produce titanium-laminated/cored, diffusion bonded diamond-shaped blade test specimens. Two of the major accomplishments demonstrated under this phase of the program included (1) the feasibility of fabricating hollow blade specimens using a laminated ply/core assembly HIP bonding approach, and (2) the feasibility of the flat ply layup assembly approach which is comparatively inexpensive and easily performed while maintaining proper core registry. Under Task 2, nine full size hollow fan blades were produced using the hollow specimen design and fabrication technology which evolved from Task 1 along with specialized tooling manufactured for the camber, twist, and isothermal forging operations required to finish-form the blades. Two blades were finish-machined and delivered to Pratt & Whitney Aircraft and NASA for further visual evaluation. Some of the major accomplishments demonstrated under this phase of the program include (1) computer aided design and manufacture of plies and cores, and (2) the feasibility of isothermally forging a smooth airfoil finish and demonstrating the potential technology for meeting blueprint dimensional specifications.

The Shroudless, Hollow Fan Blade Technology program was beneficial in establishing manufacturing processes that can be applied to the production of large hollow airfoil structures. This provides a technological base for reference in future program efforts directed at evolutionizing hollow blade technology for utilization in future energy efficient gas turbine engines.

2.0 INTRODUCTION

The objective of the Energy Efficient Engine Component Development and Integration Program, sponsored by the National Aeronautics and Space Administration, is to develop, evaluate, and demonstrate the technology for achieving lower installed fuel consumption and lower operating costs in future commercial turbofan engines. NASA has set minimum goals of 12 percent reduction in thrust specific fuel consumption (TSFC), 5 percent reduction in direct operating costs (DOC), and 50 percent reduction in performance degradation for the Energy Efficient Engine (flight propulsion system) relative to the JT9D-7A reference engine. In addition, environmental goals on emissions (meet the proposed EPA 1981 regulation) and noise (meet FAR 36-1978 standards) were established at the beginning of the program.

In order to meet these objectives, the program is currently structured into three technical tasks:

Task 1	Propulsion System Analysis, Design, and Integration
Task 2	Component Analysis Design and Development
Task 4	Integrated Core/Low Spool Design, Fabrication, and Test

Under Task 2, an advanced single stage fan component is being designed and fabricated for the Energy Efficient Engine which incorporates advanced technological concepts such as (1) a shroudless, hollow fan blade, (2) designed contour airfoils, and (3) rotor tip grooves with an abradable material. These features contribute 3.8 percent to the overall improvement in thrust specific fuel consumption relative to the JT9D-7A reference engine.

This document describes the Shroudless, Hollow Fan Blade Supporting Technology Program which was structured to evaluate the feasibility of hollow fan blade fabrication concepts. Section 3.0 contains a general description of the hollow fan blade with its aeromechanical design requirements, goals, and criteria. Also included in this section is information detailing the predicted performance of the hollow fan blade in relation to established Energy Efficient Engine program goals. Section 4.0 describes the manufacturing challenges associated with hollow fan blade fabrication and discusses the candidate fabrication methods considered for blade production in accordance with the NASA-approved fan detail design. Section 5 provides a detailed description of the program effort. Two subcontractors, each employing unique manufacturing techniques with different hollow blade internal configurational concepts, were chosen to perform the task. Rockwell International was retained as a subcontractor to provide a test specimen of a hollow fan blade fabricated by the superplastic forming/diffusion bonding (SPF/DB) technique. TRW was retained as a subcontractor to evaluate a construction method using multiple layers of titanium laminate that are hot isostatically pressed (HIP)/diffusion bonded, and isothermally resized to final aerodynamic shape. Section 6 presents concluding remarks relative to the program effort.

SECTION 3.0 FAN BLADE DESIGN

3.1 Introduction

In comparison to conventional solid fan blades used in current turbofan engines, the shroudless blade concept offers a substantial reduction in aerodynamic drag which is directly translatable into a more efficient component resulting in lower fuel consumption. Utilization of shroudless blade technology in the Energy Efficient Engine is projected to provide a fuel savings of 3.8 percent relative to the base JT9D-7A reference engine currently being used in commercial aircraft.

The shroudless blade concept introduces certain technical challenges. Removal of the aft partspan shroud eliminates the high aerodynamic losses associated with a shroud, but results in potential aeroelastic instabilities. Although stability can be ensured by reducing the aspect ratio, this reduction necessitates a hollow configuration to offset the weight penalty produced by the large chord of the airfoil.

The hollow blade concept partially resolves the weight penalty problem associated with a shroudless blade by introducing a blade configuration that is two-thirds hollow. This hollow fan blade approach also permits (1) a reduction in the weight of the blade attachment and disk due to the diminished centrifugal force being generated, and (2) weight reduction of the fan containment case since the blade it must retain is lighter and, hence, has less energy. However, the hollow blade concept has several areas requiring technological verification. These areas include fabrication feasibility -- the subject of this report -- and structural integrity, including sensitivity to foreign object damage, and repairability.

The following sections summarize the salient design features and predicted performance of the shroudless, hollow fan blade for the Energy Efficient Engine. A complete description of the blade design effort is contained in the Energy Efficient Engine Fan Detailed Design Report, CR-165466.

3.2 Fan Blade Aeromechanical Design

The mechanical definition of the shroudless, hollow fan blade is presented in Figure 3-1., with the general design parameters for this blade listed in Table 3-I. The blade is a low aspect ratio (2.5) design with integral platforms. The blade definition consists of a combination of multiple circular arc (MCA) sections and design contour sections. Design contour sections, located in the outer 30 percent span of the airfoil, were used to minimize shock losses and increase efficiency. The remainder of the foil consists of multiple circular arc sections.

Compared to a conventional solid fan airfoil, the shroudless, hollow airfoil has a long chord and thick airfoil sections. As shown in Figure 3-1, the blade span is 62 cm (24.6 in) while the chord dimension is 23.1 cm (9.1 in) at the root and 33.8 cm (13.3 in) at the tip. To reduce the mass concentration near the tip and thereby reduce the centrifugal load, approximately two-thirds of the blade is hollow. This internal section, also shown in Figure 3-1, is formed by three radial ribs and one cross rib. In addition, the leading and trailing edges are solid titanium for 2.3 cm (0.940 in) of the chord.

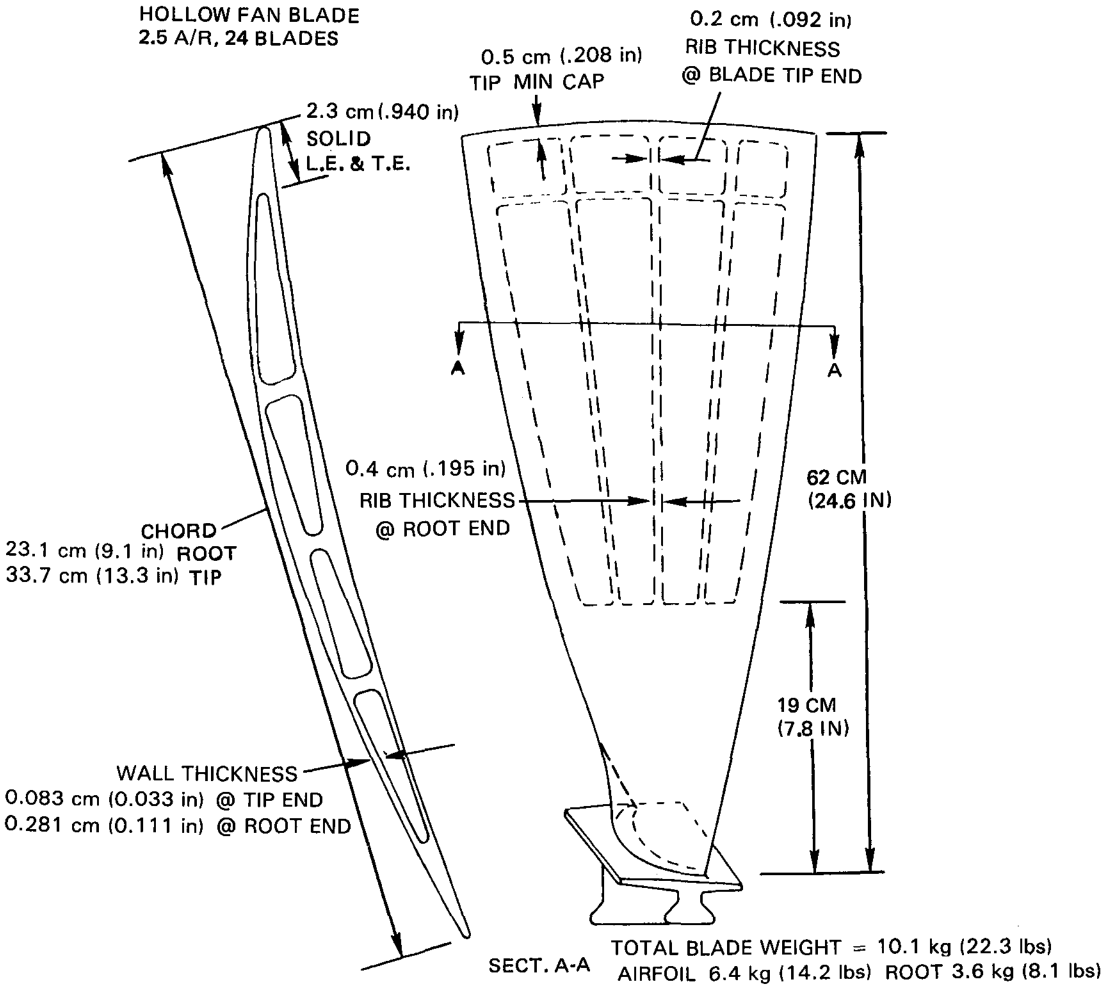

HOLLOW FAN BLADE
2.5 A/R, 24 BLADES
0.2 cm (.092 in)
RIB THICKNESS
@ BLADE TIP END
0.5 cm (.208 in)
TIP MIN CAP
2.3 cm (.940 in)
SOLID
L.E. & T.E.
A
A
0.4 cm (.195 in)
RIB THICKNESS
@ ROOT END
62 CM
(24.6 IN)
CHORD
23.1 cm (9.1 in) ROOT
33.7 cm (13.3 in) TIP
19 CM
(7.8 IN)
WALL THICKNESS
0.083 cm (0.033 in) @ TIP END
0.281 cm (0.111 in) @ ROOT END
SECT. A-A
TOTAL BLADE WEIGHT = 10.1 kg (22.3 lbs)
AIRFOIL 6.4 kg (14.2 lbs) ROOT 3.6 kg (8.1 lbs)

Figure 3-1 Shroudless Fan Blade Cross Section

The selection of this internal structure was based on results of a comprehensive NASTRAN analysis performed on various candidate configurations. This method of construction is predicted to provide adequate rigidity to successfully meet bird injestion criteria, flutter, and vibration requirements.

The entire blade, including the rib structure, is fabricated from AMS 4928 titanium alloy with an estimated total weight of 10.1 kg (22.3 lbs).

TABLE 3-I

SHROUDLESS FAN BLADE GENERAL PARAMETERS

Hub/Tip Ratio	0.34 Leading edge 0.393 average
Aspect Ratio - average span/root chord	2.50
Average Span - cm (in)	62.412 (24.572)
Average Root radius - cm (in)	40.431 (15.918)
Root chord - cm (in)	23.096 (9.093)
Taper ratio - average span/root chord	1.46
Thickness/Chord @ root	0.0954
Thickness/Chord @ tip	0.0252
α chord @ root (deg)	85.82
α chord @ tip (deg)	21.88
Root angle (deg)	24.28
Tip angle (deg)	4.14
Number of blades	24
Material	AMS 4928 (Ti 6Al-4V)
Airfoil root fillet radius - cm (in)	0.889 (0.35)
Redline rotor speed - rpm	4267
Low cycle fatigue rotor speed - rpm	3988
Tip speed @ redline speed - m/sec (ft/sec)	461 (1515)
Tip speed @ aerodynamic design point - m/sec (ft/sec)	422 (1385)
Tip speed corrected @ ADP - m/sec (ft/sec)	455 (1496)
Torsional stall flutter parameter - bw_t (flight propulsion system)	1895

3.3 Predicted Performance

The Energy Efficient Engine shroudless, hollow fan blade design is predicted to meet all aerodynamic, performance, and structural design goals established by the program. Performance predictions at the aerodynamic design point are presented in Table 3-II. As shown, the predicted efficiency is 87.3 percent which is one full percentage point higher than the efficiency level obtained with a conventional shrouded fan blade.

Based on structural analyses performed, the shroudless, hollow fan blade either met or exceeded all requirements determined for stage vibration, steady stress, foreign object damage, untwist/uncambering applications, and low cycle fatigue. The large size and low aspect ratio of the blade diminishes the possibility of gross bending or torsional failure resulting from bird injestion. An analysis of local leading edge tolerance to bird impact indicates the blade has acceptable bird strike structural characteristics.

TABLE 3-II

SHROUDLESS FAN BLADE PERFORMANCE AT AERODYNAMIC DESIGN POINT

Parameter	Shroudless Fan Performance
Corrected total engine airflow - kg/sec (lbm/sec)	622 (1372.8)
Corrected rotor speed - rpm	4215
Fan tip speed - m/sec (ft/sec)	455 (1496)
Corrected flow/unit area - kg/sec-m^2 (lbm/sec-ft^2)	19 (43.0)
Duct/pressure ratio	1.740
Duct goal efficiency - percent	87.3
Surge margin goal - percent	15

SECTION 4.0 SHROUDLESS, HOLLOW FAN BLADE FABRICATION TECHNIQUES

4.1 Fabrication Requirements

To manufacture the Energy Efficient Engine hollow blade, as designed, required the development of a new fabrication technique because of the wide chord of a shroudless fan blade and the requirement for precise dimensional control of the cavities that comprise approximately two-thirds of the airfoil length. The size of the Energy Efficient Engine fan blade alone would make conventional forging of a solid configuration difficult. The addition of cavities further compounds the manufacturing complexities to be considered.

The success of the fabrication process was contingent upon accurate leading and trailing edge thickness, accurate wall thickness control, and smooth, full internal cavity radii. The requirement for precisely located and close tolerance cavities was the greatest challenge.

An additional requirement, as defined by the program, was to select a manufacturing method that provides the capability to fabricate hollow fan blades in production quantities and at a competitive unit cost. These requirements reaffirm the intent of the program to develop a viable blade fabrication process and not a procedure for producing unique experimental hardware.

4.2 Fabrication Techniques

Early in the Energy Efficient Engine program, a review of possible fabrication techniques identified three potential methods for manufacturing hollow titanium fan blades. These included:

- A Superplastic Forming/Diffusion Bonding process (SPF/DB).
- A two-piece hot isostatic press/diffusion bonding process.
- A laminate-core-hot isostatic press/diffusion bonding and isothermal forging process.

4.2.1 Superplastic Forming/Diffusion Bonding

The SPF/DB process, developed by Rockwell International, is a relatively new fabrication technique for titanium that permits economical production of complex structures. This technology takes advantage of the inherent ability of titanium to be superplastically formed and readily diffusion bonded at the same temperature. Theoretically, any number of diffusion bonds may be performed simultaneously, resulting in a greatly reduced number of subassembly joining operations required by more conventional methods. The ability of titanium to elongate large amounts superplastically, means that components may be formed to final shape or near final shape with a minimum amount of post-form machining.

For producing hollow blades, three titanium sheets are diffusion bonded in selected areas (through the use of a unique stop-off pattern between sheets) and then expanded apart by internal argon gas pressure into precise die tooling. This fabrication procedure is referred to as expanded sandwich. The stop-off pattern applied to selected areas on both sides of the center sheet prevents diffusion bonding in these areas. Virtually unlimited configurations are possible. Figure 4-1 shows an example of how a simple truss core can be fabricated. Simultaneous diffusion bonding of edge and root details is possible by adding these details to the sheet pack assembly. The details then become part of the assembly during the expansion process where they become bonded to the exterior sheets.

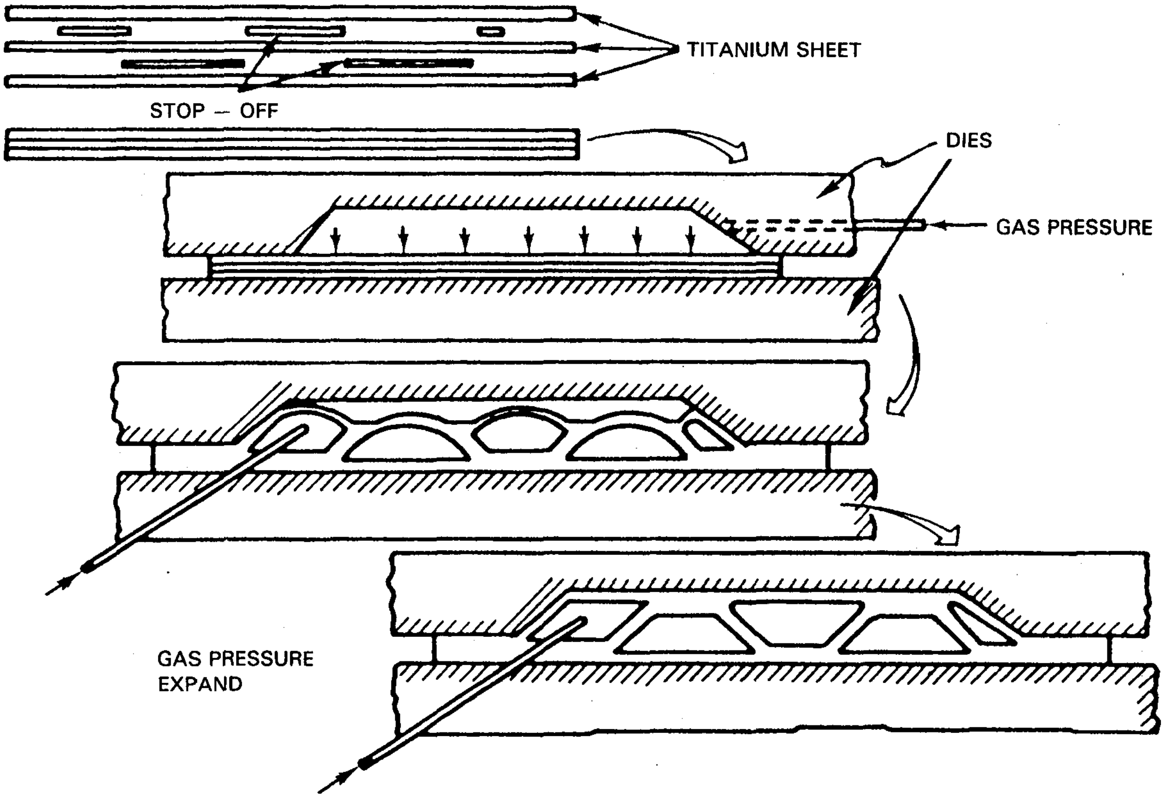


Figure 4-1 Superplastic Forming/Diffusion Bonding Expanded Sandwich Process

The SPF/DB process provides advantages that make it a suitable candidate for fabrication of hollow airfoils. In addition to producing unique hollow structures, this process offers several advantages that result in potentially lower production costs as compared to current methods. These include:

- diffusion bonds that produce parent metal properties;
- use of inexpensive titanium sheet metal compared to costly machined forgings;

- reduced post-form machining and the number of additional details required;
- concurrent multiple diffusion bonds reducing the number of subassembly joining operations required by more conventional methods;
- good dimensional control;
- and no residual stresses.

4.2.2 Two-Piece Bonding

In this two-piece manufacturing approach, hollow cavity cross rib definitions are machined into the titanium detailed halves utilizing a conventional forging/machining-to-size approach. These two pieces of machined titanium are mirror images of each other (i.e., split on the airfoil mean chord line) with their airfoil surface and hollow cavity accurately finished to final dimensions. The parts are then press bonded in accurate dies in an effort to produce acceptable bonds while maintaining the necessary hollow sectional dimensions. A more in-depth study of this process disclosed several limitations that made it impractical for producing hollow fan blades. These included:

- A requirement for a leachable core which presents an involved and costly design and fabrication process.
- The projected high cost of fabrication in the eventual production environment.

Consequently, this fabrication technique was eliminated from further consideration.

4.2.3 Laminate/Core/HIP Diffusion Bonding and Isothermal Forging Process

The third fabrication technique, the laminate-core-hot isostatic press/diffusion bonding and isothermal forging process, was proposed by TRW, Inc. This method, like superplastic forming/diffusion bonding and two-piece press bonding mentioned previously, takes advantage of the forming and bonding properties of titanium to form an airfoil using sheet titanium and leachable steel cores.

A schematic of this blade fabrication process is shown in Figure 4-2. In brief, the computer generated ply and core designs and stainless steel HIP container are fabricated by conventional methods. The cores and plies are then assembled and received by the retort. Hot isostatic pressing/diffusion bonding is then performed at a predetermined temperature and pressure. The part is removed from the container and the blade is hot cambered and twisted to near final dimensions in accurate dies. The isothermal forging is subsequently performed to accurately duplicate the airfoil to final blueprint dimensionals. Chemical core leaching and root-tip-edge machining is accomplished prior to final inspection of the part.

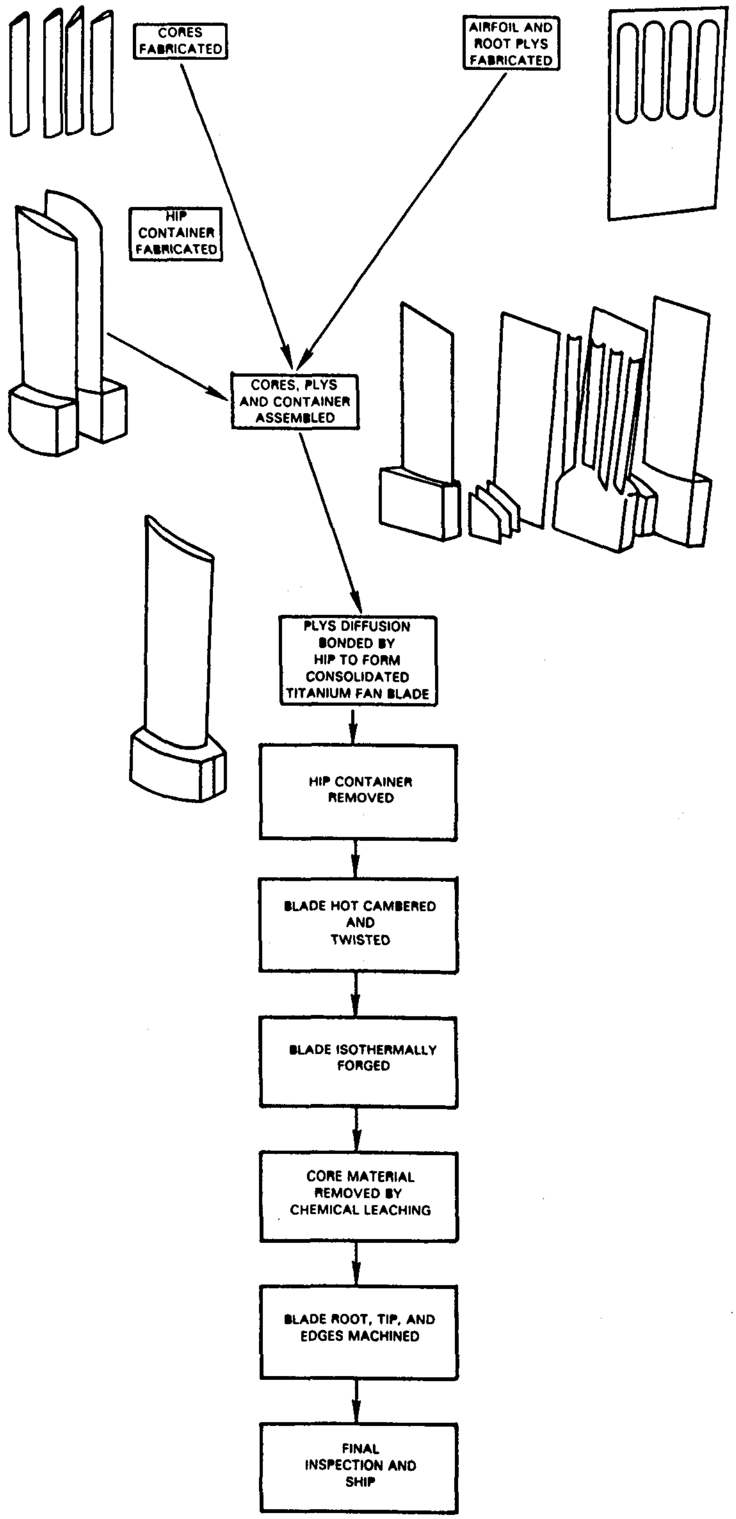

CORES FABRICATED
AIRFOIL AND ROOT PLYS FABRICATED
HIP CONTAINER FABRICATED
CORES, PLYS AND CONTAINER ASSEMBLED
PLYS DIFFUSION BONDED BY HIP TO FORM CONSOLIDATED TITANIUM FAN BLADE
HIP CONTAINER REMOVED
BLADE HOT CAMBERED AND TWISTED
BLADE ISOTHERMALLY FORGED
CORE MATERIAL REMOVED BY CHEMICAL LEACHING
BLADE ROOT, TIP, AND EDGES MACHINED
FINAL INSPECTION AND SHIP

Figure 4-2 Schematic of TRW Laminate/Core Hollow Blade Fabrication Process

The laminated process was envisioned as one that could be automated in the production environment to the point where its total cost would be comparable with the conventional blade in spite of the added complications of laminates and cores. In this production scenario, individual laminates would be made by automated stamping techniques and the cores by automated machining or casting methods. Also, blade assembly could be automated or accomplished manually by semi-skilled assembly personnel. Overall, this approach, when compared to current forging processes, offers a considerable cost savings potential.

SECTION 5.0 SHROUDLESS, HOLLOW BLADE FABRICATION PROGRAM

5.1 Introduction

This section describes the detailed efforts conducted by Rockwell International and TRW, Inc. to establish the feasibility of their respective hollow fan blade fabrication processes. The following paragraphs contain a detailed discussion on each phase of the program including the type of tooling required, specimen fabrication trial evaluations, a summary of the test results, and TRW full size protoype blade fabrication activity.

5.2 Rockwell International Specimen Fabrication Program

This phase of the hollow blade fabrication program was undertaken to establish the feasibility of the superplastic forming/diffusion bonding (SPF/DB) fabrication technique as a viable process for producing hollow airfoil parts for the gas turbine engine. To accomplish this goal, the following two primary objectives were established.

- o Demonstrate that a titanium alloy structure of the type required for large, hollow fan blades can be produced by the superplastic forming diffusion bonding fabrication technique.
- o After demonstrating the feasibility of this fabrication approach, produce specimens for subsequent fatigue testing.

The following sections provide information detailing Rockwell's effort directed towards (1) fatigue specimen design, (2) establishing viable superplastic forming diffusion bonding fabrication procedures, (3) defining and fabricating required tooling, and (4) performing experimental test runs and subsequent evaluations. Concluding remarks summarizing this technical effort follow.

5.2.1 Specimen Design and Fabrication Approach

Pratt & Whitney Aircraft provided the layout drawing of the fatigue specimen. The drawing incorporated many of the requirements applicable to large, hollow fan blades such as solid root and solid leading and trailing edges transitioning into a hollow portion stiffened by a longitudinal truss core configuration. A general view of the specimen with its basic dimensional specifications is shown in Figure 5-1.

The major technical challenge presented by superplastic forming/diffusion bonding a test specimen was to have successful transitions from solid to hollow sections in which the junctions are rounded at the interfaces. These transition zones from the hollow sandwich to the solid portions are shown in Figures 5-2 and 5-3. The excess stock provided by the as-formed part was later machined to specific geometric dimensions. The fabrication approach undertaken by Rockwell was to design a SPF/DB specimen that was symmetrical about the plane of the core with the solid portions consisting of press bonded individual elements and the hollow portion gas pressure bonded and inflated. The final transition from solid to hollow portions would be accomplished by post-expanding secondary pressure diffusion bonding to provide a fully monolithic structure. To accommodate this fabrication approach, the specimen was designed to have eleven individual subcomponents (as shown in Figure 5-4) layed up in a pack assembly comprising the entire part configuration.

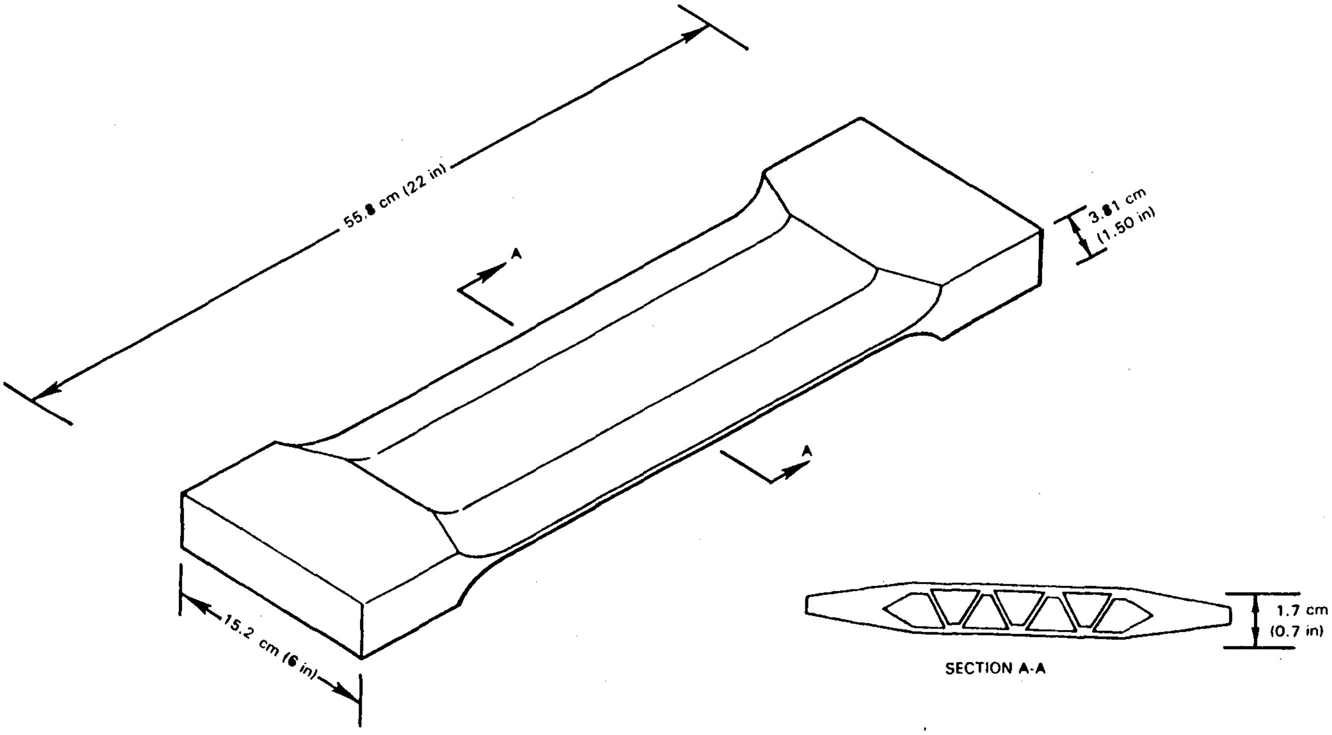

55.8 cm (22 in)
A
A
3.81 cm
(1.50 in)
15.2 cm (6 in)
1.7 cm
(0.7 in)
SECTION A-A

Figure 5-1 Energy Efficient Engine Hollow Blade Fatigue Specimen

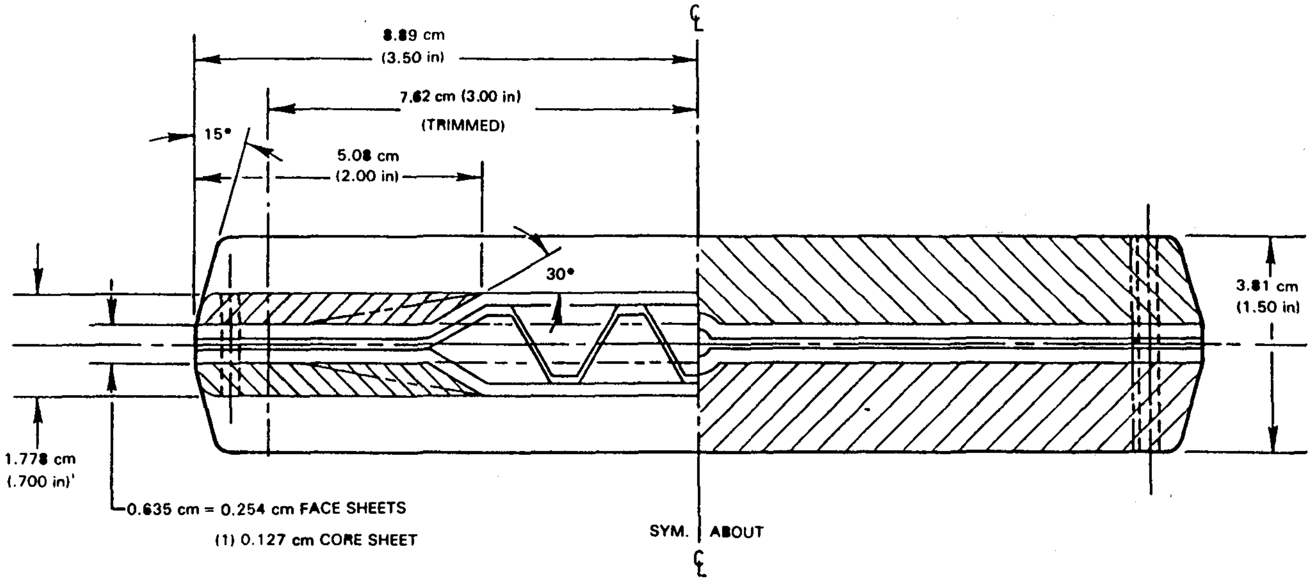

8.89 cm
(3.50 in)
7.62 cm (3.00 in)
(TRIMMED)
15°
5.08 cm
(2.00 in)
30°
℄
3.81 cm
(1.50 in)
1.778 cm
(.700 in)'
0.635 cm = 0.254 cm FACE SHEETS
(1) 0.127 cm CORE SHEET
SYM. ABOUT
℄

Figure 5-2 Transverse Section of Superplastically Formed/Diffusion Bonded Fabricated Part

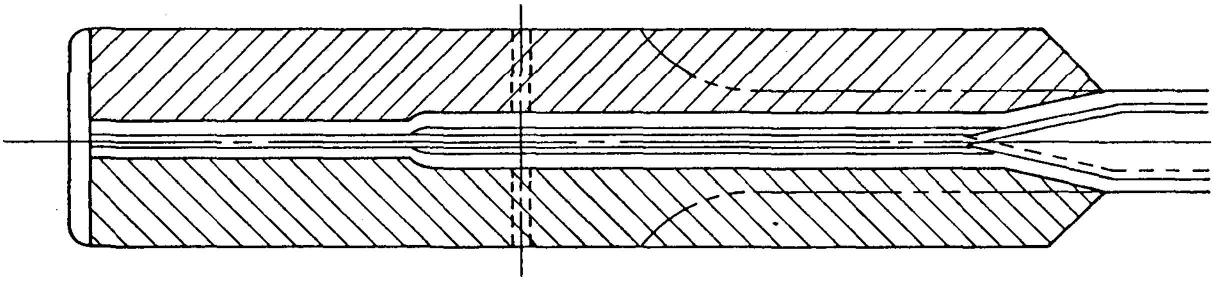


Figure 5-3 Longitudinal Section of Superplastically Formed/Diffusion Bonded Fabricated Part

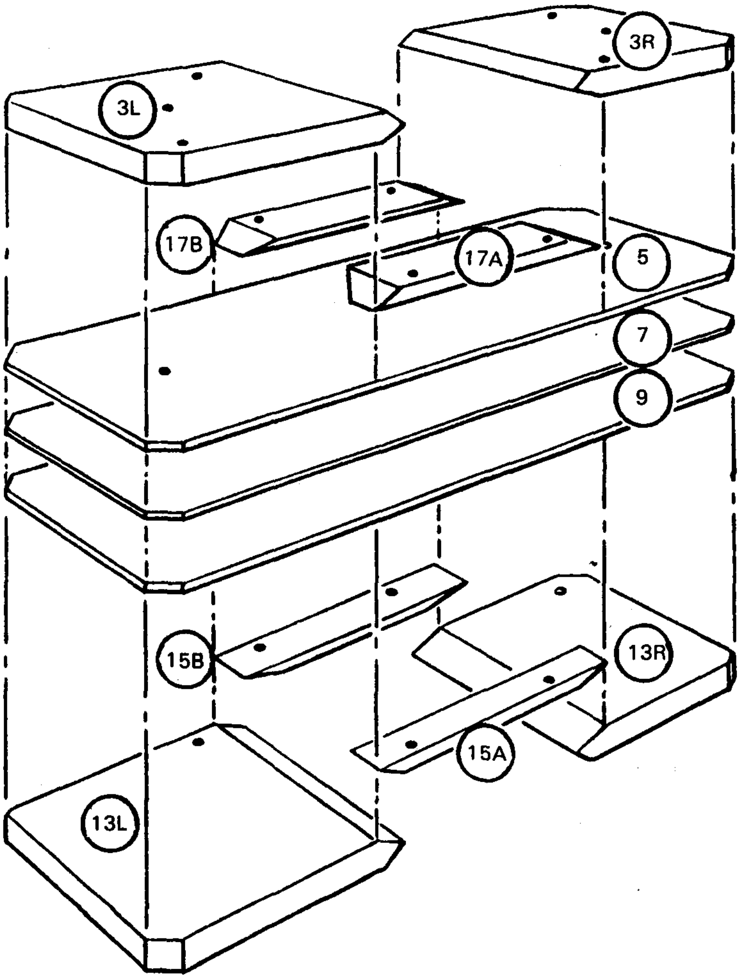

3R
3L
17B
17A
5
7
9
15B
13R
15A
13L

Figure 5-4 Hollow Blade Specimen Featuring Eleven Subcomponents

5.2.2 Process Tooling

Required tooling for specimen fabrication consisted of a two-piece SPF/DB press bonding tool and a set of silk screens used for the longitudinal truss core portion of the fatigue specimens. The SPF/DB tool was designed to produce up to three parts per run to simulate fabrication of production part quantities. It consists of a lower and upper (see Figure 5-5) set of high temperature stainless steel plates with three machined cavities designed to accommodate the assembled packs. The lower tool has alignment dowels and argon gas inlet and outlet tubes to provide purging argon gas to the periphery of the part and purging gas/vacuum to the central portion of the part. The upper tool was designed with (1) alignment slots for the lower tool alignment dowels, (2) gas inlet and outlet tubes having the same applications as mentioned for the lower tool, and (3) inlet and outlet tubes for the tubeless injection system used in the post-expanding gas pressure diffusion bonding cycle described in section 5.2.3. The upper and lower tools were rough machined, stress relieved, then finish machined and preoxidized at 926°C (1700°F) prior to use. Silk screens were prepared to provide the longitudinal truss core configuration for the hollow portion of the experimental parts.

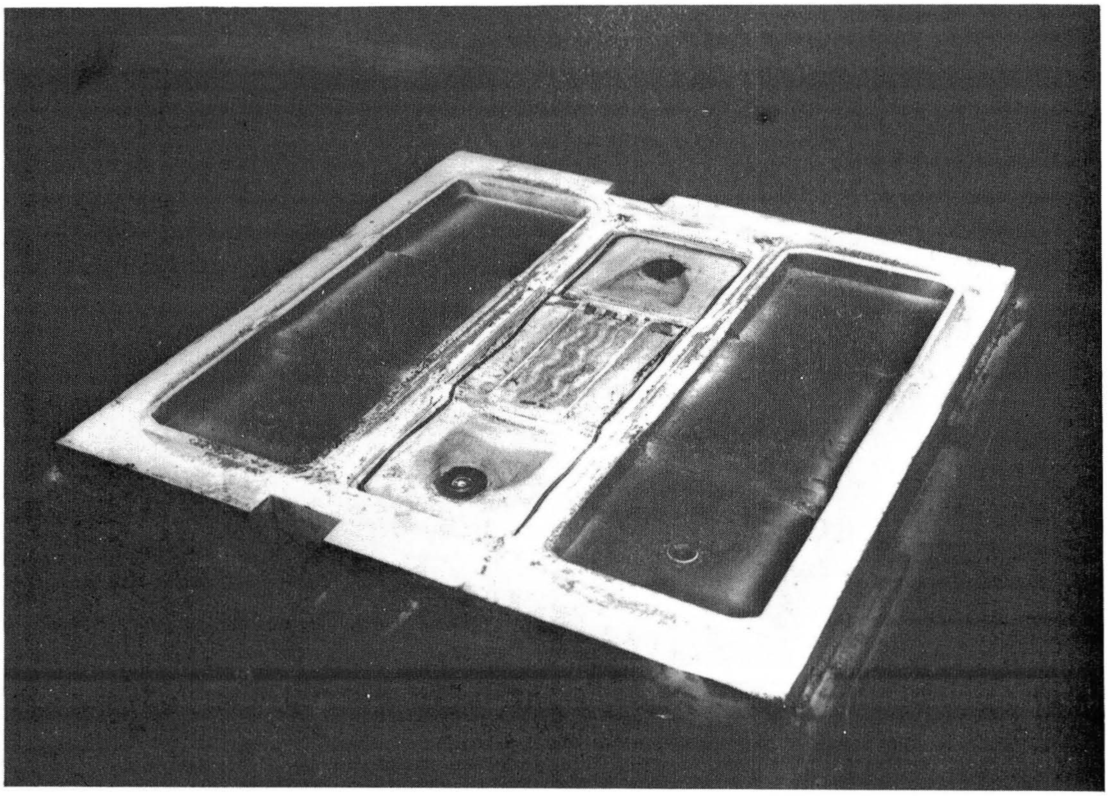


Figure 5-5 Superplastic Forming/Diffusion Bonding Tool (Upper Cavity) Used In Fabrication Of The Hollow Fatigue Specimen

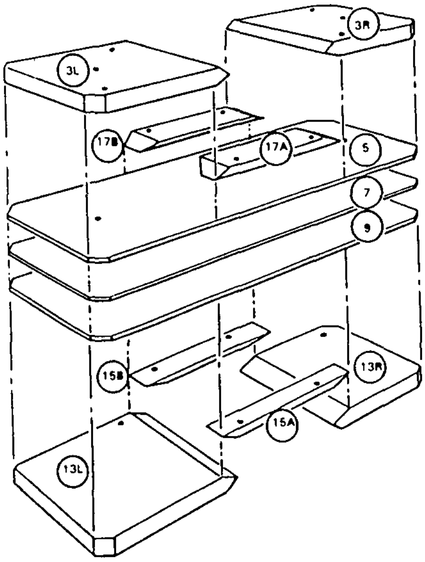
5.2.3 Fabricated Specimen Evaluation Results

Rockwell produced a total of fourteen specimens. Baseline procedure, tooling and part design modifications evolving from this effort were incorporated into each successive run until a technically successful part was produced in experimental run 14. The initial baseline fabrication procedure used in the first ten experimental runs resulted in unsatisfactory secondary bonds. Visual and nondestructive evaluation results from experimental runs 1-10 are briefly described further on in the text. Because of these recurring problems in achieving acceptable secondary bonds, an analysis of the baseline procedure was undertaken. It was determined that the secondary bonding problems were a direct result of part overexposure to operational temperature conditions. Based on this premise, a decision was made to modify the original baseline procedure to a two-heat cycle process in order to reduce the exposure time being experienced by secondary bonding areas. The modified two-heat cycle fabrication procedure, described below, was used for experimental runs 11-14.

TWO HEAT CYCLE FABRICATION PROCEDURE

- Prepare the eleven subcomponents for each specimen, record their thickness and heat number data on a record sheet form (Figure 5-6) for specimen layup.
- Apply the stop-off pattern to each side of the center sheet and verify registry by radiography.

P&W SPF/DB TEST SPECIMEN
SERIAL NUMBER ____________ (REFERENCE DRAWING SK 16978, SHEET 2)



MACHINING CONTROL NO.	DETAIL	HEAT NUMBER	MACHINED THICKNESS
	- 3L		
	- 3R		
TOP FACE SHEET T	- 5		
CORE	- 7		
LWR FACE SHEET	- 9		
	- 13L		
	- 13R		
	- 15A		
	- 15B		
	- 17A		
	- 17B		

Figure 5-6 Recording Sheet For Initial Specimen Lay Up

First Heat Cycle: The primary purpose of the first heat cycle was to flat bond center and face sheets into a pack assembly for later use in the second heat cycle. Three methods were used to prebond the center and face sheets. The first method, shown in Figure 5-7, resulted in trapped residue from the stop-off binder and excessive alpha case on the outer surfaces. The second method, illustrated in Figure 5-8, was not successful because of susceptibility to surface contamination. The third and final method (see Figure 5-9), was to flat bond the sheets in a vacuum pumped, sealed steel can. This third method proved successful and was used to produce the core assembly for use in experimental runs 11-14. Procedures incorporated into the first heat cycle are detailed below.

- Lay up the center and face sheets and tack weld the edges to secure for eventual handling.
- Place pack (center and face sheets) in a high-temperature, stainless steel bonding can, seal can periphery by edge fusion welding, perform vacuum pump evacuation, and leak check using a mass spectrometer.
- Heat can to a bonding temperature of 926°C (1700°F) while pumping with a high vacuum pumping system.
- Perform initial bonding using argon gas at 2068.4 MPa (.3 ksi) pressure for 1 1/2 hours and allow cooling.
- Remove the bonded sheets from the steel can and electro-chemically machine .007-.012 cm (.003-.005 in) from each surface side.
- Drill inflation holes and effect breakthrough using argon gas pressure.

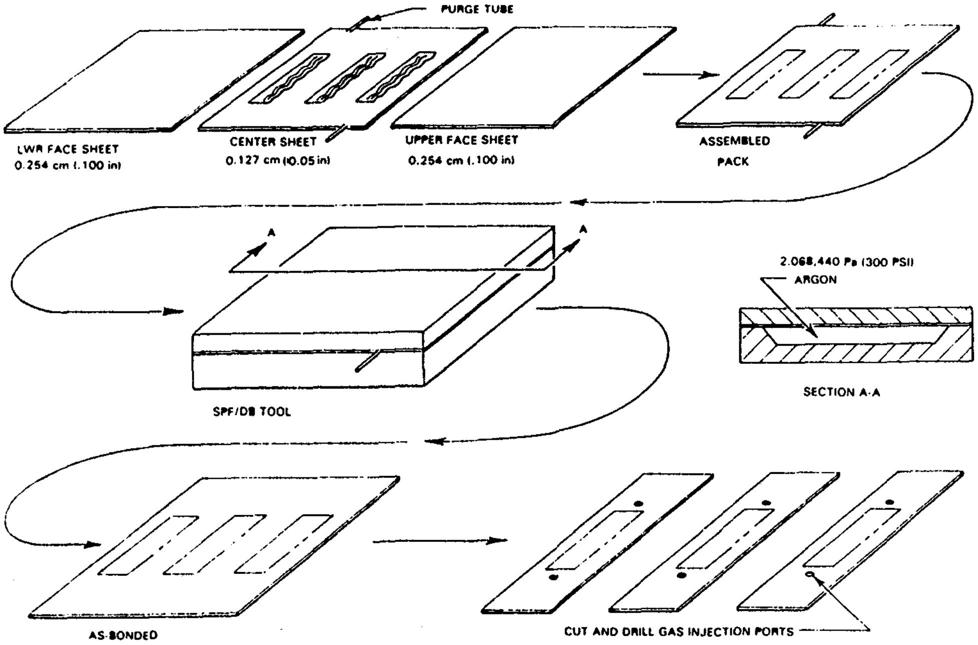

PURGE TUBE
LWR FACE SHEET
0.254 cm (.100 in)
CENTER SHEET
0.127 cm (0.05 in)
UPPER FACE SHEET
0.254 cm (.100 in)
ASSEMBLED
PACK
A
A
2,068,440 Pa (300 PSI)
ARGON
SECTION A-A
SPF/DB TOOL
AS-BONDED
CUT AND DRILL GAS INJECTION PORTS

Figure 5-7 First Method Used To Flat Bond Center and Face Sheets For SPF/DB First Heat Cycle Procedure

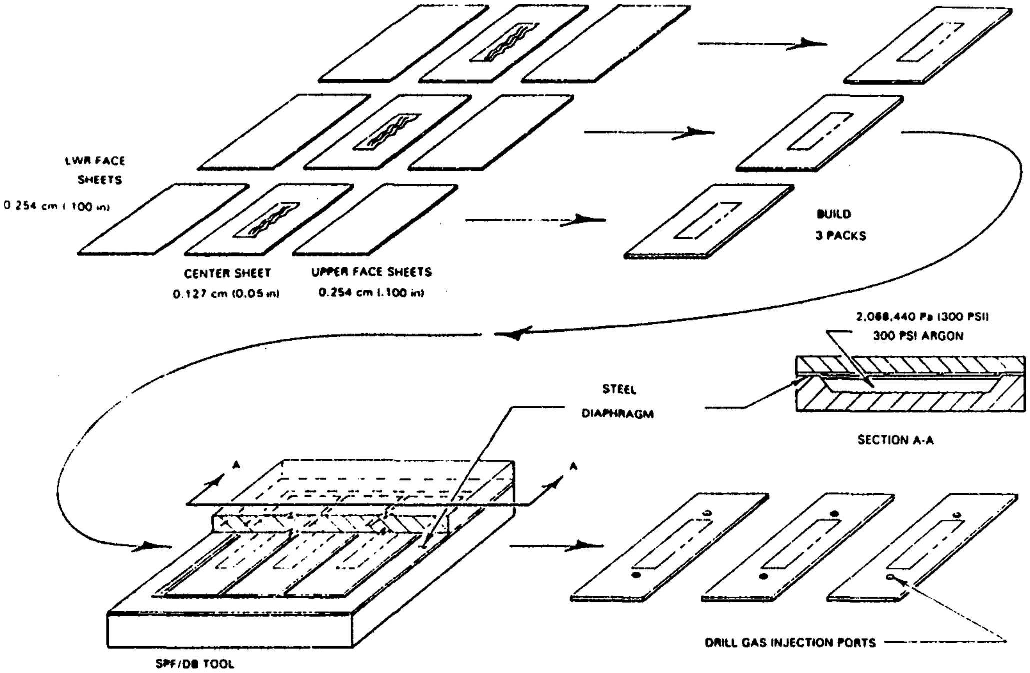

LWR FACE SHEETS
0.254 cm (.100 in)
CENTER SHEET
0.127 cm (0.05 in)
UPPER FACE SHEETS
0.254 cm (.100 in)
BUILD
3 PACKS
2,068,440 Pa (300 PSI)
300 PSI ARGON
STEEL
DIAPHRAGM
SECTION A-A
A
A
SPF/DB TOOL
DRILL GAS INJECTION PORTS

Figure 5-8 Second Method Used To Flat Bond Center and Face Sheets For SPF/DB First Heat Cycle Procedure

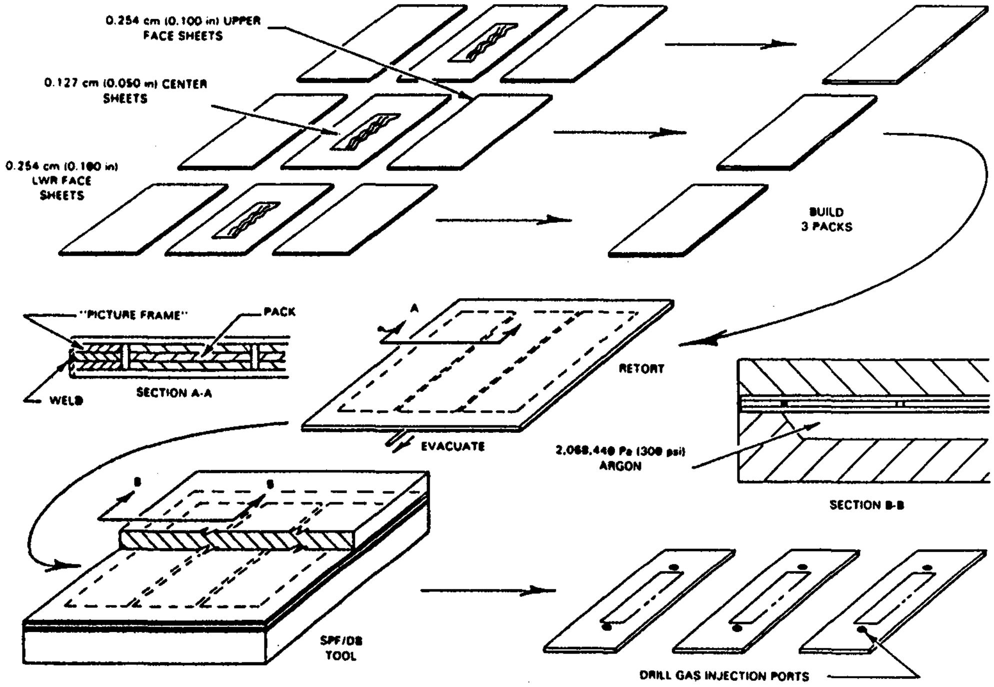

0.254 cm (0.100 in) UPPER FACE SHEETS
0.127 cm (0.050 in) CENTER SHEETS
0.254 cm (0.100 in) LWR FACE SHEETS
BUILD
3 PACKS
"PICTURE FRAME"
PACK
WELD
SECTION A-A
A
RETORT
EVACUATE
2,068,440 Pa (300 psi)
ARGON
SECTION B-B
B
B
SPF/DB
TOOL
DRILL GAS INJECTION PORTS

Figure 5-9 Third Method Used To Flat Bond Center and Face Sheets For SPF/DB First Heat Cycle Procedure

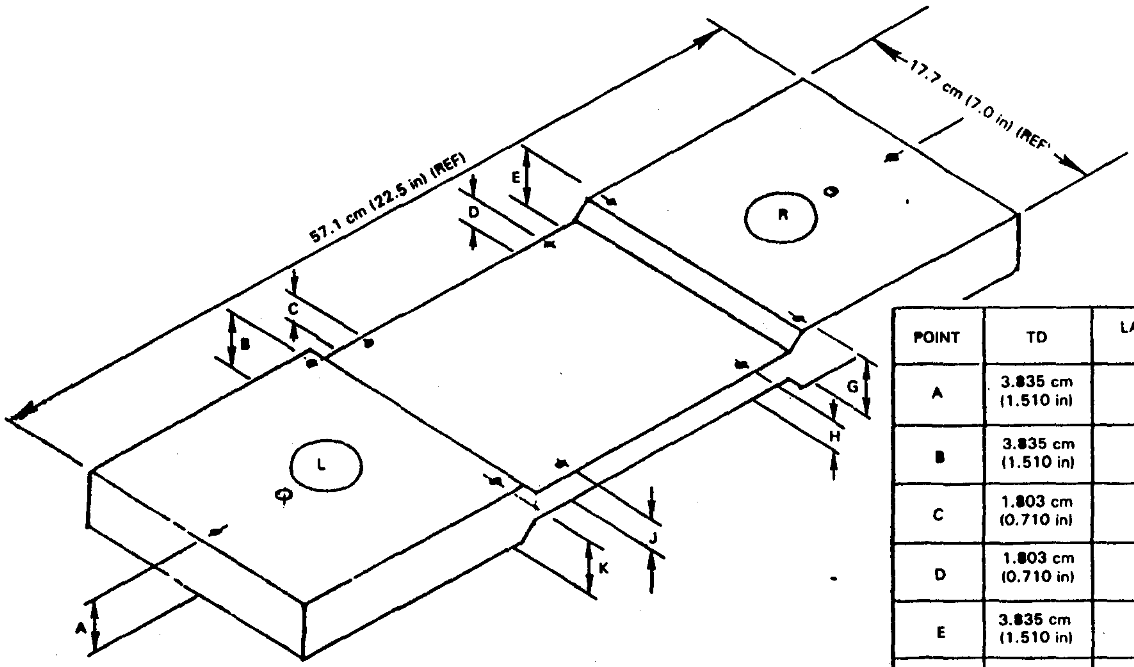
Second Heat Cycle:

The prebonded core assembly was then made available for assembly with the remaining subcomponents for second heat cycle processing to effect press bonding, inflation, and post-inflation bonding. The fabrication procedures used for the second heat cycle are detailed below.

- Lay up the remainder of the subcomponents incorporating the bonded pack and tack weld the edges to facilitate handling. In addition, tack weld the titanium wire gaskets to the upper and lower surfaces of the SPF/DB tool.
- Heat the SPF/DB tool to a thermal operating condition of 537°C (1000°F).
- Once the required temperature has been attained, open the press and insert the part.
- Close the press and heat the part to approximately 926°C (1700°F).
- Once the required temperature has been attained, press bond.
- Reduce the pressure in the upper and lower cavity of the SPF/DB tool to a negative pressure of 30 mm Hg (using a mechanical vacuum pump) and run the inflation cycle.
- Increase internal argon gas pressure to 4136.9 MPa (.6 ksi) and maintain this pressure level for three hours to effect post-inflation bonding.
- Depressurize using a mechanical vacuum pump and remove the hot part.
- Examine the part and enter dimensions on record sheet (see Figure 5-10) for finished parts, radiograph core area, and ultrasonic C-scan the secondary bonds.
- Machine the part to final dimensions.

Discussed in the following paragraphs are individual test run results determined from visual and nondestructive evaluation of the part and/or tool. As mentioned previously, experimental runs 1-10 experienced secondary bonding problems that required eventual modification of the baseline fabrication procedure to a two-heat cycle.

In the first run serious gas leaks prevented initial full bonding pressure and vacuum from being achieved. Specified argon gas pressure of 2068.4 MPa (.3 ksi) could not be maintained during the sandwich process of the inflation cycle. The outlet tube on the center cavity gas system was cracked, no core was formed and the secondary bonds were poor.



E³ fatigue test specimen no.______thickness dimensions (TD)

POINT	TD	LAYUP TD	AS-FORMED TD
A	3.835 cm (1.510 in)		
B	3.835 cm (1.510 in)		
C	1.803 cm (0.710 in)		
D	1.803 cm (0.710 in)		
E	3.835 cm (1.510 in)		
F	3.835 cm (1.510 in)		
G	3.835 cm (1.510 in)		
H	1.803 cm (0.710 in)		
J	1.803 cm (0.710 in)		
K	3.835 cm (1.510 in)		

Figure 5-10 Record Sheet For Finished SPF/DB Part

To improve top-half tool and bottom-half tool sealing for the second run, a commercially pure (CP) titanium wire seal gasket was used around the tool periphery. However, another gas leak occurred during the initial bonding phase and the run was stopped. Two outlet tubes had cracked weldments. The tool was cooled overnight while maintaining press pressure and an internal argon gas purge. After repair welding of the tubes, the tool was reheated to operational temperature. Initial bonding pressure and breakthrough were then achieved. However, a gas leak was observed during secondary bonding due to detail design error (i.e., relief groove on details 3R and 3L provided a direct path from the injection port to the upper cavity). This condition required the redesign of these detail parts. The core did not form and the secondary bonds were inadequate.

Run 3 had an additional titanium wire seal gasket attached to the upper and lower surfaces of the part, located in the trim area. Once again, gas leakage prevented initial bonding pressure from being achieved and a gas management tube cracked at the weld.

Initial bonding pressure was not attained in Run 4 due to a gas leak and a gas management tube was found cracked at the weld. After repair, the cycle was completed and the part machined and shipped to Pratt & Whitney Aircraft for use in setting up their test fixture.

Run 5 had the CP titanium gasket on the lower tool surface eliminated. Initial bonding pressure was attained, the cavity pressures reduced, but the breakthrough attempt failed. Examination of the tool indicated one of the injection ports was cracked. After repair, this part completed post-inflation bonding, and was depressurized and removed from the tool. Radiography inspection revealed nonbonded areas in the core and unsatisfactory secondary bonds.

No changes from experimental run 5 were effected for Run number 6. After achieving breakthrough, gas continuity through the core was restricted. This condition results in an undesirable pressure-time cycle through the sandwich process inflation cycle. Pressure/time cycles are determined by a computer software package developed by Rockwell that utilizes physical properties of the titanium alloy as they influence constant strain rate deformation. Pressure-time must be uniform to assure controllable constant strain.

Run 6 breakthrough problems were alleviated in Run 7 by having stainless steel tubes placed in the gas path on each side of the part to allow for the forming gas to get in and out through the root section until part expansion started. This approach was successful and the part was subjected to the entire procedure cycle. However, radiography revealed nonbonded areas in the core.

With all prior tooling problems resolved, Run 8 repeated the baseline procedure. To improve initial bonding, a 0.050 cm (0.020 in) thick by 3.81 cm (1.50 in) diameter washer was welded to details 3L and 3R over the tubeless injection holes to obtain a better seal, and a hydrox drying unit was used in the center circuit. Radiography showed a good core. The sectioned part indicated that core to solid part intersection on the side rails and the end blocks were very sharp and secondary bonds were inadequate.

In Run 9, sharp intersections were eliminated by altering the silk screen to reduce the length and width of the stop-off pattern. The central portion of the tool cavity was modified to improve secondary bonding. Radiography inspection indicated the core was good but the secondary bonds were unsatisfactory.

Detail subcomponents were modified for Run 10 to better accommodate expanding face sheets and improve secondary bonds. These contoured end blocks (details 3L,3R, 13L, 13R) did improve the interface between the face sheets and the end blocks; however, secondary bonds were still unsatisfactory.

At this point in the program, all tooling problems were alleviated and procedures up to the secondary bond phase were reproducible and satisfactory. To provide for successful secondary bonds, the original baseline procedure (used for experimental runs 1-10) was modified to the two-heat cycle procedure for experimental runs 11-14 with the following results.

In Run 11 the part was processed to its completion. Evaluation results indicate surface roughness with creases near the end blocks (attributed to trapped gas) and poor secondary bonds (caused by alpha case on the flat sheet pack surface).

The same two-heat cycle procedure used in Run 11 was used in Run 12 with the same results. Further analysis indicated rough surface creases were formed by flow forming of the end blocks and that inadequate secondary bonds were again a result of alpha case on the flat bonded center sheet surface. Even initial bonds from the first heat cycle were inadequate.

In Run 13 the secondary stack-up was reduced by 0.101 cm (0.040 in) to eliminate the creasing problem and facilitate part removal. In addition, secondary bonding was improved by increasing the secondary bonding time and pressure, and electro-chemically milling the alpha cased flat sheet pack surface. A gas leak prevented internal argon gas pressure of 4136.9 MPa (.6 ksi), used for post-inflation bonding, from being attained. This gas leak contributed to contamination of the secondary bond. This part was shipped to Pratt & Whitney Aircraft for scheduled metallographic evaluations.

Prior to initiating the same part fabrication process for Run 14, SPF/DB tooling cracks in the trim area were ground out and the areas weld repaired using Inconel 'A'^{TM}, a ductile, nickle base alloy. The part was then run to its conclusion. Subsequent visual, nondestructive, and metallographic examination of the part indicated that secondary bonding was achieved. However, surface creases near the end blocks and edge details were apparent along with visible surface depressions in the hollow section at the center sheet bond location. A cross-section of test specimen 14, highlighting a fully formed core with complete bonding, is shown in Figure 5-11.

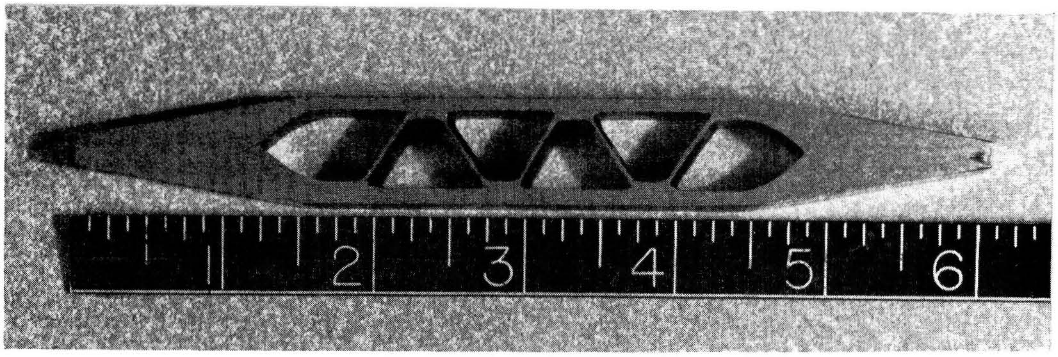


Figure 5-11 SPF/DB Cross Section Of Experimental Run Part 14 Indicating Complete Bonding and Fully Formed Core

5.2.4 Summary of Results

The Rockwell International program demonstrated (1) the SPF/DB fabrication process can produce large, hollow titanium structures of the type required for gas turbine application; (2) extensive development of the process is required in order to provide hardware of the consistently high quality necessary for future gas turbine fan blades. The program, while uncovering problem areas of concern in the SPF/DB process, provided insight into the directions required to refine the manufacturing cycle in order to reduce or eliminate some of these problems.

Bond contamination and poor secondary bonding, as discussed in the preceding text, received much attention during the course of the program due to its criticality to process feasibility. The two-heat cycle, which incorporated an intermediate chemical milling step and a final secondary bonding in a vacuum environment, greatly improved the bond quality in the specimens. However, extensive metallographic examination of bond quality to determine the consistency of the process was not undertaken. This metallographic work will be required to ensure process repeatability.

Sharp internal radii between center sheet and face sheets is a characteristic of SPF/DB titanium. Perimeter hollow section radii can be controlled satisfactorily by the solid root and edge details. The center sheet to sheet radii, however, cannot be controlled during the expansion process and are typically less than 0.012 cm (0.005 in). The effect of these sharp corners on fatigue life was to be determined during the originally scheduled specimen test program. Since fabrication difficulties encountered in the course of the program exhausted allotted funding prior to the completion of the required number of specimens, the effect of these sharp radii on the design life of a hollow blade could not be assessed. During the initial review of the SPF/DB process, the sharp radii were recognized as a potentially serious problem that could affect the suitability of the process to the highly stressed environment of a fan blade; but to modify the fabrication process in an effort to eliminate this problem was considered beyond the scope of the contract program.

Surface roughness was determined to be a problem with SPF/DB. A seam was formed at the secondary bond joint between the surface sheets and the other mating details on all parts produced employing the two-heat cycle. Increased secondary bonding time and increased pressure improved this condition but did not eliminate it. Further effort is required to completely eliminate this surface defect. The seam was removed in the final two Rockwell parts by a light surface machining. This is an undesirable step in the process since a basic advantage of SPF/DB is fabrication of as-formed shaped parts.

A second surface problem was apparent in various degrees in all specimens produced. This problem was a depression or lack of complete expansion in the hollow section at the location of the primary bonds. This occurred randomly in all specimens and did not involve the entire bond surface. Increased expansion pressure and time improved this condition but did not eliminate it completely. The depression was removed in the final two parts by a light surface machining which, as stated above, is an undesirable step, and in this situation, reduced the wall thickness of the parts. The additional effort required to resolve this problem was considered beyond the scope of the program.

Dimensional measurements were recorded before and after forming. In general, the measurements recorded indicate that the process is repeatable and accurate within a reasonable tolerance range. No data on part flatness, sectional interrelationships, post machining records, or internal hollow section measurements were acquired. Again, the additional effort required to establish the accuracy and repeatability of parts made by this process was considered beyong the scope of the program.

And finally, no attempt was made to estimate final fabrication costs for a large hollow fan blade considering the knowledge gained in this fabrication effort.

5.3 TRW Specimen/Blade Fabrication Program

The TRW fabrication program was undertaken to establish feasibility of the full lamination/diffusion bonding and isothermal forging process as a viable approach in fabricating full size hollow blade parts for the gas turbine engine. To accomplish this goal, a two task program was conducted at TRW. The primary objectives for Task 1 were to (1) define a set of general instructions for use in computer aided design of the individual sheets and cores, and (2) establish fabrication processing techniques for producing a cored, diffusion bonded, titanium laminated blade specimen. The primary objective for Task 2 was to fabricate full size hollow titanium fan blades employing fabrication techniques established in Task 1 and demonstrate the isothermal forging method for finish forming the blade. The following sections present information detailing TRW's effort directed towards achieving these objectives.

5.3.1 Task 1 - Diamond Specimen (DS) Process Development

5.3.1.1 Design and Fabrication Approach

In order to establish the elements of blade design and fabrication processing, TRW evaluated various process parameters for possible use in fabricating a diamond shaped, fully laminated and cored test specimen, shown schematically in Figure 5-12. Elements of blade design considered were laminate thickness, cost effective ply cutting approaches, core design, hot isostatic press (HIP) can design and fabrication, and inspection tooling for ultrasonic, radiographic non-destructive evaluations of the fabricated specimen. A total of twenty-five test specimens were fabricated during the performance of this task. The elements required for this fabrication effort, including ply definition, core design, and HIP can design and fabrication, are presented in the following subsections.

Diamond Specimen Ply Definition: Two types of ply designs were considered for the fabrication of the diamond shaped specimens, depending upon whether the diamond specimen was solid or hollow.

Ply design for the solid configuration (DS1) consisted of sixteen primary laminations all parallel to the outside surface. Eight laminates were 0.076 cm (0.030 in) thick and eight laminates were 0.025 cm (0.010 in) thick with a filler in-between to control the volume of the specimen. However, evaluation of this configuration in regard to hollow blade specimen fabrication indicated the titanium laminates would intersect the hollow specimen steel cores at an angle which could result in irregular cavity surface. To alleviate this possible problem and to have better ply definition, the laminates for the hollow specimens were redesigned.

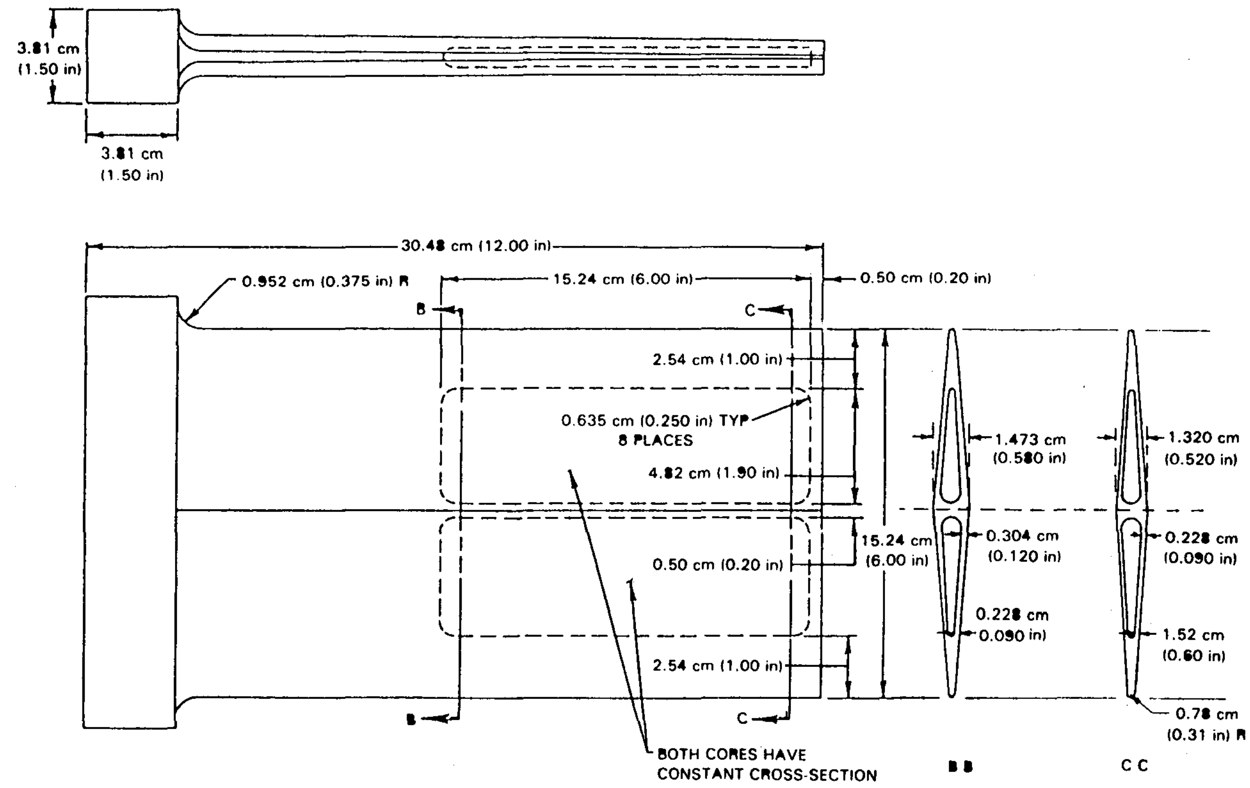
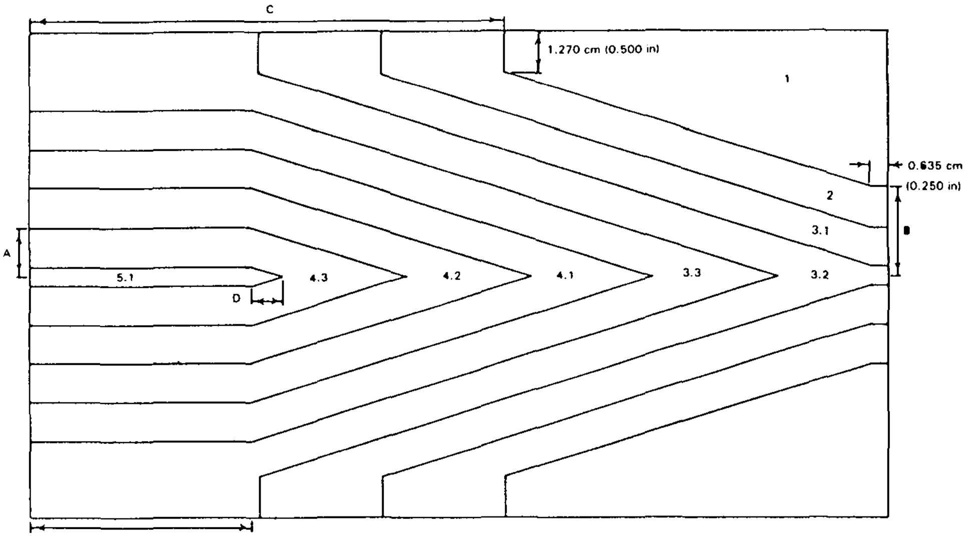

3.81 cm
(1.50 in)
3.81 cm
(1.50 in)
30.48 cm (12.00 in)
0.952 cm (0.375 in) R
15.24 cm (6.00 in)
0.50 cm (0.20 in)
B
C
2.54 cm (1.00 in)
0.635 cm (0.250 in) TYP
8 PLACES
4.82 cm (1.90 in)
0.50 cm (0.20 in)
2.54 cm (1.00 in)
15.24 cm
(6.00 in)
1.473 cm
(0.580 in)
0.304 cm
(0.120 in)
0.228 cm
0.090 in)
1.320 cm
(0.520 in)
0.228 cm
(0.090 in)
1.52 cm
(0.60 in)
0.78 cm
(0.31 in) R
B
C
BOTH CORES HAVE
CONSTANT CROSS-SECTION
B B
C C

Figure 5-12 TRW Test Specimen Design

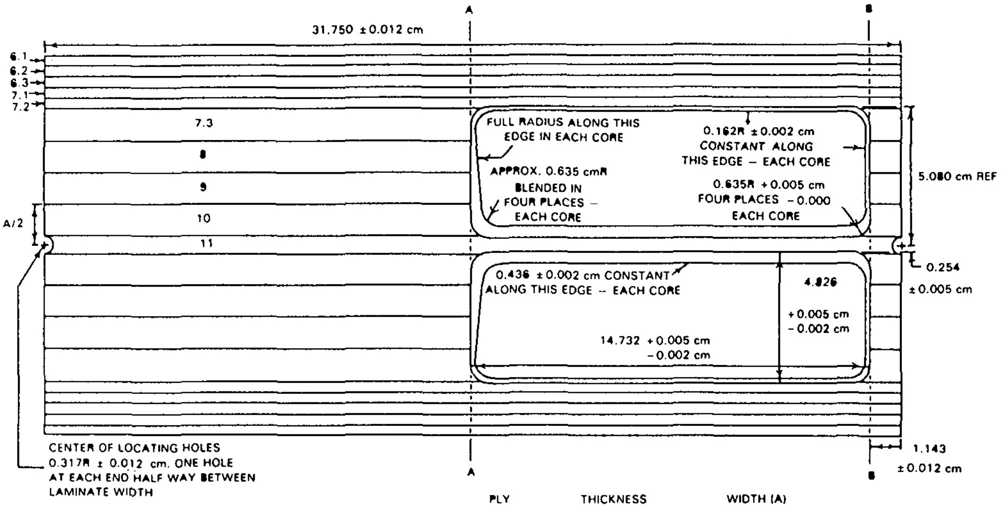
The revised configuration for use in the fabrication of the hollow specimen consisted of ten outermost layers (Figure 5-13) parallel to the outside surfaces, a 0.025 cm (0.010 in) thick ply that lays in contact with the plane of cores, and ten core laminates (Figure 5-14) that form the central portion of the specimen half. These twenty-one laminates form one-half of the specimen configuration with additional miscellaneous pieces, shown in Figure 5-15, used to fill any voids at the edges of these pieces. All plies consisted of Ti 6Al-4V sheet material procured in 0.025 cm (0.010 in), 0.076 cm (0.030 in), 0.157 cm (0.062 in), and 0.317 cm (0.125 in) thicknesses and meeting the Pratt & Whitney Aircraft material specifications for acceptable microstructures.

Core cavities in most of the plies were cut by a stamping die. This technique proved to be a very inexpensive, high volume production approach. Some core cavities were also electro-discharge machined where the core plies were layed up for each specimen half and machined as an assembly with a graphite electrode shape resembling one-half of the core. This approach was advantageous in that the contact surfaces between the core and the plies were parallel at all points to maintain better core registry. Wire electro-discharge machining was also considered for cutting the plies, but because this method could only cut one ply at a time it was not selected.


C
1.270 cm (0.500 in)
1
0.635 cm
(0.250 in)
2
3.1
B
A
5.1
4.3
4.2
4.1
3.3
3.2
D
8.255 cm (3.250 in)

PLY	THICKNESS	A	B	C	D
1	0.076 cm (0.030 in)	8.8 cm (3.5 in)	8.8 cm (3.5 in)	31.750 cm (12.500 in)	–
2	0.076 cm (0.030 in)	8.8 cm (3.5 in)	3.192 cm (1.257 in)	17.688 cm (6.964 in)	–
3.1	0.025 cm (0.010 in)	8.8 cm (3.5 in)	1.775 cm (0.699 in)	13.096 cm (5.156 in)	–
3.2	0.025 cm (0.010 in)	8.8 cm (3.5 in)	0.355 cm (0.140 in)	8.544 cm (3.364 in)	–
3.3	0.025 cm (0.010 in)	6.027 cm (2.373 in)	–	–	19.438 cm (7.653 in)
4.1	0.025 cm (0.010 in)	4.610 cm (1.815 in)	—	–	14.869 cm (5.854 in)
4.2	0.025 cm (0.010 in)	3.192 cm (1.257 in)	—	–	10.297 cm (4.054 in)
4.3	0.025 cm (0.010 in)	1.775 cm (0.699 in)	—	—	5.725 cm (2.254 in)
5.1	0.025 cm (0.010 in)	0.358 cm (0.141 in)	—	–	1.153 cm (0.454 in)

Figure 5-13 Outermost Titanium Laminates For Hollow Diamond Specimen


A
B
31.750 ±0.012 cm
6.1
6.2
6.3
7.1
7.2
7.3
8
9
10
11
A/2
FULL RADIUS ALONG THIS EDGE IN EACH CORE
APPROX. 0.635 cmR BLENDED IN FOUR PLACES – EACH CORE
0.162R ±0.002 cm CONSTANT ALONG THIS EDGE – EACH CORE
0.635R +0.005 cm -0.000 FOUR PLACES EACH CORE
5.080 cm REF
0.254 ±0.005 cm
0.436 ±0.002 cm CONSTANT ALONG THIS EDGE – EACH CORE
4.826 +0.005 cm -0.002 cm
14.732 +0.005 cm -0.002 cm
CENTER OF LOCATING HOLES 0.317R ± 0.012 cm. ONE HOLE AT EACH END HALF WAY BETWEEN LAMINATE WIDTH
1.143 ±0.012 cm
A
B

PLY	THICKNESS	WIDTH (A)
6.1	0.025 cm (0.010 in)	13.954 cm (5.494 in)
6.2	0.025 cm (0.010 in)	13.167 cm (5.184 in)
6.3	0.025 cm (0.010 in)	12.382 cm (4.875 in)
7.1	0.025 cm (0.010 in)	11.595 cm (4.565 in)
7.2	0.025 cm (0.010 in)	10.810 cm (4.256 in)
7.3	0.025 cm (0.010 in)	10.022 cm (3.946 in)
8	0.076 cm (0.030 in)	7.663 cm (3.017 in)
9	0.076 cm (0.030 in)	5.306 cm (2.089 in)
10	0.076 cm (0.030 in)	2.946 cm (1.160 in)
11	0.076 cm (0.030 in)	0.589 cm (0.232 in)

Figure 5-14 Innermost Titanium Laminates For Hollow Diamond Specimen

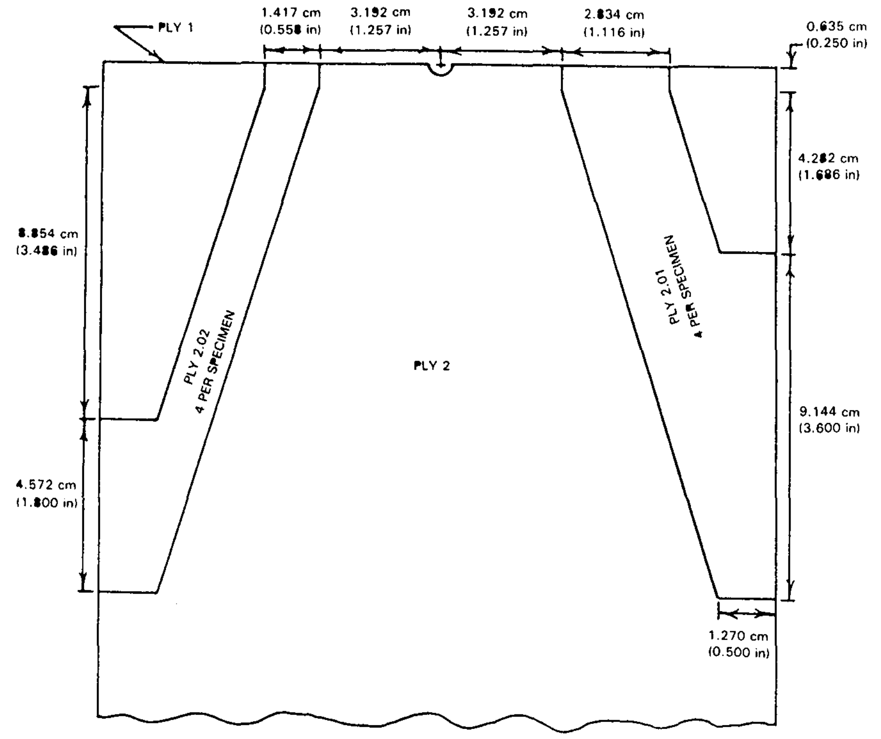

PLY 1
1.417 cm
(0.558 in)
3.192 cm
(1.257 in)
3.192 cm
(1.257 in)
2.834 cm
(1.116 in)
0.635 cm
(0.250 in)
4.282 cm
(1.686 in)
8.854 cm
(3.486 in)
PLY 2.02
4 PER SPECIMEN
PLY 2
PLY 2.01
4 PER SPECIMEN
9.144 cm
(3.600 in)
4.572 cm
(1.800 in)
1.270 cm
(0.500 in)

Figure 5-15 Miscellaneous Hollow Diamond Specimen Laminates Used To Fill In Void At Ply Endings

In addition to the laminate designs for the hollow 'airfoil' section, various specimen root design layups were evaluated during the fabrication process. The first layup, a step root, consisted of a layup of sixteen laminates per half. The eight laminates closest to the hollow airfoil surface were stepped in width, each laminate being 0.076 cm (0.030 in) wider than the previous. The eight remaining laminates were 3.8 cm (1.5 in) wide. The length of the first seven laminates was 17.7 cm (7.0 in) while the remaining nine laminates were two-piece with the length varying as a function of the diamond angle. The edge of the assembled root layup formed the root/airfoil radius. The second layup considered used a solid premachined titanium insert to form the root to airfoil radius. The root laminates in this design were all the same width. The third root layup was the straight design with all laminates 3.8 cm (1.5 in) thick. In this design the root to airfoil radius would be installed using conventional machining methods.

Diamond Specimen Core Design: All cores machined were 14.7 cm (5.8 in) long and 4.8 cm (1.9 in) wide. The two types of materials used for these cores were AISI 1045 steel or TRW VMS-478 valve steel. Several basic core designs reflecting various leading/trailing edge and centerline radii were evaluated. In addition, the core ends at the specimen end were either machined square with the breaking of the sharp corners or machined with a full radius. Examples of these cores are shown in Figures 5-16 and 5-17.

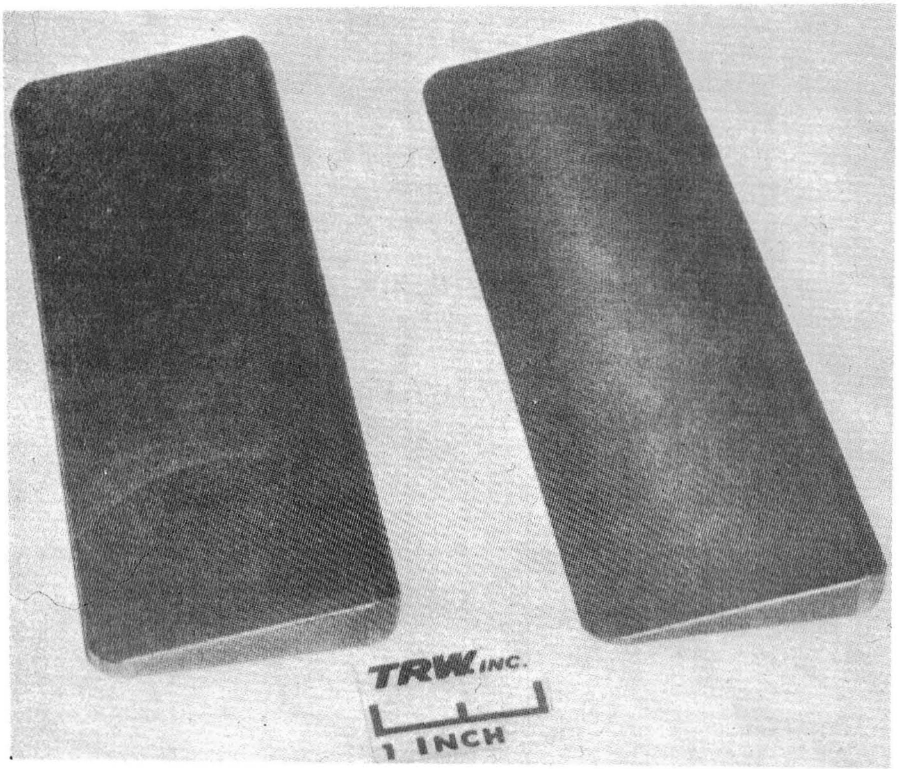


Figure 5-16 Steel Cores Used To Produce Hollow Diamond Blade Specimens 4.826 cm Wide, 14.732 cm Long: Leading-Trailing Edge/Centerline Core Radii: Left .157 cm/.432 cm; Right 0.038 cm/0.393 cm

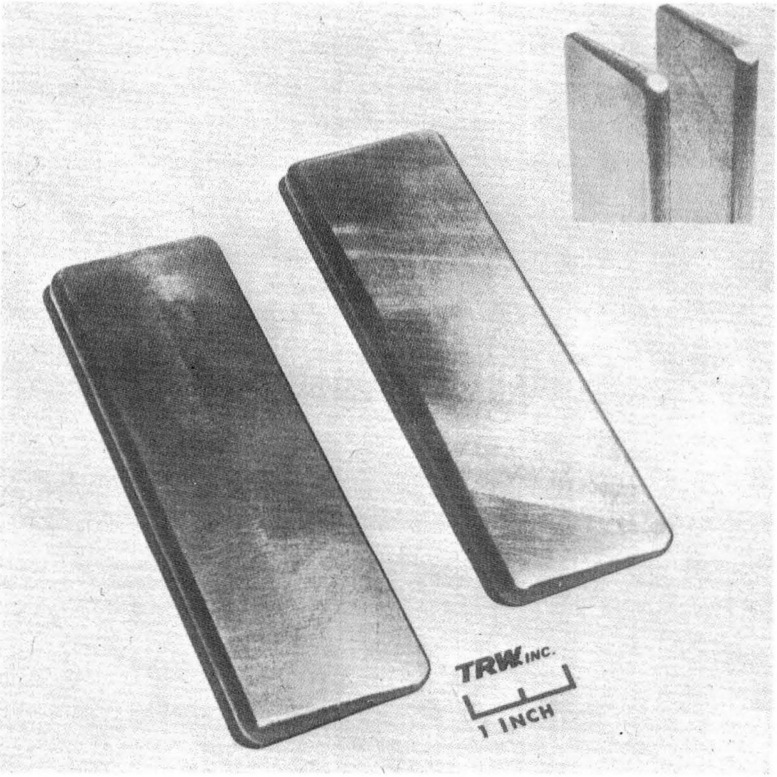


Figure 5-17 Typical .157 cm (.062 in) Radius Cores Showing Differences In End Detail

5.3.1.2 Process Tooling

Cans for hot isostatic press/diffusion bonding were manufactured utilizing the Guerin rubber pad forming method. This method is considered an expedient, cost effective approach. The can materials selected for use in the program were DQAK (AISI 1006/1008) low carbon steel for the primary can, and Inconel 744 and Ti 6Al-4V sheet material for the purpose of overcanning which is discussed in the specimen evaluation results section of this report. These cans were fabricated to a 31.7 cm (12.5 in) length and 17.7 cm (7.0 in) width both with and without a root cavity (see Figure 5-18). The flanges of the cans were used in achieving a weld between the two can halves after assembly.

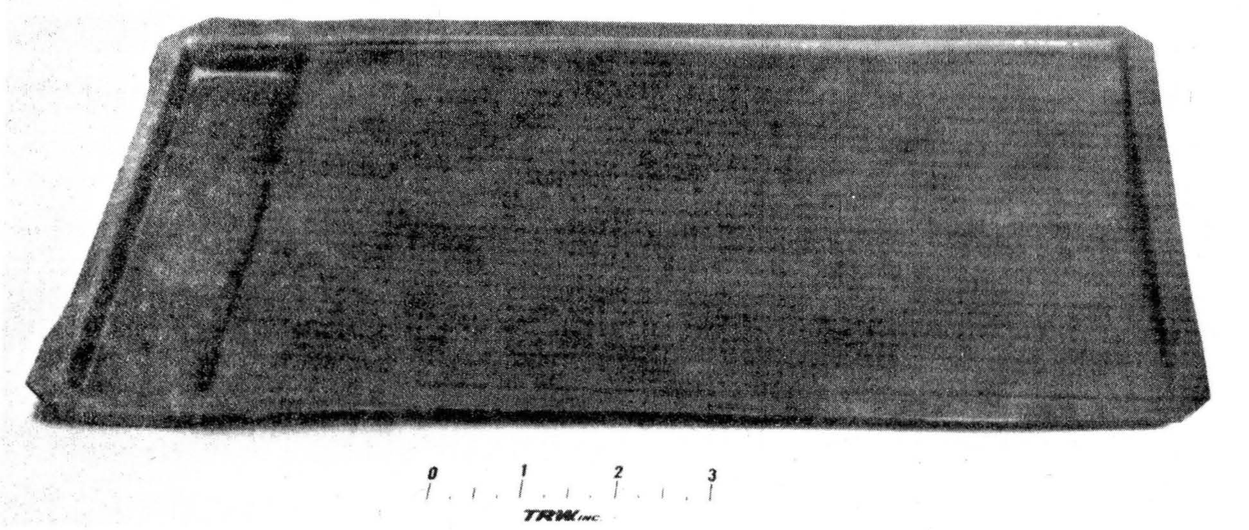


Figure 5-18 Steel Can Half Made By Pressing a Flat .152 cm (.060 in) Thick Low Carbon Steel Sheet Into a Die Using a Pad of Rubber

5.3.1.3 Fabrication Evaluation Results

TRW produced a total of 25 diamond specimens, hereinafter identified as DS1 through DS25. Baseline procedure, tooling and part design modifications evolving from this effort were incorporated into each successive run until a technically successful specimen was produced. These parameters are discussed in the following paragraphs along with the various evaluation results for each of the completed experimental runs. A complete listing of the raw material, dimensional characteristics, and fabrication parameters for diamond specimens 1 through 25 are shown in Table 5-I.

TABLE 5-I

DS1 - DS25 Specimen Characteristics

Specimen Number	Core Material	Core Edge Radius - cm (in)	Ply Cavity	Root Layup	Can Cover	Other Comments
DS1	Solid	No core	-	No root	Ti Sheet	
DS2	1045	0.157 (0.062)	Hand Cut	Straight	Carburized Can	Two Cores - One core Ti 6Al-4V foil wrapped. Second core cut in half - one piece polished
DS3	1045	0.157 (0.062)	Hand Cut	No root	Ti Sheet	Special Ti inserts around cores
DS4	VMS-478	0.157 (0.062)	EDM	Step	Carburized Steel	Stainless Steel Overcan
	1045	0.038 (0.015)	Hand Cut		Grapho11	
DS5	1045	0.157 (0.062)	EDM	Insert	Carburized Foil	Stainless Steel Overcan
	1045 Polished		Hand Cut		Graphite Spray	
DS6	1045	0.157 (0.062)	EDM	Straight	Carburized Can	Stainless Steel Overcan
	1045		Hand Cut			
DS7	1045	0.157 (0.062)	EDM	Insert	Graphite Spray	
	1045		Hand Cut			
DS8	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS9	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	TIG Weld in Helium Environment
DS10	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	TIG Weld in Air Under Argon Blanket
DS11	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS12	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	Inconel 744 Overcan
DS13	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS14	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS15	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS16	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS17	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS18	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS19	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	Ti 6Al-4V Overcan
DS20	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS21	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS22	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS23	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS24	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	
DS25	1045	0.157 (0.062)	Stampings	Step	Graphite Spray	

The DS1 assembly was solid (i.e., it had no steel cores) with no root blocks. As mentioned in the ply design section, sixteen plies were assembled parallel to the outside surface. A can was formed by TIG welding, in an argon atmosphere, the outer laminates together along their length to diamond shaped end plates along the width. After a successful leak check using a mass spectrometer, the can was placed in an electron beam weld chamber, evacuated for a minimum of 6 hours, and sealed. DS1 was then hot isostatically pressed at 954°C (1750°F) at 103,422 MPa (15 ksi) for 2 1/2 hours. Figure 5-19 shows DS1 prior to HIP while Figure 5-20 shows DS1 after HIP. Evaluations performed on DS1 included nondestructive ultrasonic C-scan and metallography inspection as well as visual inspection indicating a well-bonded specimen.

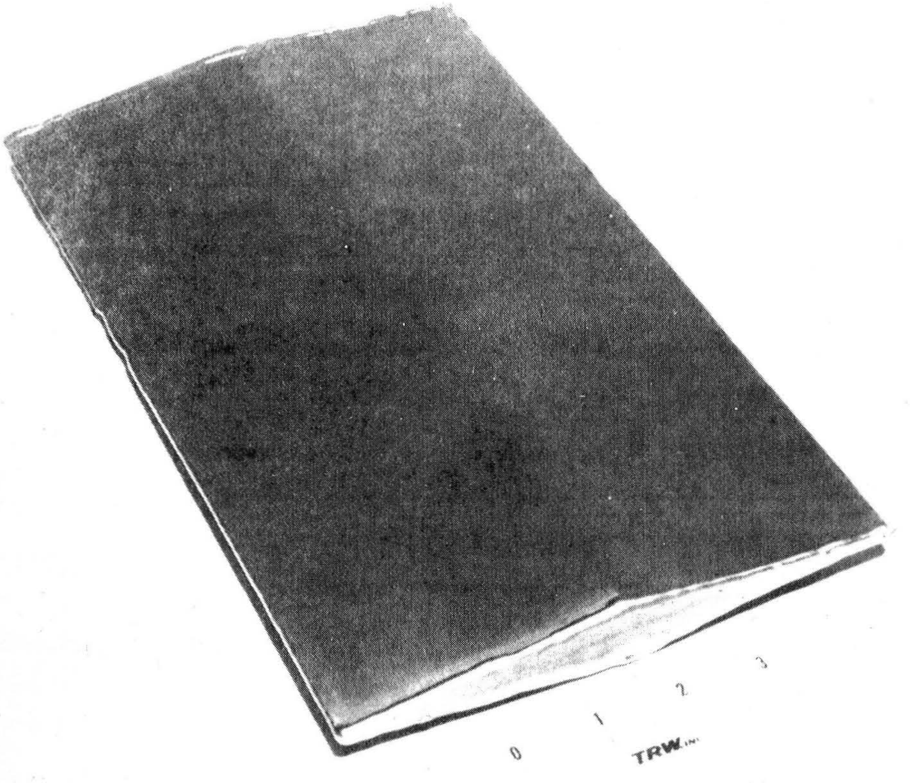


Figure 5-19 Solid Diamond Specimen (DS1) Before Hot Isostatic Pressing

DS2 and DS3 were the first hollow diamond specimens fabricated. The laminates for these and all succeeding specimens were those designed to be parallel to the core surface as discussed in paragraph 5.3.1.

The DS2 specimen was expected to provide information on the flow of the steel cores with respect to the titanium laminate at the HIP conditions. The surface condition of the cores was also to be evaluated. This was achieved by having one DS2 core wrapped in two layers of 0.0005 cm (0.0002 in) thick Ti 6Al-4V foil for 13.4 cm (5.3 in) of length. The second DS2 core was cut equally into two parts, each 6.98 cm (2.75 in) long. One half was polished on abrasive paper while the surface for the other half remained as machined. Neither half had a radius at the end nor were they wrapped in foil. Specimen

DS2 also had laminated root blocks but without an airfoil-to-root radius. This specimen was encapsulated in a carburized steel can for HIP. However, embrittlement of the carburized can caused a leak during the HIP process. The DS2 canned package was placed in a second can of mild steel, leak checked, sealed, and sent for re-HIP'ing. Subsequent X-ray and C-scan inspection indicated insufficient bonding at the core/titanium interface at the root end and in the area between one of the cores and the root. This lack of total bond was attributable to leakage encountered during the first HIP run resulting in entrapment of argon gas. This lack of bonding at the core/laminate interface made evaluation of the various core surfaces unattainable.

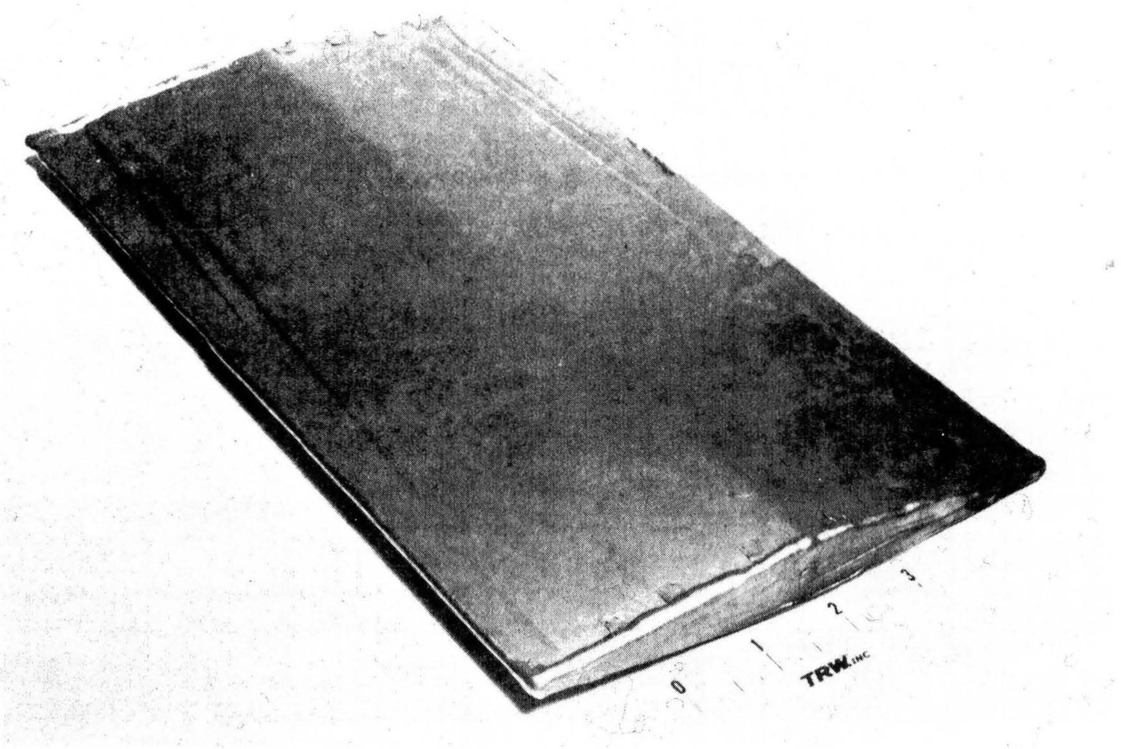


Figure 5-20 DS1 After Hot Isostatic Pressing - The collapse of the outer ply over the ply step can be clearly noticed

Specimen DS3 used the same basic laminate configuration as DS2 with two carbon steel cores cut to 13.4 cm (5.3 in) in length and separated by a matching titanium insert. Two additional titanium inserts match the cores leading and trailing edges as shown in Figure 5-21. DS3 was originally encapsulated in a carburized steel can. However, due to can cracking during EB welding the carbon steel container and root-block plies were removed and DS3 was encapsulated in titanium sheet similar to that used for DS1. After a successful leak check using a mass spectrometer, the can was placed in an electron beam weld chamber, evacuated, and sealed. DS3 was then hot isostatically pressed at 954°C (1750°F) at 103,422 MPa (15 ksi) for 2 1/2 hours. Visual inspection of DS3 indicated a successful HIP. To establish inspection criteria for the steel cores, an ultrasonic C-scan inspection was conducted (see Figure 5-22). This evaluation indicated no areas of concern and metallographic examination of samples of sections AA, BB, and CC indicated no unbonded areas (see Figure 5-23).

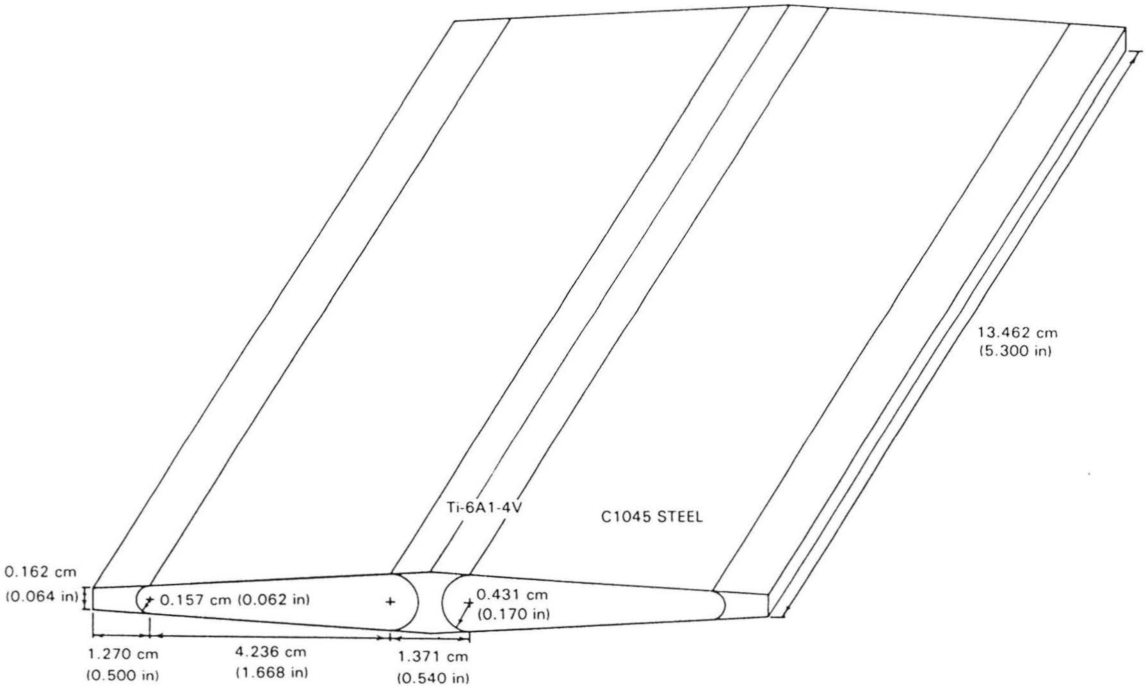

13.462 cm
(5.300 in)
Ti-6A1-4V
C1045 STEEL
0.162 cm
(0.064 in)
0.157 cm (0.062 in)
0.431 cm
(0.170 in)
1.270 cm
(0.500 in)
4.236 cm
(1.668 in)
1.371 cm
(0.540 in)

Figure 5-21 Steel-Titanium Fitted Insert Used In Specimen DS3

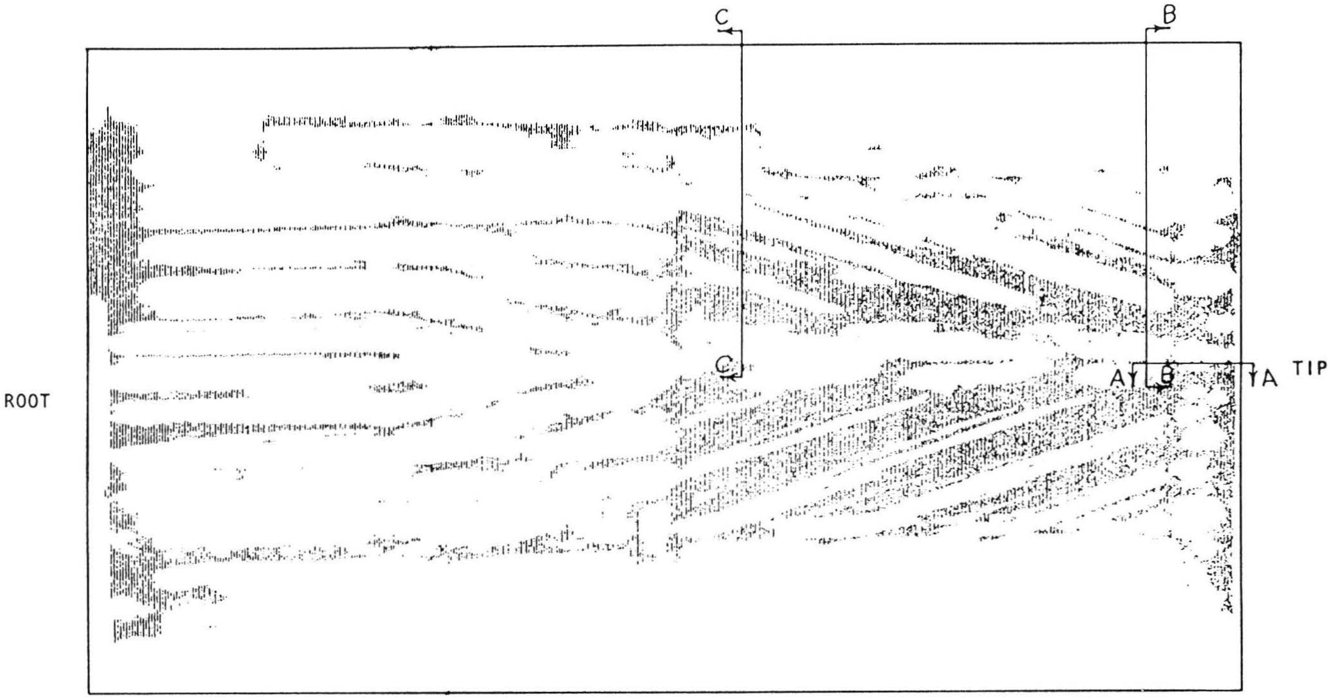
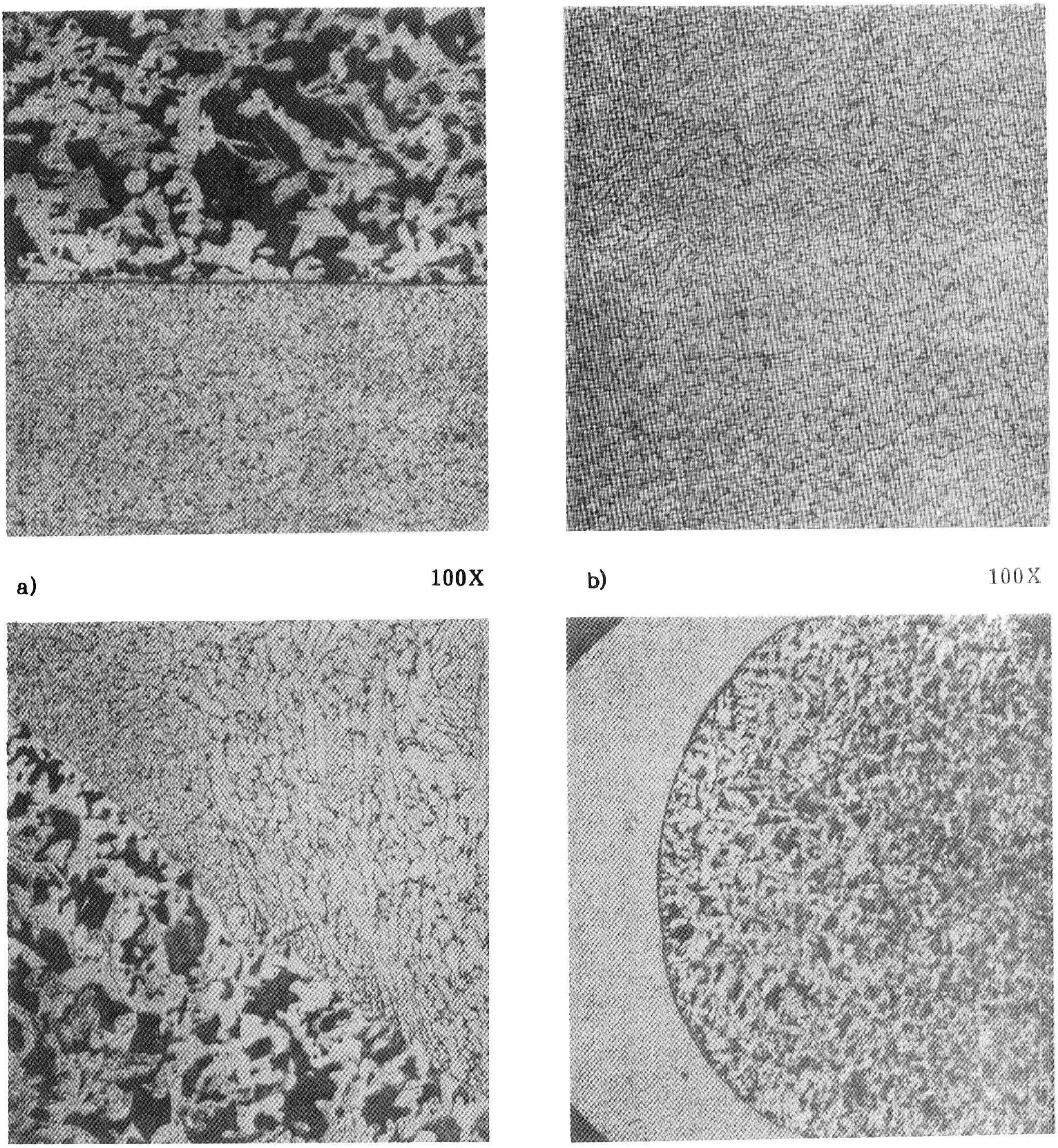


Figure 5-22 Ultrasonic Through-Transmission C-Scan For Specimen DS3 - Note Indicated Sections AA, BB, and CC That Were Cut For Metallography Inspection



a) 100X

b) 100X

c) 1[illegible]X

d) 30X

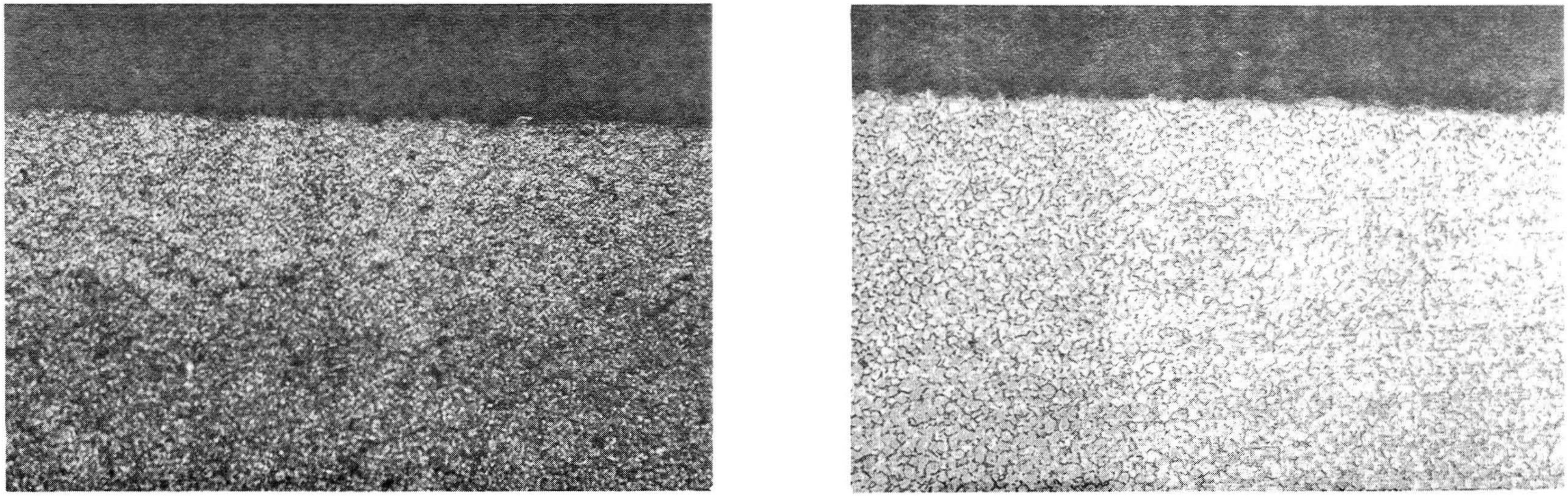
Figure 5-23 Representative Microstructures of DS3 Sections AA, BB, and CC
a) Portion of Section AA;
b) Portion of Sections BB and CC - Steel Core/Titanium Interface;
c) Portion of Sections BB and CC - Steel Core/Titanium Interface;
d) .157 cm (.062 in) Radius of the Steel Core.

Specimens DS4, DS5, and DS6 were the next group to be assembled for HIP. The raw material, dimensional characteristics, and fabrication parameters for these diamond specimens are shown in Table 5-I. In addition to can carburization, other approaches were evaluated to allow for easier stripping of cans from the HIP'ed specimens and to prevent reaction between can material and the titanium laminates. These alternative methods included using graphoil (a sheet of graphite), carburized steel foil, and graphite spray. The graphoil and carburized steel foil were placed between the can and the titanium laminates during assembly. The graphite spray was applied by spraying the area. Metallographic evaluations of the titanium-can interface indicated all four methods of can surface treatment were successful in accomplishing their intended objectives. Microstructures of titanium-can interfaces are shown in Figure 5-24.

Small leaks were detected in two out of the three cans. The cans were TIG welded in argon with mild steel weld rod material. Subsequent weld testing indicated that welding with with a stainless steel rod would yield a better weld and eliminate weld porosity. All future cans were electron beam welded in this manner. Because of the recurring leakage problems encountered, all diamond specimens were double-canned from flat stainless steel (IN 744) sheets welded at the edges. After a successful leak check, the cans were sealed and the assemblies HIP'ed. Visual examination of these diamond specimens indicated DS4 and DS5 were successfully HIP'ed while DS6 showed evidence of a leak. However, there were deformations detected on the diamond specimens (flattened appearance) that were attributed to nonuniformed pressure distributions due to the stronger stainless steel can used for double-canning during HIP. Three different cores and/or core materials were evaluated (see Table 5-I) with TRW VMS-478 valve steel providing the best cavity definition.

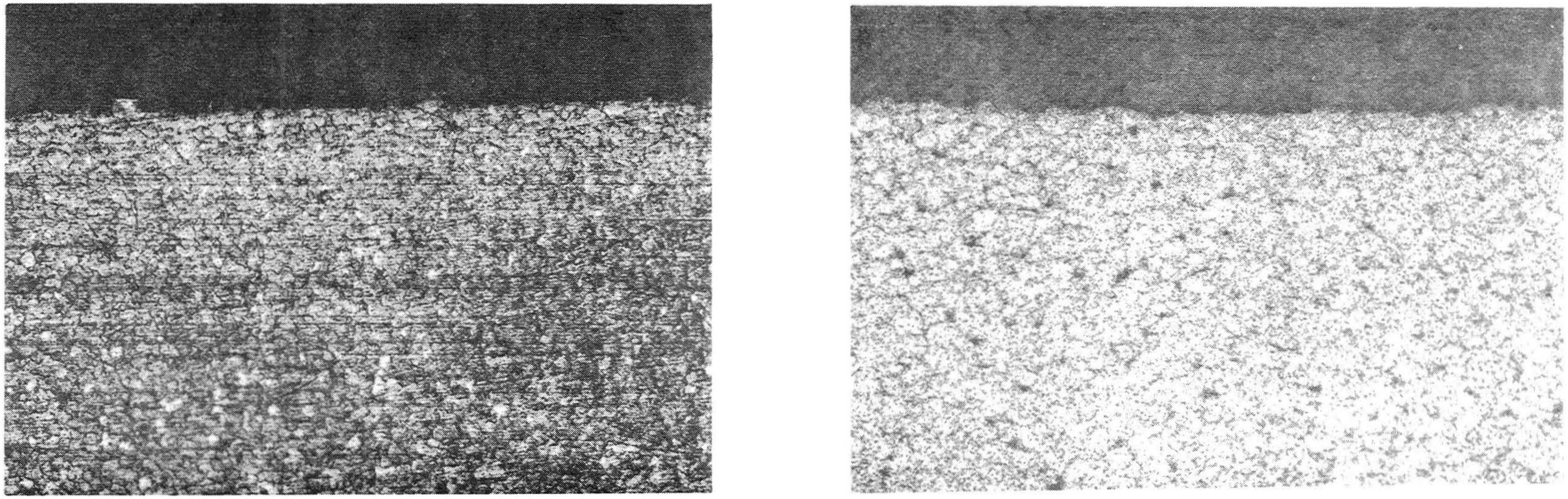
A preliminary twisting of DS6 was accomplished by heating the part to 954°C (1750°F), placing the part in a vise after removal from the furnace, and hand twisting the airfoil in the core sections using specially fabricated wrenches. Results of this specimen twisting effort indicated the core and titanium laminates behaved isotropically. This result indicates the flat laminate layup assembly approach being employed is feasible.

DS7 was assembled similar to DS5 with graphite spray used for both can halves and was sealed in a single low-carbon steel can. After TIG welding in an argon environment, leak checking, and sealing the specimen was HIP'ed. X-ray and C-scan evaluations indicated DS7 was successfully HIP'ed with no evidence of voids or delaminations. However, nonuniform hydrostatic pressure caused a buildup of titanium along the 0.157 cm (0.062 in) radius of the core. Metallographic evaluations indicate good bonds were achieved with the exception of some unbonded areas (see Figure 5-25) at the bond lines probably attributable to argon. Since the cans are TIG welded in an argon atmosphere and mass spectrometer leak checked using helium, some adsorption of these gasses is possible. The final sealing by electron beam welding does not allow removal of all these gases.



a. Carburized Can

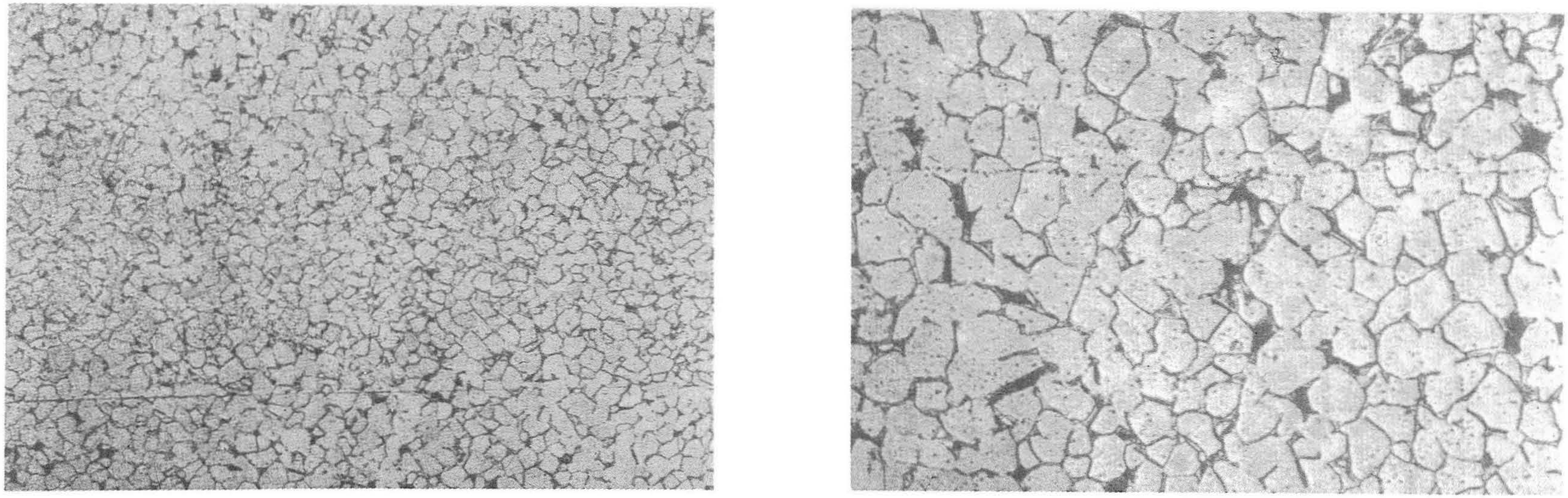
b. Carburized Foil



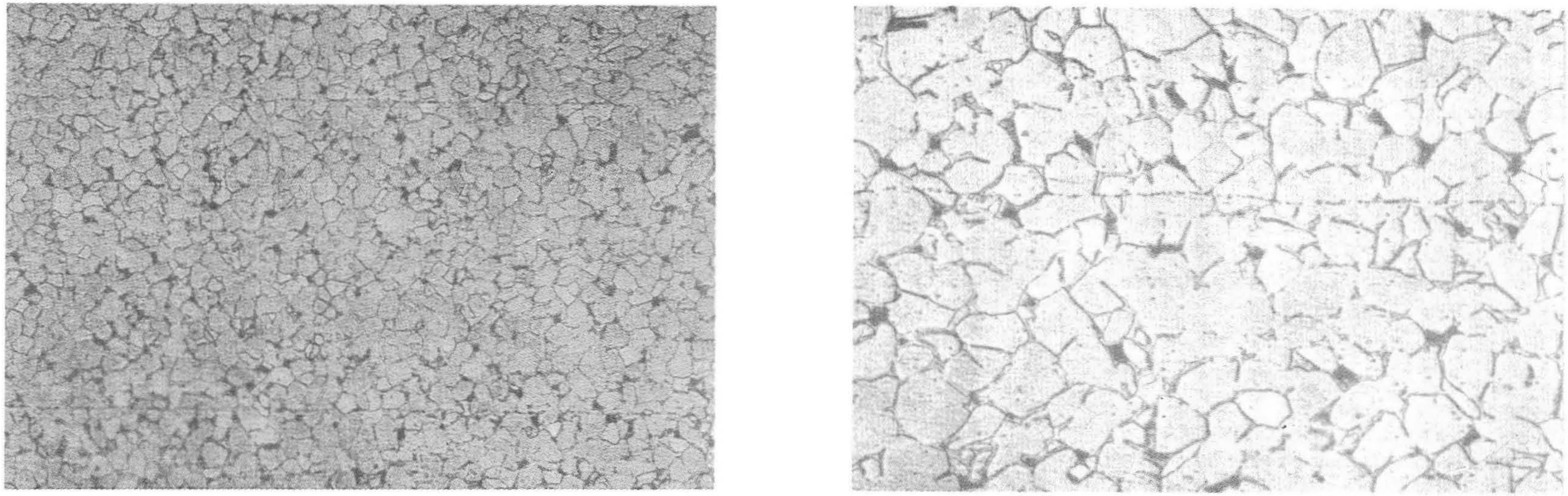
c. Graphite

d. Graphoil

Figure 5-24 Surface Condition of Titanium After HIP Using Can Surface Treatment or Interfaces as Noted



a. Near the Tip 200X 500X



b. Root 200X 500X

Figure 5-25 Typical Microstructure in DS7 at Several Areas - Bond Lines Are Evident

Because of the bond interface problems experienced with DS7, three alternate methods were selected for evaluation for can welding and sealing in fabrication of DS8, DS9, and DS10. These methods include:

- DS8 Fabrication - TIG weld can in argon, leak check using helium, outgas in vacuum at 426-537°C (800-1000°F), and seal outgassing port by electron beam welding.
- DS9 Fabrication - TIG weld can in helium, leak check using helium, outgas in vacuum at 426-537°C (800-1000°F), and seal outgassing port by electron beam welding.
- DS10 Fabrication - TIG weld can in air under an argon blanket, leak check using helium, outgas in vacuum at 426-537°C (800-1000°F), and seal outgassing port by electron beam welding.

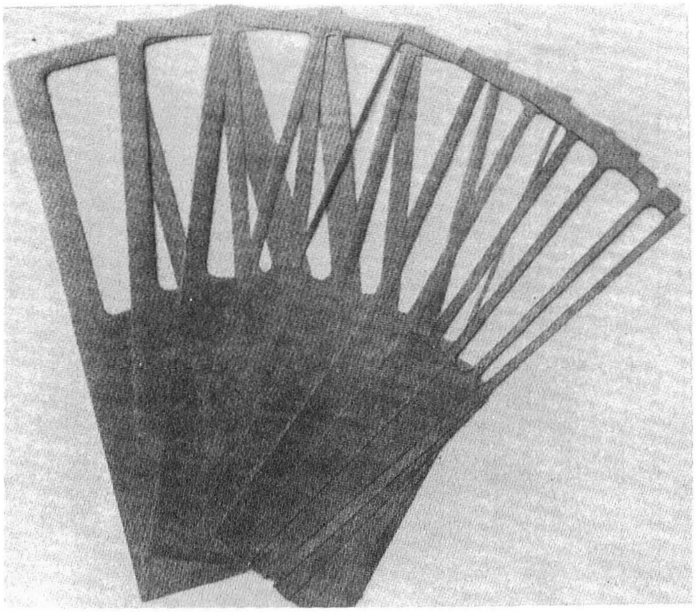
The vacuum outgas cycle was added at this time to remove any adsorbed gasses.

Because of previous debulking caused by the filling in of voids between the titanium and steel core at the center of the specimen, an additional ply was added to the center of each half. In addition, a 0.025 cm (0.010 in) full size sheet was added to each half of the specimen to compensate for some of the undersize areas at the trailing edges.

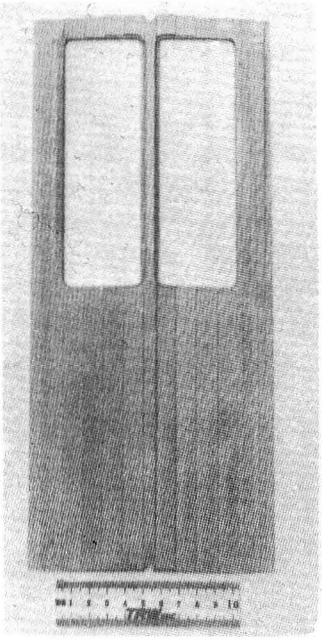
In order to improve the uniformity of the pressure during the initial stages of HIP and eliminate the extrusion of material from the edge, the HIP cycle was modified to the following procedure for use in fabricating DS8, DS9, and DS10.

> Heat diamond specimens to 954°C (1750°F) with lowest pressure compatible with facility operation. Once this temperature is attained, apply pressure gradually up to 103,422 MPa (15 ksi) and hold for 2.5 hours. Previously, 103,422 MPa (15 ksi) pressure was applied at 537°C (1000°F).

DS8, DS9, and DS10 were the first diamond specimens to utilize core plies produced by stamping. Figures 5-26, 5-27, and 5-28 illustrate these plies along with the remaining plies required to produce one-half of the specimen. Basically, the plies shown in these figures were those used for the remaining diamond specimens (i.e., DS11-DS25). These diamond specimens incorporated (1) hand cut plies and stamped plies (core plies only), (2) a laminated step root assembly (Figure 5-28), and (3) AISI-1045 material cores with a 0.157 cm (0.062 in) leading and trailing edge radius. HIP cans were all sprayed with graphite to prevent bonding between the titanium laminates and the can.

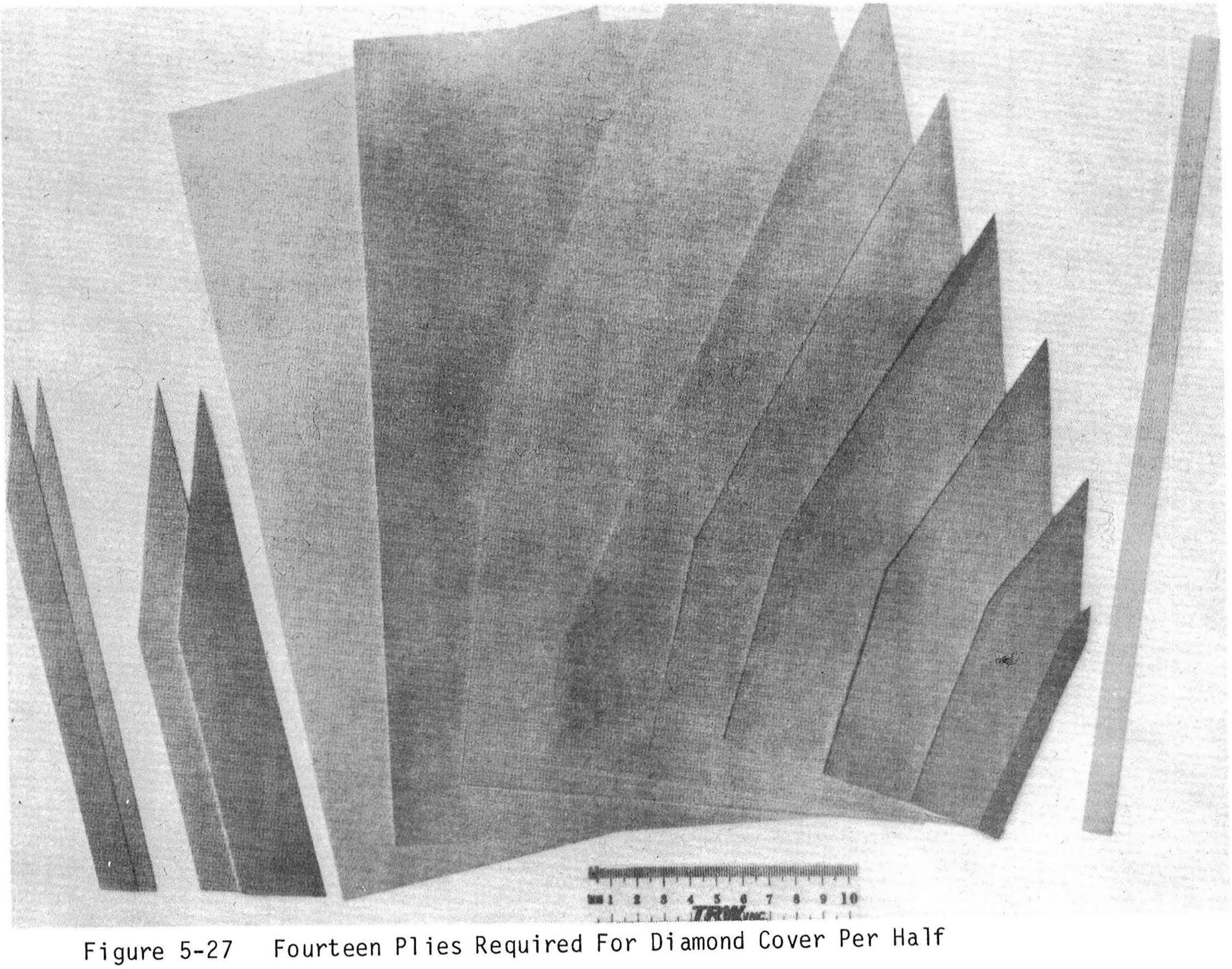


a. Ten Core Plies Required Per Half Specimen.



b. Core Plies Assembled.

Figure 5-26 Core Plies



1 2 3 4 5 6 7 8 9 10
TRW INC.

Figure 5-27 Fourteen Plies Required For Diamond Cover Per Half

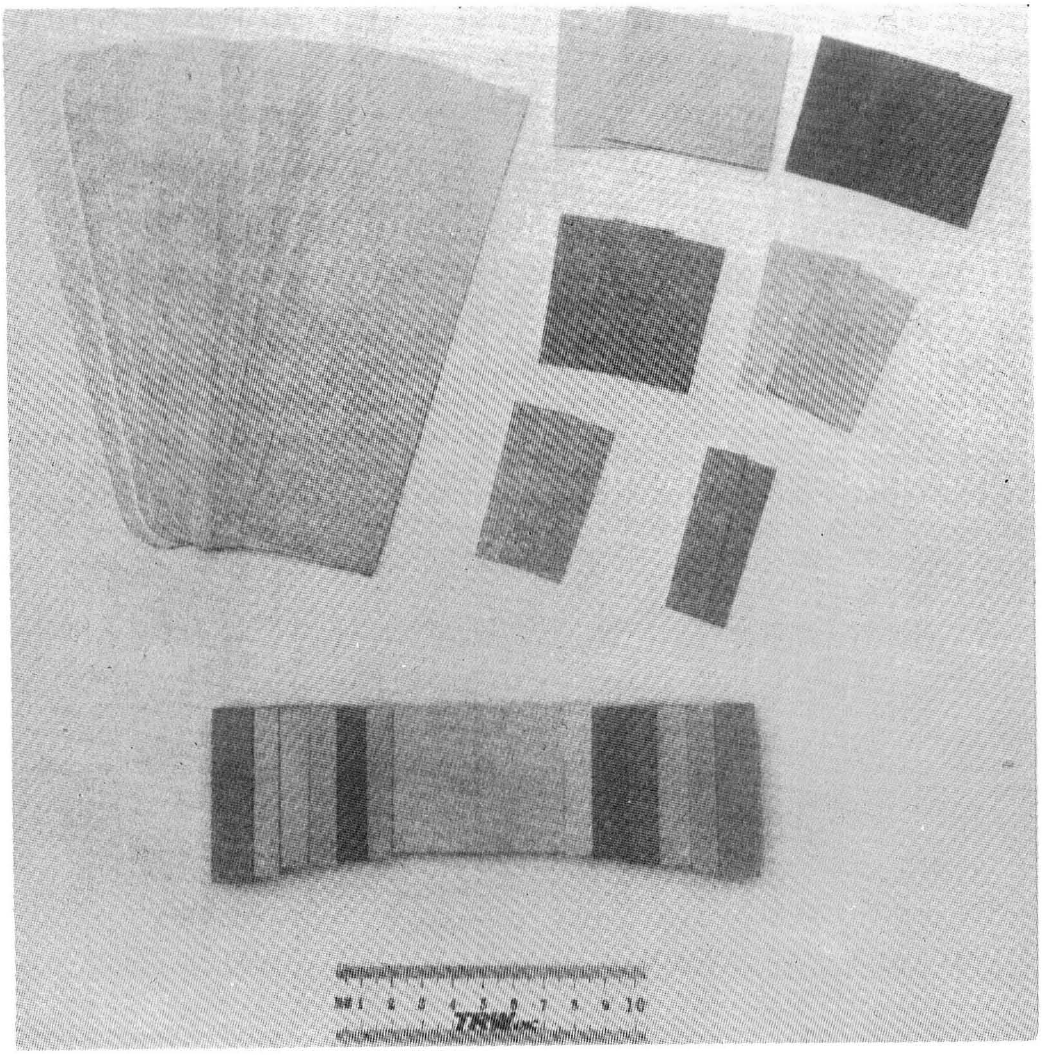


Figure 5-28 Twenty-Two Plies (Assembled and Unassembled) Required For Root Per Half

After assembly, can welding, leak checking, hot outgassing, and sealing - the DS8, DS9, and DS10 can assemblies were hot isostatic pressed using the modified cycle indicated above. Visual examination indicated successful HIP except for a core shift in DS9. In addition, dimensional analyses indicated the three diamond specimens met blueprint specifications (indicated in Figure 5-12) with the exception of the core shift area in DS9. The modified HIP cycle seemed to have no impact on the material buildup at the 0.157 cm (0.062 in) radius of the core. Since the HIP vendor has to continuously increase pressure in both heat cycles to operate the equipment efficiently, the concept of minimum pressure to eliminate material buildup at the edges was determined not to be feasible. No further modifications were planned for the diamond specimen plies.

After evaluation of diamond specimens 8, 9, and 10, fabrication of deliverable diamond specimens DS11 through DS25 to Pratt & Whitney Aircraft was initiated. As mentioned previously, DS11 through DS25 incorporated hand cut plies and stamped plies (core plies only) along with a laminated step root assembly and AISI-1045 material cores with a 0.157 cm (0.062 in) leading and trailing edge radius. A ply-core-can assembly procedure that evolved from previous diamond specimen experimental runs was used for DS11 through DS25 and is listed below.

- Clean all individual plies using a three step procedure: (1) rinse the individual plies in an acid bath (-50H_2O;48HNO_3;2HF), (2) water rinse the plies after bathing, and (3) alcohol rinse the plies and dry.
- Assemble the plies for each specimen into six subassemblies (i.e., two-halves for the core, cover, and root) and tack weld these subassemblies.
- Degrease the as-machined cores using acetone followed by alcohol rinsing.
- Final assemble the six subassembled plies and the degreased cores into the bottom-half of a graphite sprayed mild steel HIP can. Place the other half of the graphite sprayed HIP can on top and TIG weld the two-halves together in a helium environment.
- Check for can leaks using mass spectrometer and helium gas. Hot outgas the can in a vacuum furnace (10^{-6}-10^{-7} mm Hg) at 482-537°C (900-1000°F) for 18 hours.
- Seal the HIP can by electron beam welding and X-ray the assembled can to look for any shift in the core registry.

The fabrication procedures and run evaluation results for diamond specimens DS11 through DS25 are discussed in the following paragraphs.

Initially, only DS13 and DS15 were hot isostatically pressed. The HIP cycle used allowed for no gradual buildup of pressure and full pressure buildup was initiated at 537°C (1000°F). In an effort to improve overall microstructure of the specimens after HIP, both DS13 and DS15 were heat treated in the mild steel can after HIP. The specimens were heat treated at 954°C (1750°F) for 1 hour, factory air cooled and reheated to 737°C (1360°F) for 2 hours, and then air cooled. X-ray inspection of DS13 and DS15 indicated that the cores remained in position during the HIP cycle, as shown in Figure 5-29, but some delineation of the plies did occur. Visual inspection of the removed cans indicated both cans leaked. To alleviate these leak problems, it was suggested that a wider flange in the root area of the can would improve weld reliability and improve the evacuation tube area that undergoes shear stresses during hot isostatic pressing.

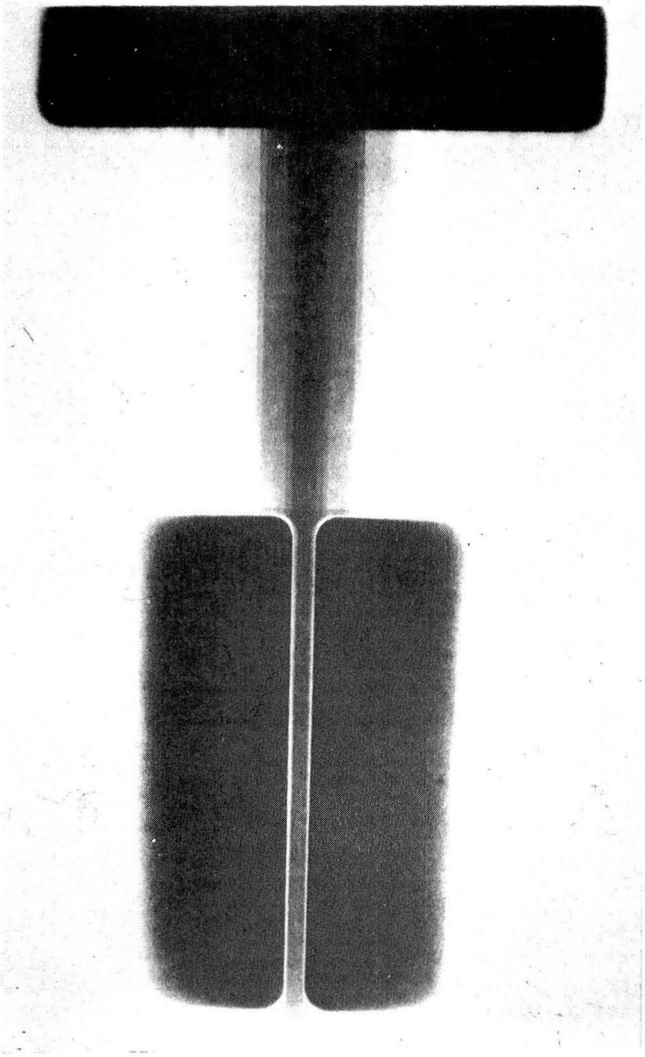


Figure 5-29 X-Ray of Diamond Specimen 13 After Hot Isostatic Pressing

To bypass preparation of new cans having wider flanges (and delay scheduled delivery date of the specimens), it was decided to overcan the remaining specimens to be fabricated. DS12 was overcanned with Inconel 744, a superplastic, iron-base alloy while DS19 used Ti 6Al-4V material for its double can. DS25 was sealed along the periphery by seam welding in an air environment and was not double canned. DS12 and DS19 double cans were TIG welded at the edges and then sealed in an electron beam weld chamber. To ensure true isostatic pressure during the HIP cycle, the double cans were heated in an autoclave to provide a more adherent form to the overcan material around the sealed diamond specimens. DS12, DS19, and DS25 were then HIP'ed. Visual inspection indicated DS12 and DS19 leaked during HIP. However, DS25 appeared to be successfully HIP'ed and was given heat treatment in the mild steel can at 954°C (1750°F) for 1 hour and factory air cooled - reheated to 704°C (1300°F) for 2 hours and air cooled. DS25 appeared fully bonded with no visible voids at the end of the specimen. X-ray, ultrasonic C-scan, and metallography evaluations verified that DS25 was well-bonded with proper core registry as shown in Figure 5-30.

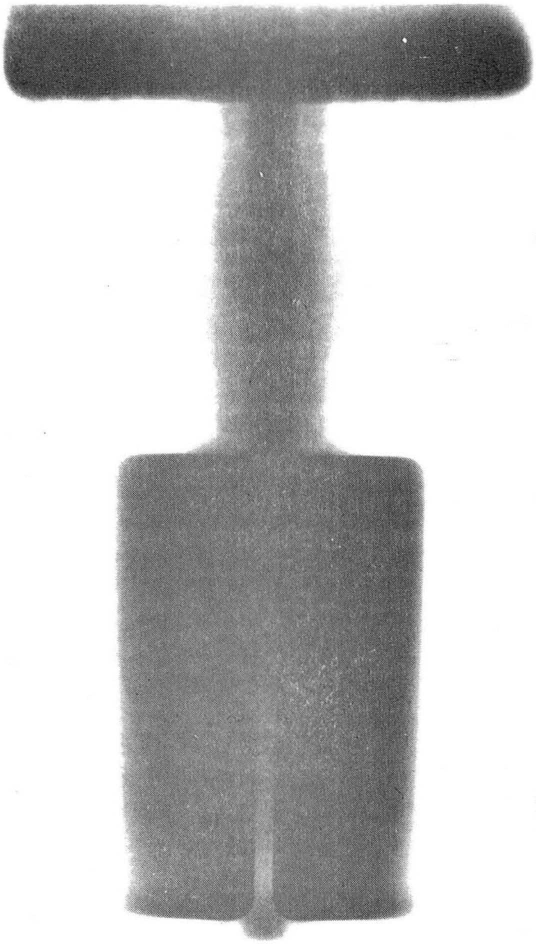


Figure 5-30 X-Ray of Diamond Specimen 25 After Hot Isostatic Pressing

Based on Pratt & Whitney Aircraft's analysis of the diamond specimen design, it was determined that specimen failure during fatigue testing would always occur in the root area and not in the hollowed portion of the specimen. Because of this determination, TRW rubber padded new mild steel cans without a root. Ten diamond specimens (DS11, 14, 16, 17, 18, 20-24) were then canned using this new redesigned rootless can. Based on the success achieved by DS25, HIP cans were seam welded instead of TIG welded, leak checked using a mass spectrometer, hot outgassed and electron beam sealed in a vacuum. The ply-core-can assemblies were X-rayed to ensure proper core registry and then HIP'ed at 954°C (1750°F) for 2.5 hours at 103,422 MPa (15 ksi). Following hot isostatic pressing, all ten specimens were heat treated (954°C/1 hour/FAC + 704°C/2 hours/AC) and then decanned. Visual inspection indicated four (DS18, DS20, DS22, and DS23) of the ten cans leaked. The six specimens that visually appeared well-bonded were further evaluated using X-ray and ultrasonic C-scan inspection methods. The specimens appeared to be well-bonded.

Eight diamond specimens (i.e., DS8, DS11, DS14, DS16, DS17, DS21, DS24, and DS25) were machined to length and width and their cores were removed by hot acid leaching in a water/nitric acid bath at a temperature of 65°C (150°F). This leaching was made possible by drilling 0.317 cm (0.125 in) diameter holes at the ends of each core. After leaching, the interior cavities were chemically milled by pumping a cold acid solution ($5HF/35HNO_3/60H_2O$) through the cavities for a period of thirty minutes. In addition, DS8 and DS25 had their surfaces abrasive belt polished in an attempt to simulate the smoother surface produced on the blades after isothermal forging.

5.3.1.4 Summary of Results

Task 1 was technically successful in meeting its objectives of defining general instructions for use in computer aided design of the individual sheets and cores and establishing fabrication processing techniques to produce titanium-laminated/cored, diffusion bonded blade specimens. Criteria established in this phase of the TRW effort provided the necessary information used to fabricate a full size hollow fan blade in Task 2. After resolving preliminary developmental design and fabrication problems relative to specimen components and process tooling, well-bonded specimens were produced that met the basic feasibility criteria established for the Energy Efficient Engine hollow fan blade.

The approach used to produce the specimens required the assembly of hand cut plies and stamped plies (core plies only) and AISI-1045 material radiused cores. The assembled pack was then placed into a redesigned rootless can and seam welded in preparation for hot isostatic pressing. The HIP process used was a delayed pressurization approach in which the can, encapsulating the assembled part, was heated to 954°C (1750°F) with pressure gradually applied up to 103,422 MPa (15 ksi) and held for 2.5 hours. Following HIP, the specimens were heat treated and decanned. X-ray and ultrasonic C-scan inspection evaluations indicated that the majority of the fabricated diamond specimens were well-bonded. These well-bonded specimens were machined to length and width, core leached using a water/nitric acid solution and delivered to Pratt & Whitney Aircraft for further evaluation.

Some of the major accomplishments demonstrated under this Task 1 effort include (1) the feasibility of fabricating hollow specimens using a laminated ply/core assembly HIP bonding approach, (2) the feasibility of the flat layup assembly approach which is comparatively inexpensive and easily performed while maintaining proper core registry, and (3) the relatively inexpensive approach used to leach steel cores in a hot water/nitric acid bath.

5.3.1.5 Pratt & Whitney Aircraft Test and Evaluation Program on TRW Specimens

Part of the Shroudless, Hollow Blade Technology program included a series of tests designed to evaluate the laminated/diffusion bonded TRW specimen material and fan blades. The specimen testing was established to evaluate the tensile and fatigue properties of the material in a hollow section configuration. The blade testing scope included bench vibration testing and spin pit dynamic testing. However, due to technical, schedule, and budgetary problems that developed during the course of the TRW fabrication program the Pratt & Whitney Aircraft test program was revised to include only specimen material testing. The effort directed toward this program is discussed in the following paragraphs.

Initial effort in the evaluation program involved a tensile property test of small specimens that were made from the root section of DS25. Eight 0.317 cm (0.125 in) diameter threaded specimens were fabricated to evaluate tensile properties transverse to the laminated bonds. Testing was done in a standard tensile testing apparatus. Test results, as shown in Table 5-II, indicate failure origins were not along the bond planes even though minimum tensile properties were not met. Further investigation of this phenomenon was beyond the scope of the program.

TABLE 5-II

TENSILE PROPERTY TEST RESULTS ON DS25 SPECIMENS

Specimen	.2% Yield Strength MPa (KSI)	Ultimate Tensile Strength MPa (KSI)	Elongation (Percent)	Reduction of Area (Percent)
1	815,056 (118.2)	914,335 (132.6)	12.3	27.6
2	812,987 (117.9)	908,834 (131.8)	14.5	25.7
3	792,301 (114.9)	890,196 (129.1)	11.3	30.9
4	786,094 (114.0)	873,672 (126.7)	14.6	44.1
5	792,990 (115.0)	884,702 (128.3)	14.4	40.4
6	804,714 (116.7)	912,297 (132.3)	16.7	40.4
7	811,608 (117.7)	902,619 (130.9)	13.0	20.8
8	804,714 (116.7)	908,835 (131.8)	14.6	29.0
Minimum Requirement	827,465 (120.0)	896,393 (130.0)	10.0	20.0

Because fatigue testing of the entire DS25 specimen as a single piece would cause initiation of root failure before the preferrable hollow section failure mode could be induced, coupon specimens were sectioned from two of the diamond shaped panels (six coupons per panel) to allow testing of the hollow section of the diamond shaped part.

Figure 5-31 shows how the coupons were sectioned from the larger specimen and the test set up on the vibration generator. The ensuing excitation process produced a high cycle fatigue stress in the internal core leading edge radius. As fabricated, the radii were irregular. These radii anomalies were the result of AISI 1045 steel core material not providing the necessary hardness at hot isostatic press temperature to form the proper radii. An improved core alloy with better high temperature qualities is required to solve this problem. Figure 5-32 shows the actual radii configuration of the twelve coupons tested and the origin of failure location. Figure 5-33 provides the test results which indicate that bonded sheet fatigue strength is less than 70 percent of the minimum high cycle fatigue strength requirement of 310,266 MPa (45 ksi) for AMS4911 sheet material.

By eliminating the effect of radii less than 0.025 cm (0.010 in) at the fatigue origin, the estimated minimum fatigue strength would be 241,318-275,792 MPa (35-40 ksi). This is a 10-20 percent debit in fatigue strength compared to the 310,266 MPa (45 ksi) minimum requirement. This reduction is assumed to be the result of chemically milled part surfaces. This chemical milling is the result of inner cavity surface attack which occurred during the core acid leaching process. Historically, chemical milling of titanium adversely effects fatigue strength unless the final operation is followed by a controlled surface peening operation which, because of specimen configuration, was not possible. Therefore, a reduction of material properties may be inherent in this fabrication approach.

Detailed parts fabrication of the actual hollow fan blades was continued concurrently with the specimen test program. This fabrication effort had progressed to the point where revisions to the core details could not be incorporated based on results from the specimen test program. It was apparent that additional work with core material was required to improve the radii configuration in the hollow section.

Funding restrictions prevented additional effort in the improvement of material properties. The tensile and fatigue test results indicate the need for additional metallographic investigation and specimen test work to ensure that design minimum properties can be met. At this point in the program these problems were bypassed in favor of concentrating on actual blade fabrication feasibility problems.

The diamond shaped specimen fabrication program determined that hollow blade-like structures could be produced by the laminated/diffusion bonding process. No final forging was planned in this phase of the program.

5.3.2 Task 2 - Blade Process Development

Much of the effort in developing a hollow fan blade fabrication process was performed concurrently with the development of the specimen fabrication process in the area of tooling, ply design, and core manufacture. A total of nine blades were fabricated in this task with one of these blades delivered to Pratt & Whitney Aircraft for evaluation. A sketch of the blade is shown in Figure 5-34.

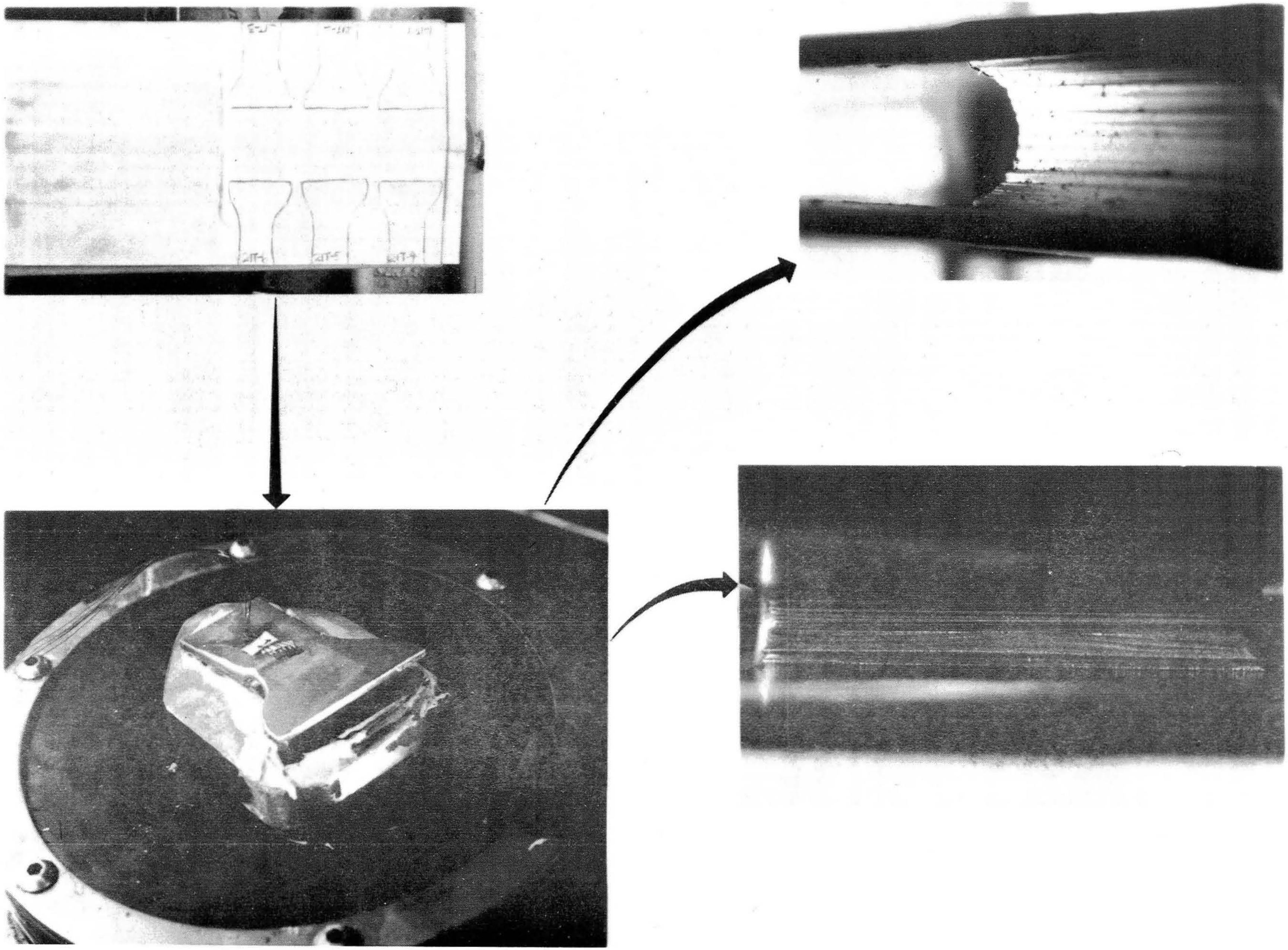
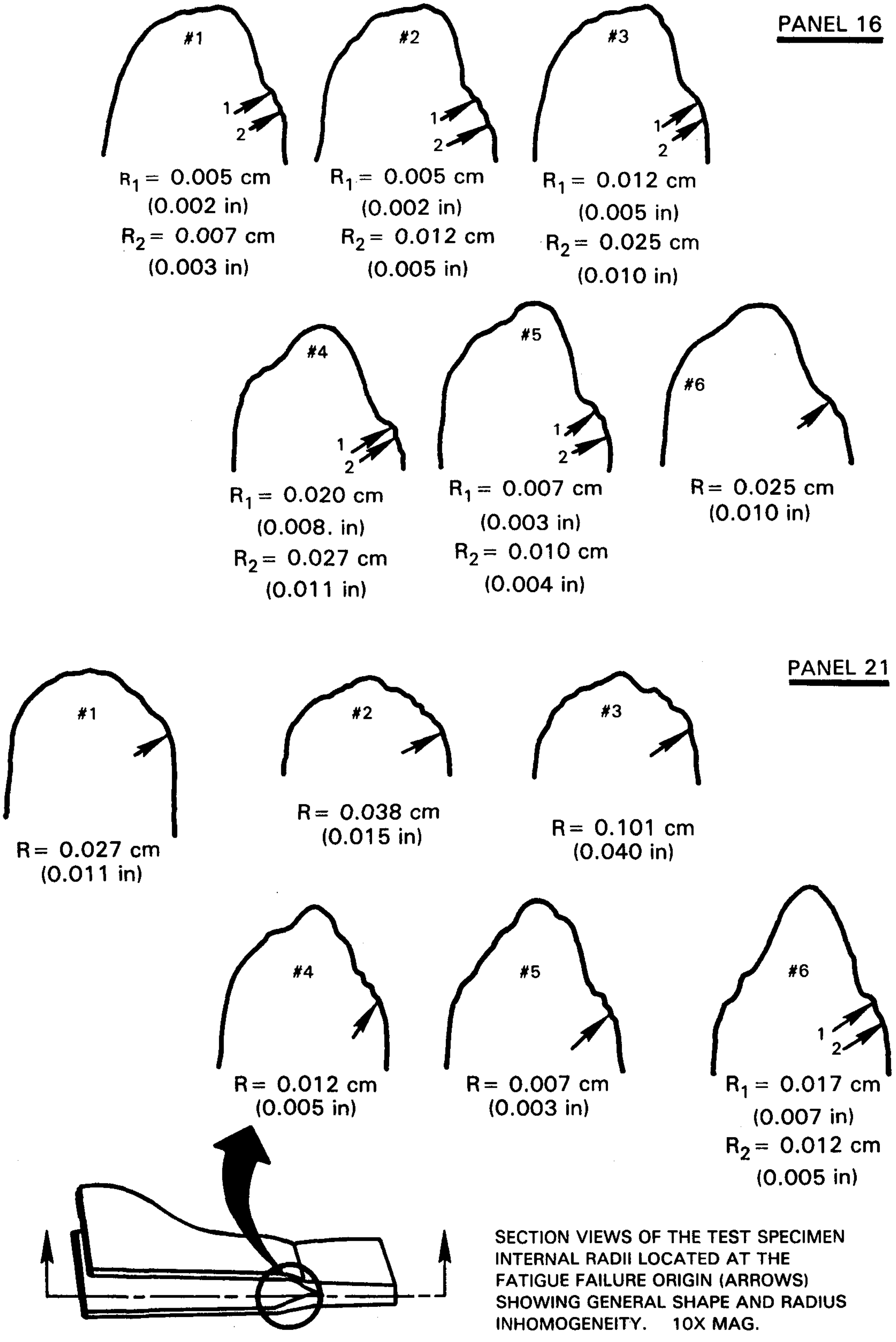

21T-6
21T-5
21T-4

Figure 5-31 Test Setup For DS25 Sectioned Coupons


PANEL 16
#1
1
2
R1 = 0.005 cm
(0.002 in)
R2 = 0.007 cm
(0.003 in)
#2
1
2
R1 = 0.005 cm
(0.002 in)
R2 = 0.012 cm
(0.005 in)
#3
1
2
R1 = 0.012 cm
(0.005 in)
R2 = 0.025 cm
(0.010 in)
#4
1
2
R1 = 0.020 cm
(0.008. in)
R2 = 0.027 cm
(0.011 in)
#5
1
2
R1 = 0.007 cm
(0.003 in)
R2 = 0.010 cm
(0.004 in)
#6
R = 0.025 cm
(0.010 in)
PANEL 21
#1
R = 0.027 cm
(0.011 in)
#2
R = 0.038 cm
(0.015 in)
#3
R = 0.101 cm
(0.040 in)
#4
R = 0.012 cm
(0.005 in)
#5
R = 0.007 cm
(0.003 in)
#6
1
2
R1 = 0.017 cm
(0.007 in)
R2 = 0.012 cm
(0.005 in)

SECTION VIEWS OF THE TEST SPECIMEN INTERNAL RADII LOCATED AT THE FATIGUE FAILURE ORIGIN (ARROWS) SHOWING GENERAL SHAPE AND RADIUS INHOMOGENEITY. 10X MAG.

Figure 5-32 Sectional Views of Test Coupons Indicating Origin of Failure Location

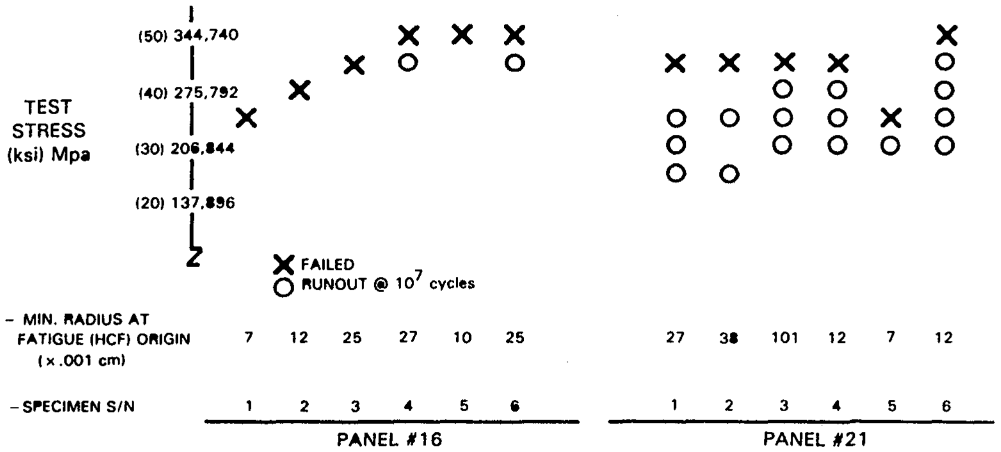


Figure 5-33 HIP/DB DS25 Coupon High Cycle Fatigue Test Results

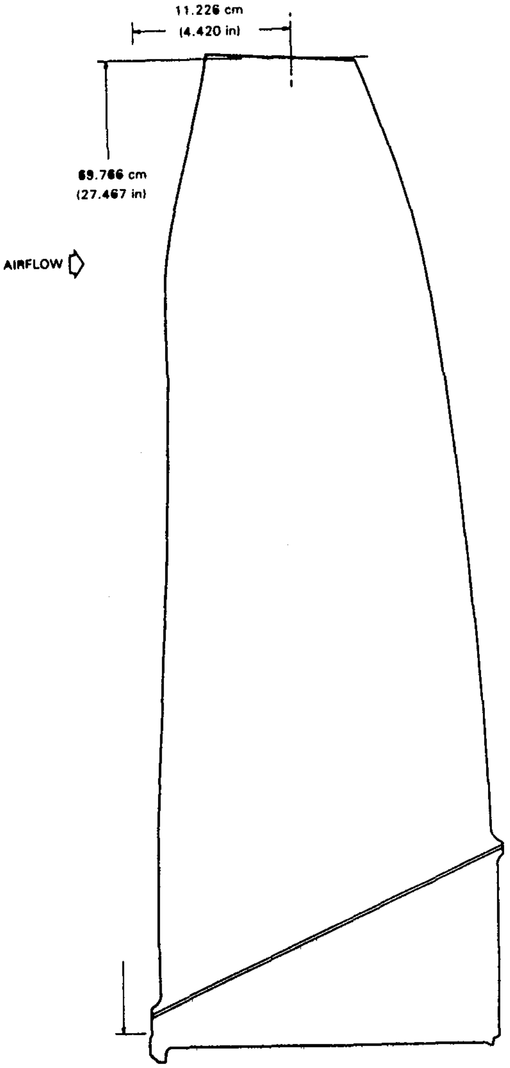

11.226 cm
(4.420 in)
69.766 cm
(27.467 in)
AIRFLOW

Figure 5-34 Sketch of Pratt & Whitney Aircraft's Hollow Fan Blade Design For Energy Efficient Engine Program

5.3.2.1 Design and Fabrication Approach

The ply design effort for the airfoil plies required the use of Pratt & Whitney Aircraft supplied Computer Aided (CA) data files. Extensive modifications were made to current TRW software programs for ply generation to better define ply ends and to plot plies with core cutouts. A problem was encountered when comparing airfoil section plots that were drawn using TRW's airfoil design system and the engineering master drawings received from Pratt & Whitney Aircraft. To solve this problem, TRW used a cubic spline interpolation program to add points at various stages of the chord length. A comparison plot using this new dataset demonstrated excellent agreement with the engineering master drawings. Some of the assumptions used in the ply generation were (1) all plies would be 0.076 cm (0.030 in) thick, (2) locate a full ply along the mean camber line, (3) locate full plies on the concave and convex surfaces of the airfoil, (4) limit maximum part deformation to 10 percent following isothermal forging, and (5) add a chemical milling envelope of 0.0063 cm (0.0025 in). Thirty-one plies defined the airfoil. Ply designs with the core cavity definitions were complex because of the core geometry. The computer defined the core cavity geometry in the ply but did not define the radii of the core corners. This effort would have caused an undesirable slippage in schedule. Consequently, the radii of core corners in the ply were manually defined.

Tape controlled punch press, stamping, and numerically-controlled (NC) milling were three methods considered for producing the blade plies. Economic and scheduling considerations made numerically controlled (NC) milling of the plies the most attractive of the three. Twelve total sets of 0.076 cm (0.030 in) Ti 6Al-4V material plies were manufactured.

Four core fabrication approaches evolved from the Task 1 specimen fabrication effort with each core using AISI-1045 steel raw material. Casting, powder metallurgy, forging, and tracer mill machining from masters were considered as candidate manufacturing methods in producing these cores. It was determined that the least costly and most direct approach for fabricating these cores for this experimental program was NC milling. Twelve sets of untwisted cores (one of which is shown in Figure 5-35) were NC machined by the vendor using TRW supplied NC tapes.

5.3.2.2 Process Tooling

Ply-Core Assembly Tooling - Ply-core assembly tooling consisted of a TRW-designed tooling fixture featuring a wooden block that had provisions for two locators at the root end. The position of the plies during assembly was maintained by two 0.952 cm (0.375 in) diameter holes which were pinned with 0.952 cm (0.375 in) diameter bars. In addition, a single pin was located at the blade tip along the stacking axis to help in the alignment of the full length plies. Alignment of the root/cover skin welded assembly was maintained with the airfoil ply assembly by two blind holes drilled in the cover skin sheet and root block to a depth of about 2.54 cm (1 in). These holes allowed outgassing in the area between the cover skin and root blocks after seam welding of the entire package. This approach was used only for blades assembled with roots.

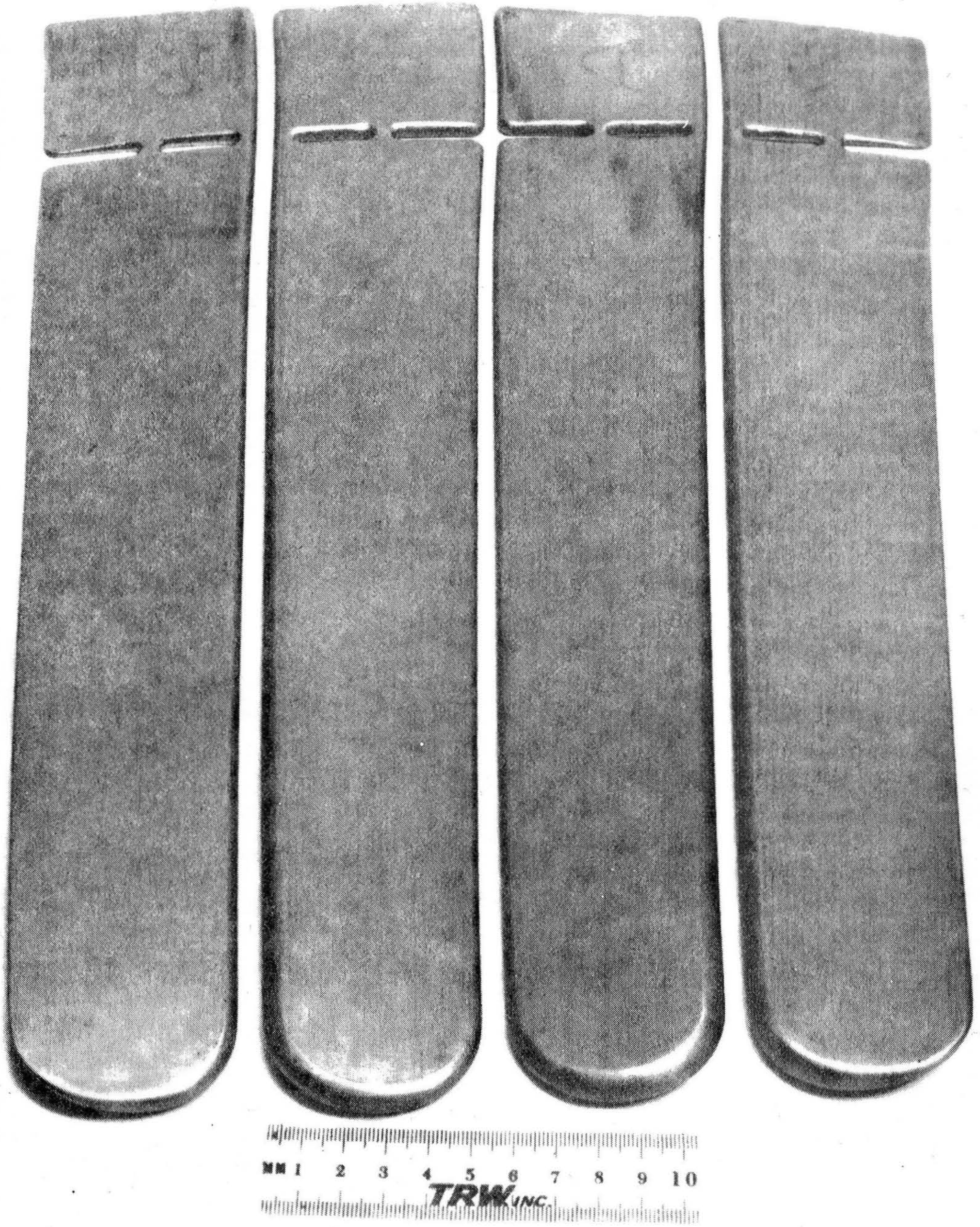
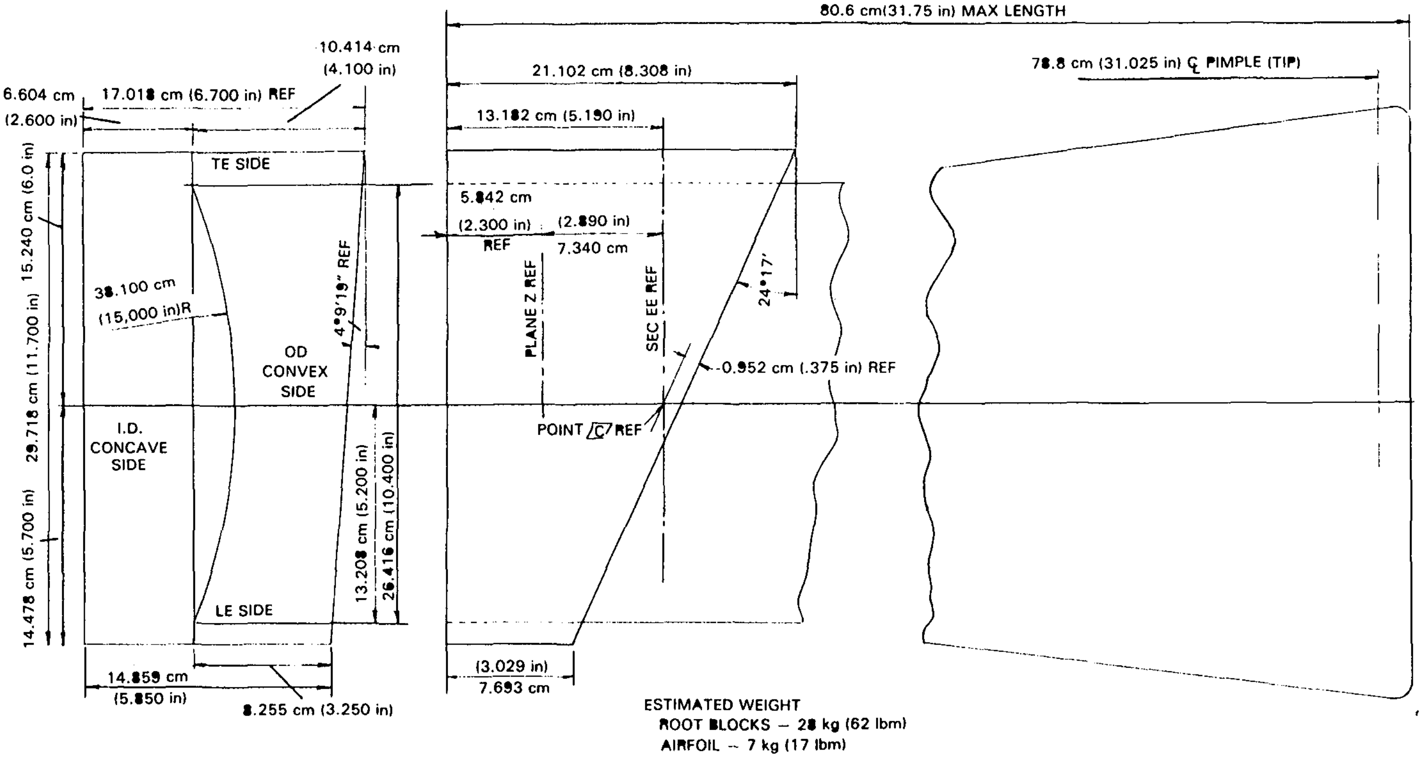


Figure 5-35 Numerically Controlled Machined 1045 Steel Cores For Hollow Fan Blade

HIP Cans for Hollow Fan Blades - Tooling for producing steel cans similar to those used in the diamond specimen program was found to be prohibitively expensive considering the limited number of parts to be made. Therefore, TRW devised an expedient method of forming an outer cover skin from 0.076 cm (0.030 in) titanium that, when bonded, would become part of the blade assembly. These cover sheets are approximately 2.54 cm wider on each side and end than the maximum width and length for the designed blade as shown in Figure 5-36. Solid root blocks were TIG welded to the sheet cover skin prior to assembly. After blade assembly, the oversized cover skins were seam welded together. This approach was also used to make rootless blades by eliminating the root blocks.



80.6 cm(31.75 in) MAX LENGTH
10.414 cm (4.100 in)
6.604 cm (2.600 in)
17.018 cm (6.700 in) REF
21.102 cm (8.308 in)
78.8 cm (31.025 in) ℄ PIMPLE (TIP)
13.182 cm (5.190 in)
TE SIDE
5.842 cm (2.300 in) REF
(2.890 in) 7.340 cm
38.100 cm (15,000 in)R
4°9'19" REF
PLANE Z REF
SEC EE REF
24°17'
OD CONVEX SIDE
-0.952 cm (.375 in) REF
POINT C REF
I.D. CONCAVE SIDE
15.240 cm (6.0 in)
29.718 cm (11.700 in)
14.478 cm (5.700 in)
13.208 cm (5.200 in)
26.416 cm (10.400 in)
LE SIDE
14.859 cm (5.850 in)
8.255 cm (3.250 in)
(3.029 in) 7.693 cm
ESTIMATED WEIGHT
ROOT BLOCKS – 28 kg (62 lbm)
AIRFOIL – 7 kg (17 lbm)

Figure 5-36 Airfoil/Root Assembly Configuration

Camber Tooling - TRW designed and built steel camber tooling dies to camber the hot isostatically pressed/diffusion bonded blade in one operation. Finish machined tooling used for blade camber is shown in Figure 5-37. A 3.8 cm (1.5 in) diameter pin extends beyond the tip of the blade and is located along the stacking axis of the blade. The alignment at the root is maintained by the sides of the root block. The blade is placed hot, i.e., 871-954°C (1600-1750°F), into the tooling dies and squeezed to camber the root and airfoil. The camber dies were operated at 204-315°C (400-600°F) while the actual cambering was performed in a 1,360,770 kg (1500 ton) hydraulic press.

Twist Tooling - TRW designed and built steel twist tooling dies to twist the cambered and HIP'ed blades in an Ajax crank press twister. These blades were twisted using a two-step approach employing a set of dies for each separate area (i.e., root, center of the airfoil, and tip) as shown in Figure 5-38. The actual twisting procedure required the airfoil to be clamped with dies at the center of the airfoil. Appropriate dies were then clamped at the tip of the airfoil allowing some twist to be put into the blade. Rotating a large bull gear attached to the center set of dies provided the remaining twist in the center-to-tip section. This process was then repeated for the root-to-center section of the blade using appropriate hardware. When twisting, only the center set of dies and either the root or tip dies were used at one time. Twisting was performed with the hot blade at a temperature of 871-954°C (1600-1750°F) while the tool steel dies remained at ambient temperature.

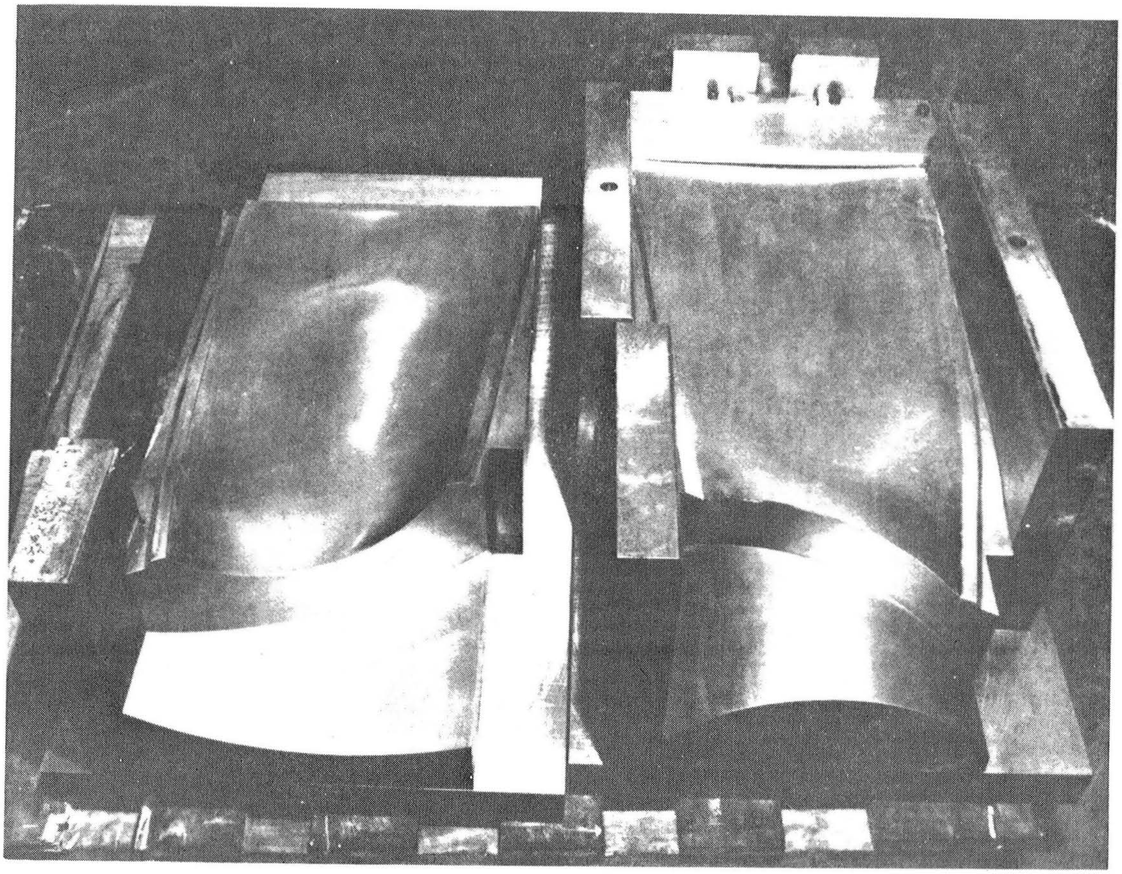


Figure 5-37 Camber Tooling

Isothermal Forge Tooling - Pratt & Whitney Aircraft supplied the hollow fan blade layout and computer aided design file which provided the necessary information used to prepare die and punch casting design drawings. Wooden model patterns were prepared by the casting vendor from these design drawings and from cross section plots of the airfoil. These models were used in casting the actual die and punch. Computer file information was also used to establish coordinate data required for numerically controlled (NC) tapes utilized in producing the necessary electrical-discharge machining (EDM) electrodes. These electrodes were used to finish machine the die and punch castings required in the isothermal forging process. The finished castings (see Figure 5-39) were the largest Inconel 100 die blocks ever produced by TRW for forging blades isothermally.

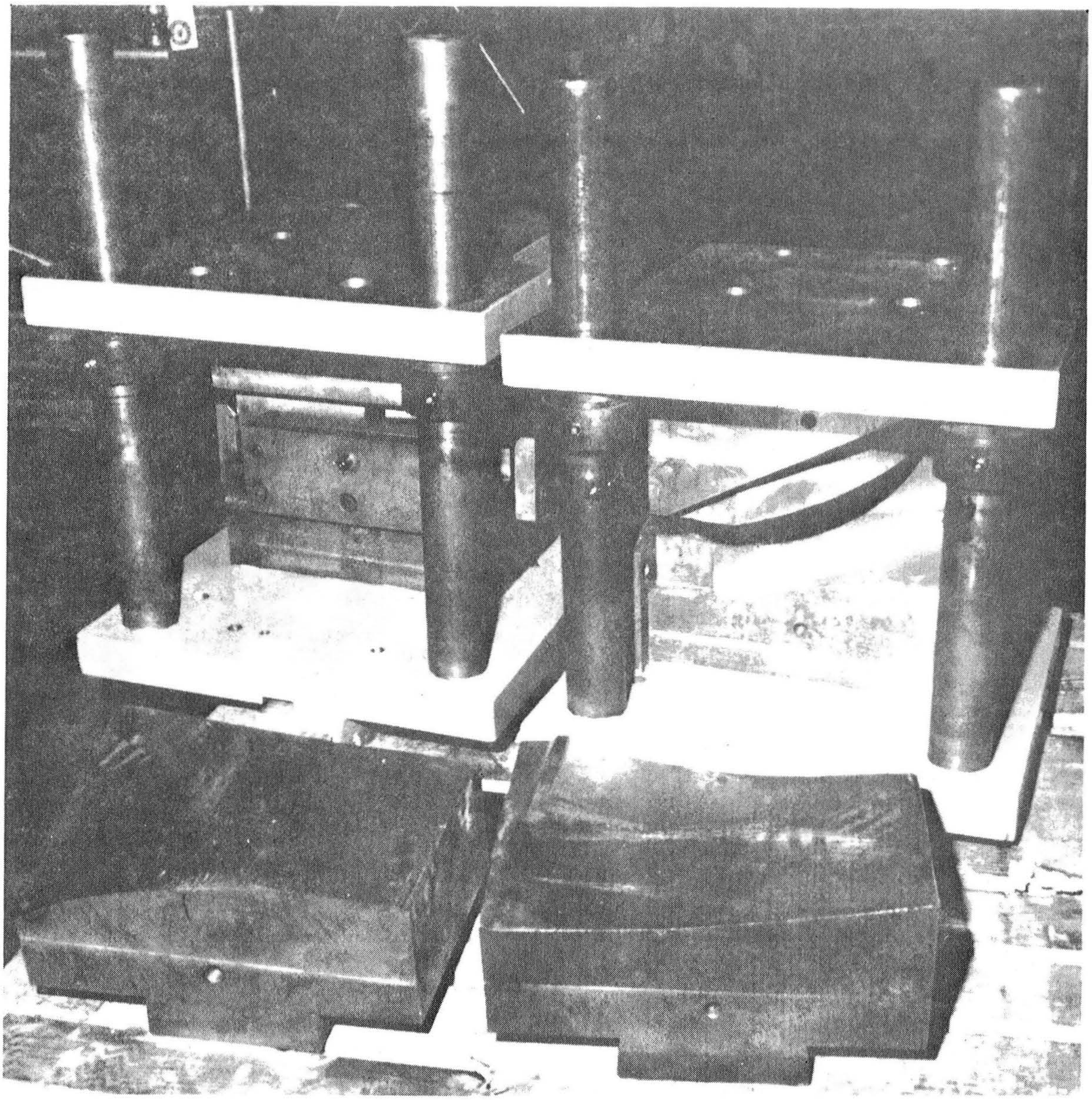


Figure 5-38 Twist Tooling

Die Nest, Heating Elements, Insulation, and Thermocouples - Using isothermal forging die design information, a four post die nest was built. Some of the features of this die nest include water cooled platens and locator inserts which provide a positive location of the die and punch with respect to each other and minimize any chance for movement of the tooling during forging. Heating elements and insulation to minimize heat loss were also part of this tooling system. Thermocouples were used to monitor temperature at twenty locations within the die and punch tooling during the actual processing.

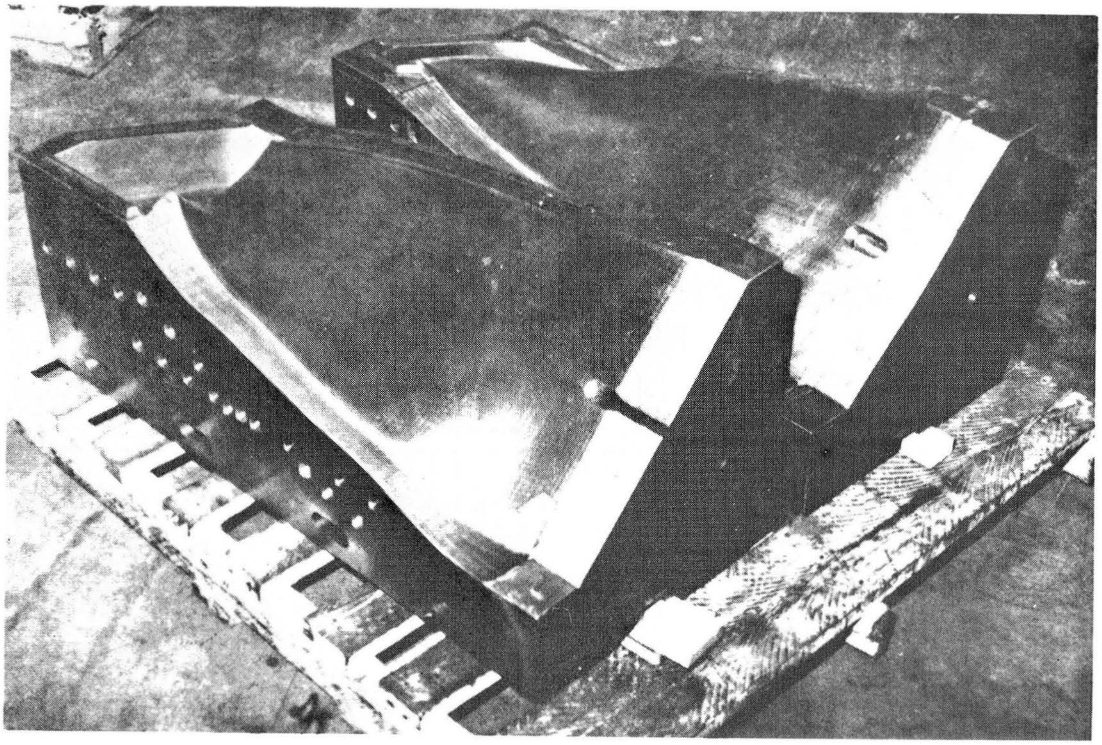


Figure 5-39 IN-100 Material Isothermal Forge Tooling

Blade Inspection Fixture - Root and tip locator pins on the forged airfoil provide positive indexing for the blade inspection fixture (see Figure 5-40). This fixture allows inspection of the blade at six sections.

5.3.2.3 Fabrication Evaluation Results

Processing parameters selected for the fabrication of the hollow fan blades were based on information evolving from the Task 1 effort. In this task, four iterations produced a total of nine blades that were assembled, hot isostatically pressed/diffusion bonded, cambered, twisted, and forged. The procedure used to accomplish these manufacturing requirements is listed below. The experimental procedures and subsequent evaluations pertaining to each iteration are presented on the following pages.

- Clean all individual plies using a three step procedure: (1) rinse the individual plies in an acid bath $(-50H_2O;48HNO_3;2HF)$, (2) water rinse the plies after bathing, and (3) alcohol rinse the plies and dry.
- Degrease the as-machined cores using acetone followed by alcohol rinsing.

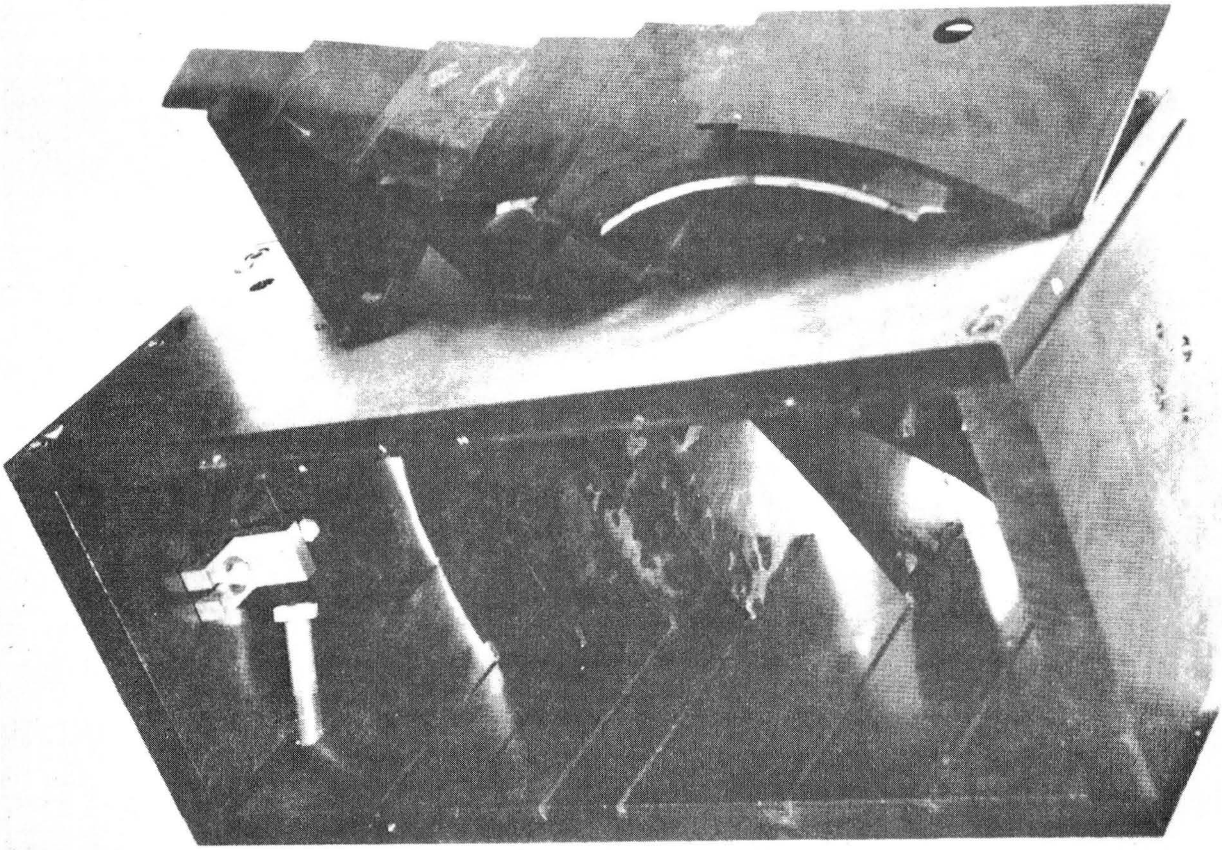


Figure 5-40 Blade Inspection Fixture and Templates

- Assemble the uncambered, untwisted flat plies and core assembly (either with or without the titanium alloy root blocks). If necessary, weld the solid root blocks to the titanium alloy sheet cover skin which is 0.076 cm (0.030 in) thick.

- Final assemble the plies and the degreased cores and place assembled package between the cover skins (HIP can). Core registry is maintained by two steel pins in root area and one steel pin in the tip area. Seam weld the periphery of the HIP can in a helium environment.

- Check for can leaks using mass spectrometer and helium gas. Hot outgas the can in a vacuum furnace (10^{-6}-10^{-7} mm Hg) at 482-537°C (900-1000°F) for 18 hours and anneal at 843°C (1550°F).

- Seal the HIP can by electron beam welding and X-ray the assembled can to look for any shift in the core registry.

- Perform hot isostatic press/diffusion bonding at 954°C (1750°F) for 4.5 hours with a gradual buildup of pressure to a maximum of 103,422 MPa (15 ksi).

- X-ray inspect the HIP'ed part for proper core registry and bonding characteristics.

- Remove blade from HIP can and trim excess cover sheet material.

- Camber, twist, and isothermally forge the HIP'ed blade using specialized steel die tooling manufactured for these applications.

- Finish machine the blade by cutting the part to designed length and width, blend in leading and trailing edge radii, and polish. Leach out the steel cores in a water/nitric acid solution (2:1 ratio) at 82°C (180°F).

- X-ray inspect for final dimensional specification evaluation.

First Iteration - One solid blade (Blade 1) and one blade with simplified cores (Blade 2) were produced in the first iteration. Titanium cover sheets were TIG welded in argon to the root halves. Two sets of titanium plies were hand cut by band sawing to the external contour designs. (NC machined plies and cores were, as yet, not available.) One-half of the blade, as defined by these plies, is shown in Figure 5-41. The addition of cores in the second blade assembly was for the purpose of learning more about core movement during HIP, camber, twist and forge operations. Core definition was similar to that used in the specimen development effort in Task 1. The Blade 2 ply-core-can package was assembled and spot welded together along the periphery to secure the assembly for handling. The package was then seam welded together in air except for an area at the root end which was designed for insertion of an evacuation tube used in the out-gassing process. This evacuation tube was placed between the cover sheets at the root end. The tube was TIG welded in argon to the cover sheets. The blade assembly was then leak checked using a mass spectrometer, vacuum out-gassed at 510-537°C (950-1000°F) for a minimum of six hours and sealed by hot forging the evacuation tube.

The two blade assemblies were then HIP'ed (see Figure 5-42). Visual observation indicated both assemblies leaked during the HIP cycle. The HIP assemblies were again leak checked using helium. Both blades leaked at the root end near the evacuation tube exit and also failed at spot welds inside the seam welded area. These areas were re-sealed and the entire assembly was leak checked again using a mass spectrometer. No other leaks were found. It was determined that spot welds should not be within the seam welded perimeter. The poor condition of the blade assemblies after HIP limited any further evaluations.

Second Iteration - The second iteration involved re-HIP'ing blade 2 in order to evaluate a new evacuation tube procedure and assemble and HIP a rootless, cored blade (Blade 3).

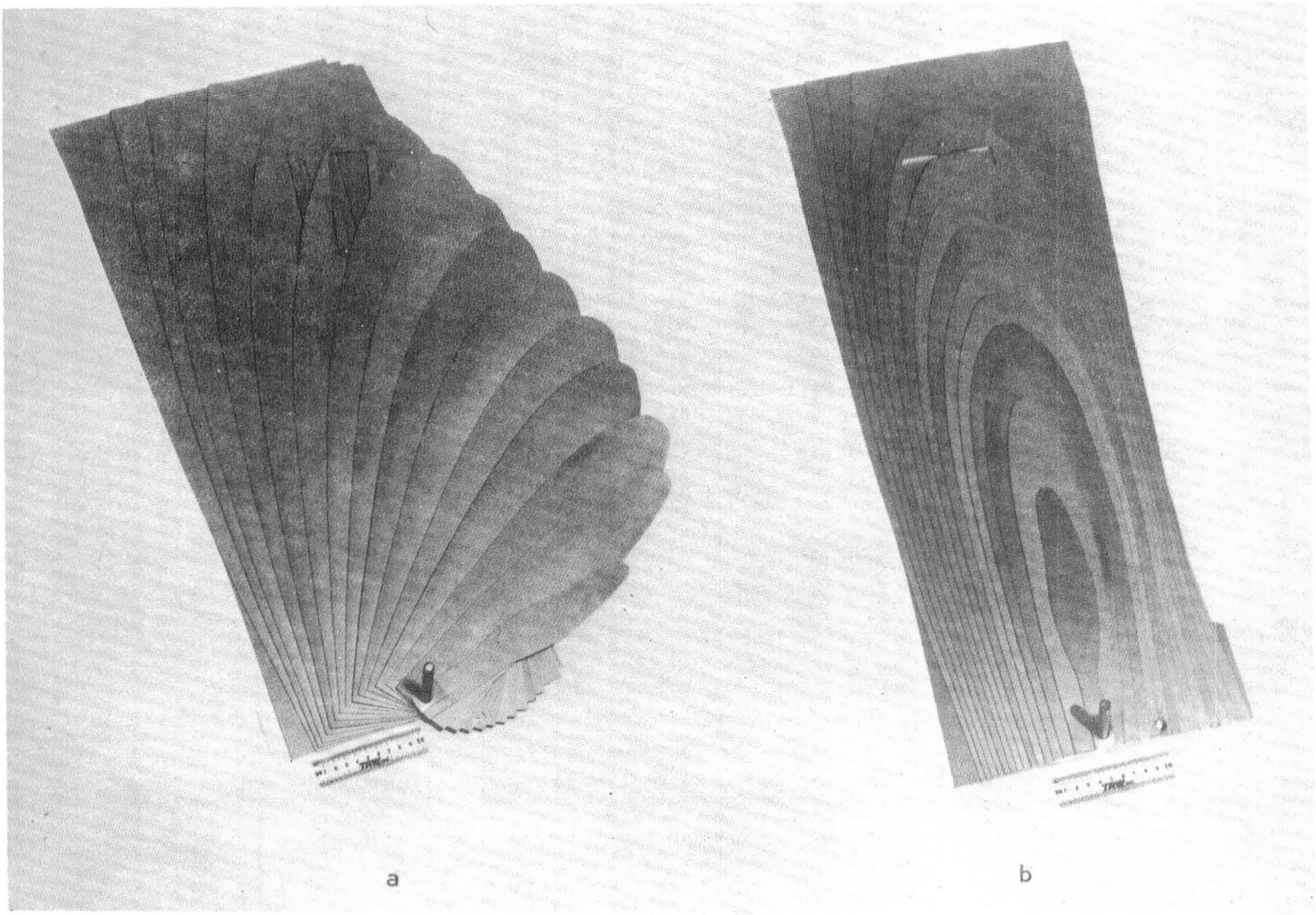


Figure 5-41 Hand Cut Titanium Alloy Plies HIP'ed In First Iteration

A different sealing approach at the root end was performed using the blade 2 assembly. A larger diameter evacuation tube was used along with a 1.27 cm (0.50 in) thick plate of titanium with a hole drilled through the plate to accept the evacuation tube. The tube was TIG welded to both sides of the plate and the plate was TIG welded to the back of the root blocks. The assembly was leak checked using a mass spectrometer, hot out-gassed and annealed at 843°C (1550°F) for one hour, leak checked again, and sealed by forging the evacuation tube. Blade 2 was then hot isostatically pressed using the delayed pressurization cycle for 4.5 hours at 954°C (1750°F) and 103,422 MPa (15 ksi). However, subsequent evaluation indicated that weld failures occurred at the can/root/TIG weld interface. The visual appearance of the blade remained the same as after the first iterative run.

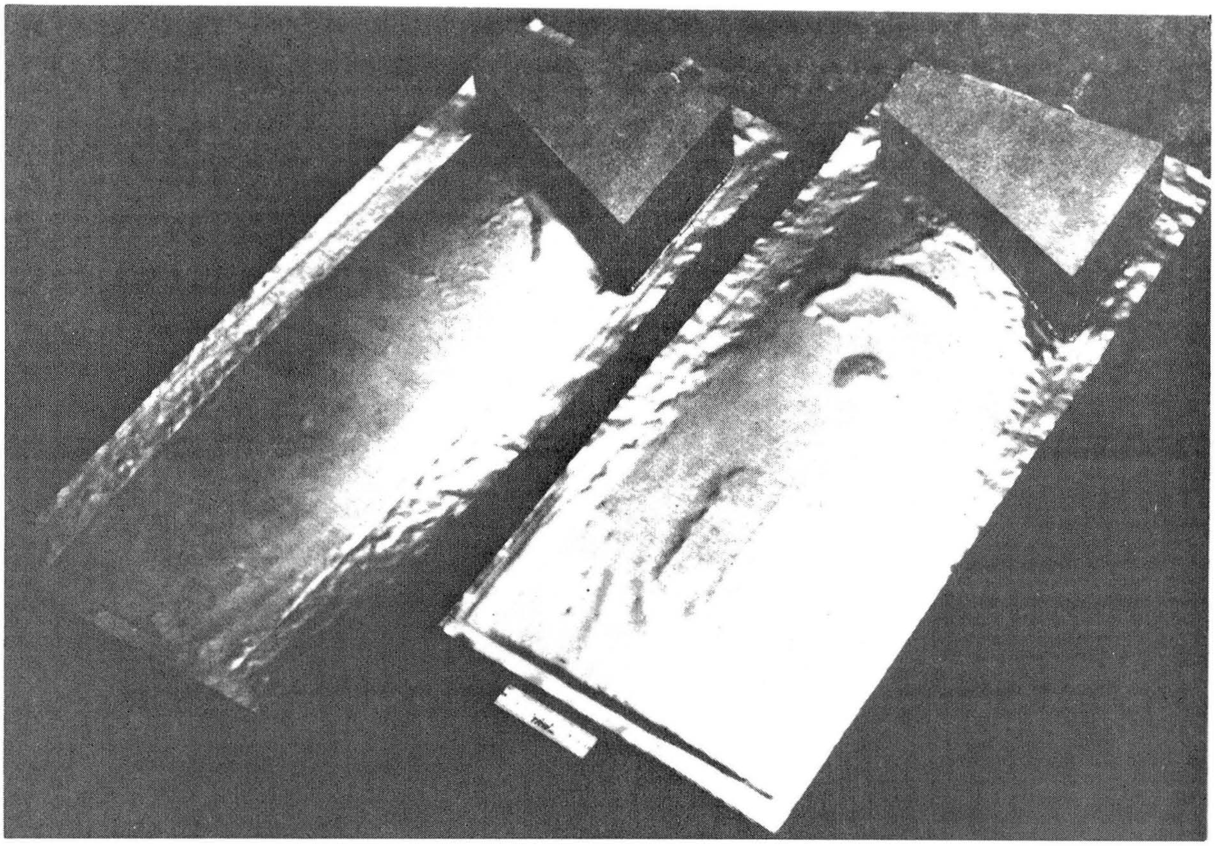


Figure 5-42 Blades 1 and 2 After First Iteration HIP

Blade 3 was assembled incorporating NC machined plies and cores (see Figure 5-43). To avoid core displacement, the edge cores were held in place by a strip of titanium alloy foil wrapped around the two central plies and tack welded to the core surface. At the root end of the blade, filler material was layed up and welded together to form a wedge shape to minimize can deformation in this area during HIP. After assembly, the package was seam welded along the periphery. Leak checking and evacuation for sealing were accomplished through a 0.241 cm (0.095 in) diameter hole drilled through the cover sheet at the root end. The assembly was leak checked through the drilled hole by using a mass spectrometer, evacuated in an electron beam chamber, and sealed by electron beam welding. Following X-ray of the assembled package to ensure proper core registry, blade 3 was HIP'ed using the delayed pressurization cycle for 4.5 hours at 954°C (1750°F) and 103,422 MPa (15 ksi). Post-HIP evaluation of blade 3 indicated that the can ruptured in several places at the junction of the root end and the filler plies due to excessive can deformation in the early stages of HIP. X-rays of the rootless blade after HIP indicated that the cores maintained registry.

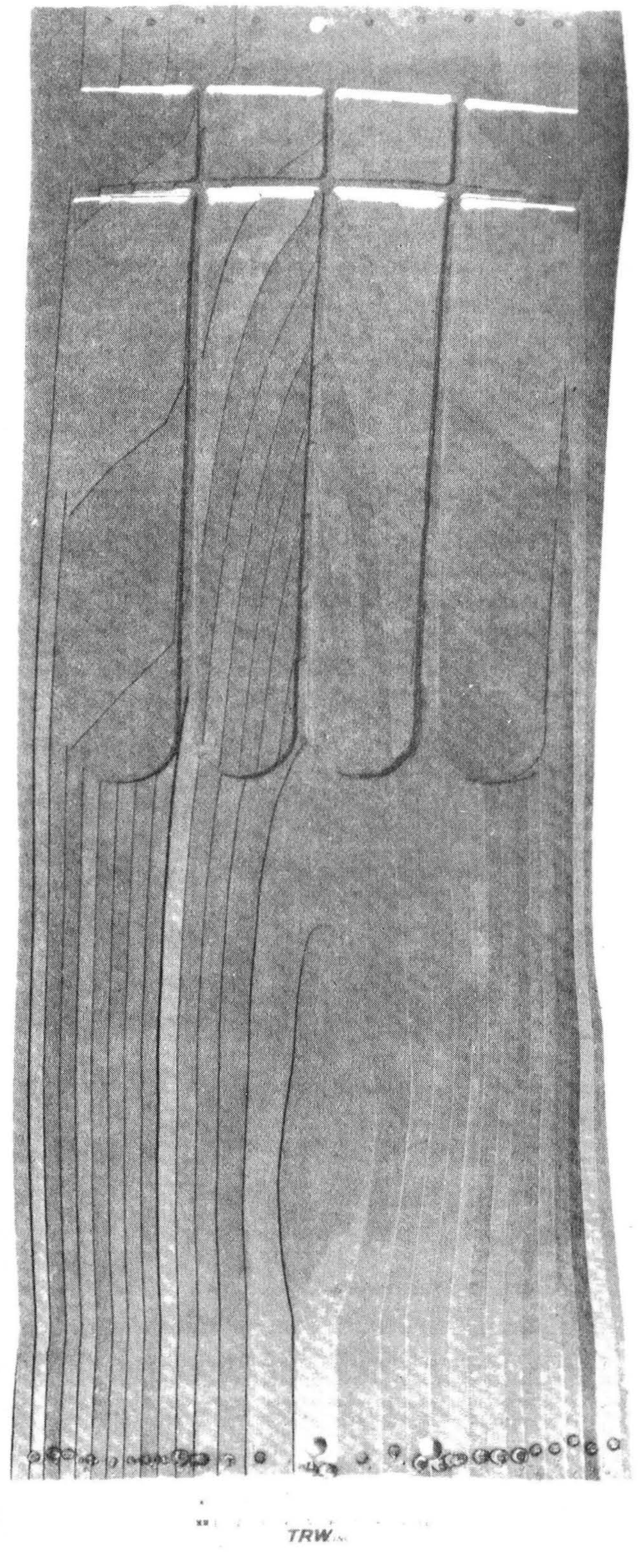
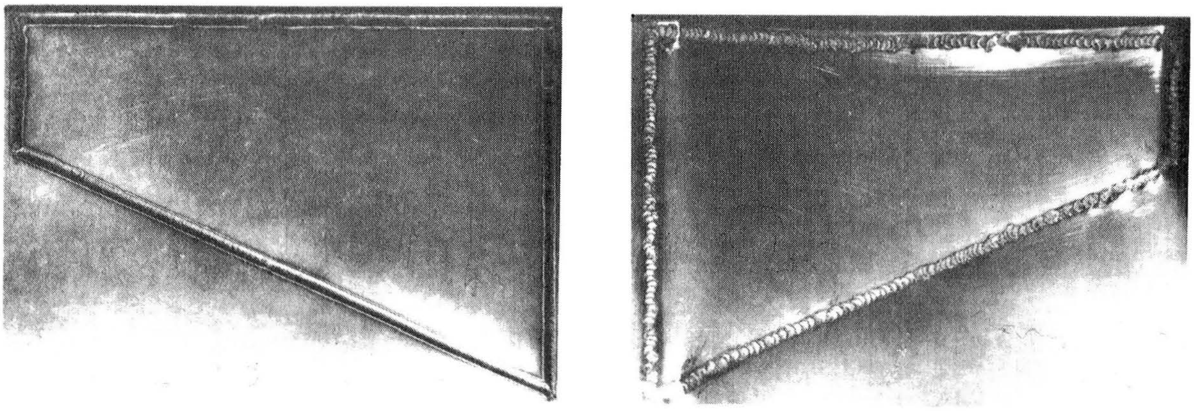


Figure 5-43 One-Half of a Typical Hollow Blade Assembly (15 Plies)

Third Iteration - Third iteration activities included the assembly and HIP of a rootless blade (Blade 4) and a blade with a root (Blade 5).

Assembly, welding, and sealing of blade 4 were the same as blade 3 with two significant differences. Filler material was attached to the root end by a titanium sheet that overlapped and was welded to the filler material and airfoil plies. The second modification was increasing the cover sheet thickness to 0.152 cm (0.060 in). Assembly of blade 5 (with the root) was the same as the blade 3 assembly except the can material was seam welded to the flat root block half and overlapping spot welded to the curved root block half as shown in Figure 5-44. The remainder of the blade assembly was identical to blade 2 including the new evacuation tube dimension and set-up used in the second iteration. Can collapse was observed after hot out-gassing but no can leakage was detected. Blades 4 and 5 were then HIP'ed employing the delayed pressurization cycle, i.e., 4.5 hours at 954°C (1750°F) and 103,422 MPa (15 ksi). Post-HIP blade evaluation indicated blade 4 to be a good, well-bonded blade while blade 5 leaked during HIP. These blades are shown in Figures 5-45 and 5-46. X-rays of blade 4 indicated good core location with no evidence of ply endings. The bumps in Figure 5-45 are excess titanium from the central plies. Blade 5 indicated leaks in several areas with the main can collapsing problem being in the cover sheet-root interface area. The blade 5 canning approach is suspect with the current ply and root designs.



a. Flat Block - Seam Weld

b. Curved block - Overlapping Spot Weld

Figure 5-44 Surface Condition of Canning Sheet Welded to Root Block

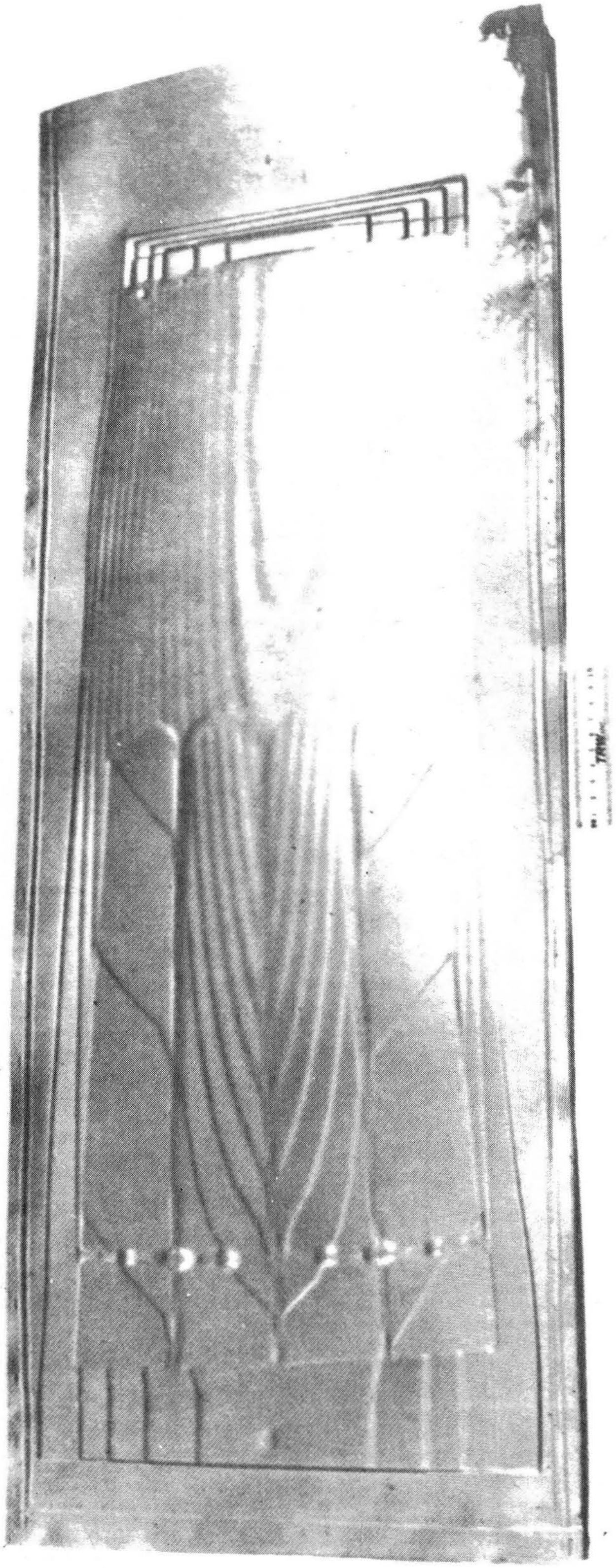


Figure 5-45 Blade 4 As-HIP'ed

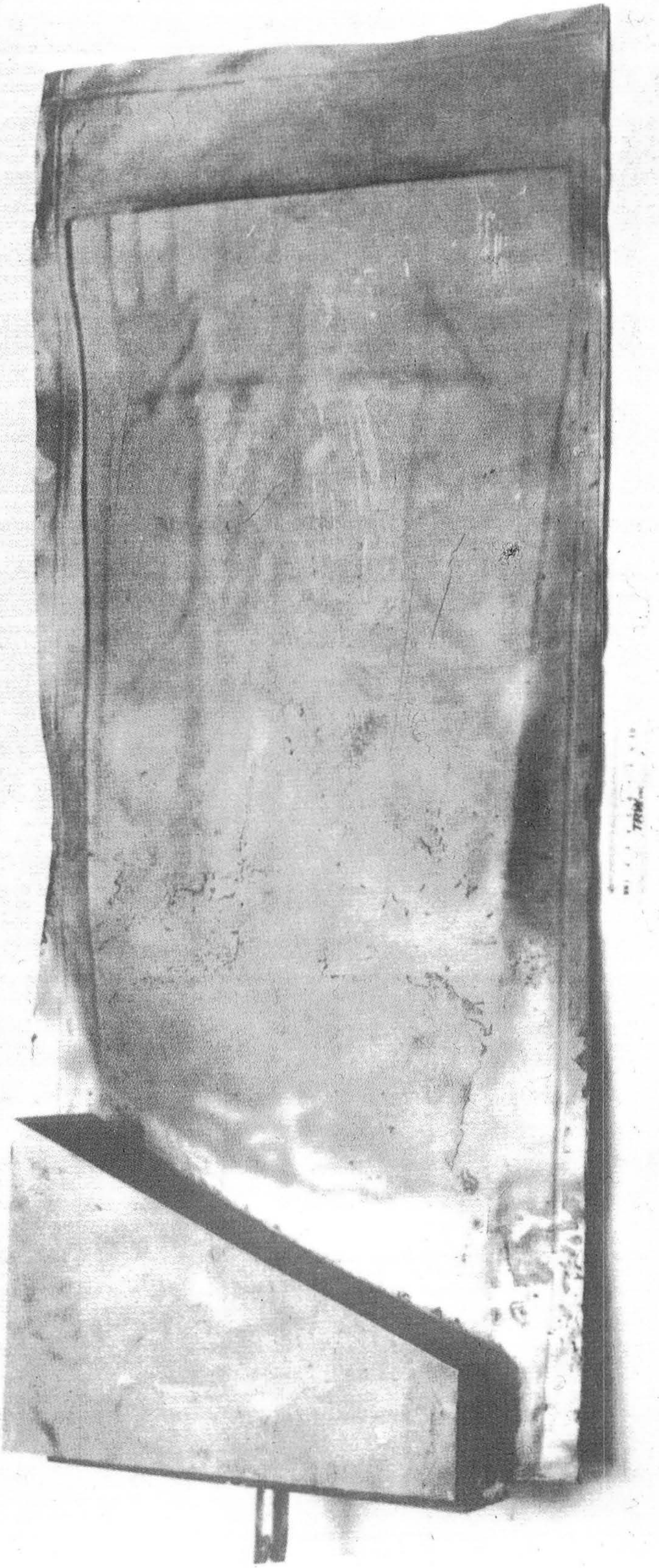


Figure 5-46 Blade 5 As-HIP'ed

Fourth Iteration - By mutual agreement between NASA, Pratt & Whitney Aircraft and TRW, the decision was made to assemble rootless blades and produce only the airfoil section of the blade. Based on the successful results from blade 4, blades 6 through 9 were assembled without a root and sealed in a 0.152 cm (0.060 in) thick cover skin titanium alloy can. These four blades were then seam welded, leak checked, sealed by electron beam welding, X-rayed, and HIP'ed employing the same cycle described in the previous iterations (see Figure 5-47). Subsequent evaluation of all four blades indicated successful bonding. The amount of can collapse after sealing and after HIP'ing was measured at eight separate locations to provide some indication as to the amount of actual can collapse.

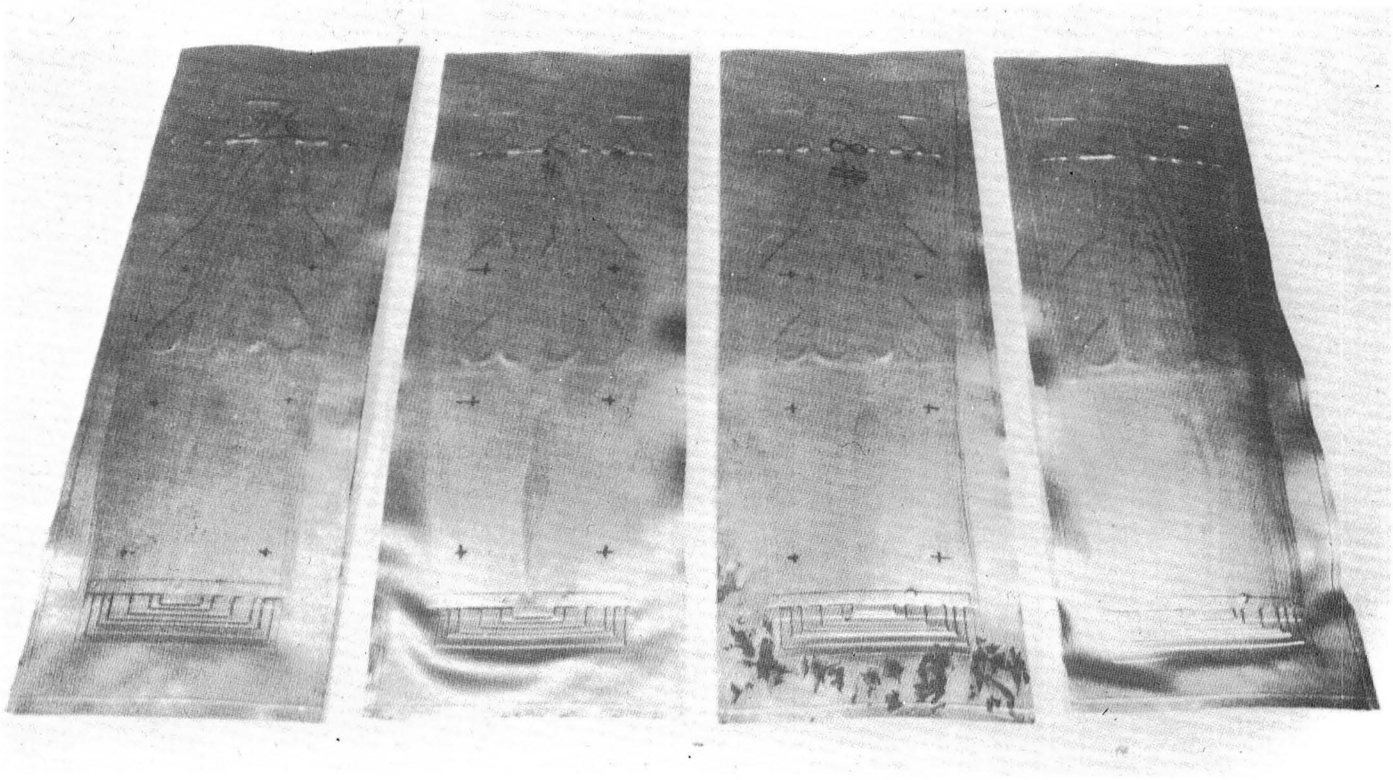


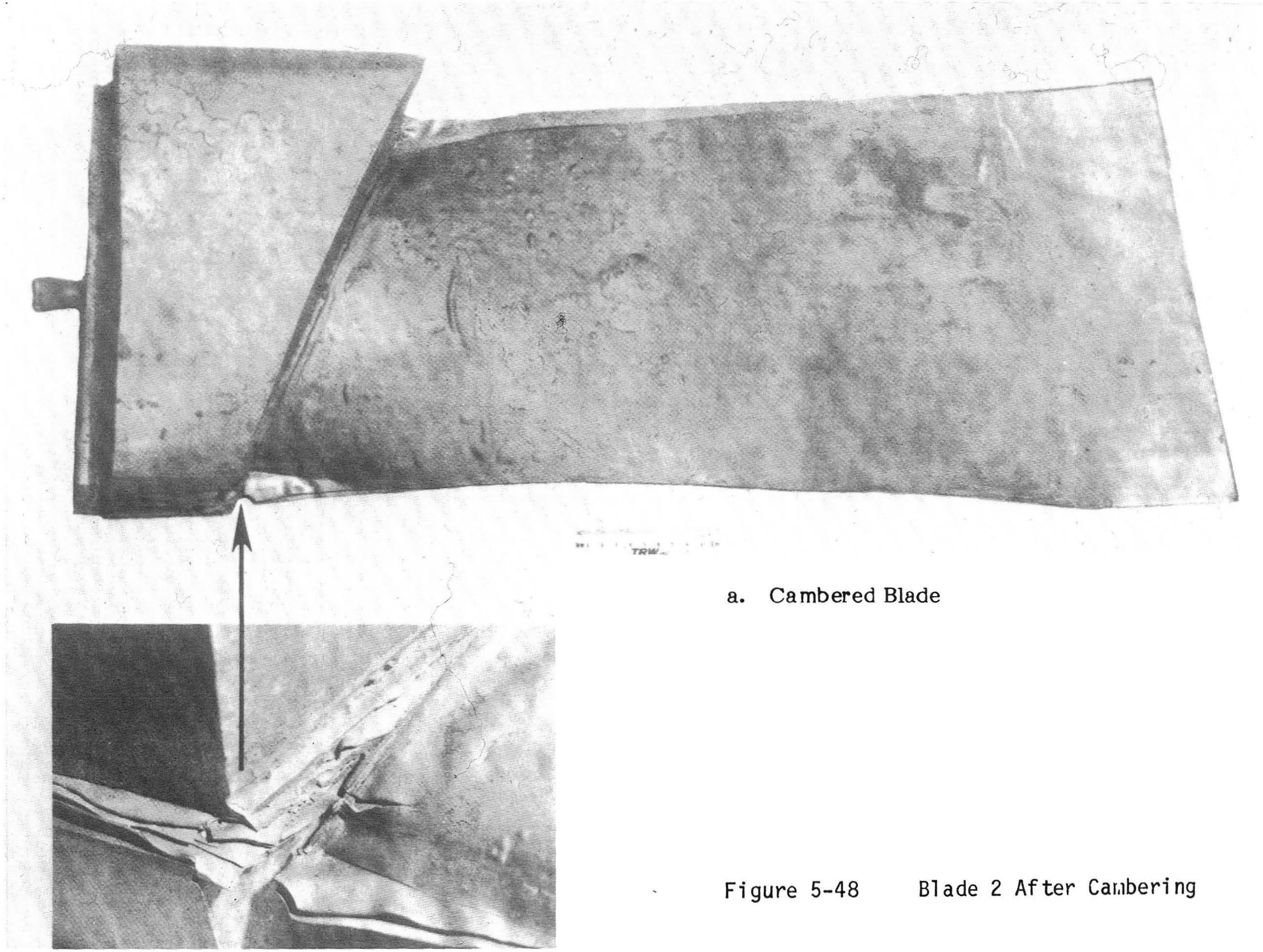
Figure 5-47 Blades 6 through 9 Shown After HIP

Hot isostatically pressed blades 4, 6, 7, 8, and 9 were cambered, twisted, isothermally forged, machined, and core leached in an effort to produce aerodynamically finished blades for delivery to Pratt & Whitney Aircraft and NASA. TRW's effort directed towards producing these finished blades is detailed below.

Camber: Camber tooling trials were conducted with blade 2, the rooted blade with many unbonded areas produced in the first iteration. Based on results of this trial run (see Figure 5-48a, b), camber die rework at the root/airfoil interface was performed. This was necessary because the die and punch made contact with the airfoil prior to making contact with the root. Camber trials were then reinitiated with blade 4. However, cambering blade 4 resulted in severe tearing near the leading and trailing edges at the intended root/airfoil interface area. Consequently, additional rework of the punch was required. Blades 6 through 9 were cambered after the second tooling rework. The cambering process included application of a protective glass coating and heating the blade in an air furnace to 954°C (1750°F) for 35-45 minutes. The blade was then manually transferred from the air furnace to the 1,360,770 kg (1500 ton) hydraulic press where the camber tooling was gas torch heated to about 204°C (400°F). The blade was installed in the hot camber tooling and a two-sequence cambering process was initiated. During the first sequence, the blade was placed in the die extending about 20.3 cm (8.0 in) beyond the root, cambered with a 453,590-544,308 kg (500-600 ton) load, the blade was then pushed another 10.1 cm (4.0 in) into the die and again cambered with a 453,590-544,308 kg (500-600 ton) load with no utilization of the tip locator. The blade was then recoated/reheated 954°C (1750°F), 35-45 minutes) and again cambered with the blade located at the tip locator in the proper position. Transfer times from the furnace to the press took less than 20 seconds for the first sequence and less than 10 seconds for the second sequence. This cambering approach was used for blade 6 and all subsequent blades. The cambered blades are shown in Figure 5-49.

Twist: The blade twisting process was planned so the tip section was twisted first and the root section area of the airfoil was twisted last. Initially, the center dies were preset for a counterclockwise 7.5^{o} twist. For the twisting operations, a protective coating was applied to the tip and root end of the blades. The blades were then heated to 954°C (1750°F) for 30 minutes. The procedure for twisting the tip end required the heated blade to be placed in the cold dies as shown in Figure 5-50. The next step was to clamp the center section dies and then, in this case, clamp the tip section dies. The twisting was then accomplished by rotating the center dies counterclockwise until a 10.5° position of the center dies is reached. Figure 5-51 shows blades 6 through 9 after twisting both the tip section and the root section of the blades. Both die sets were then released and the part removed. Visual inspection indicated that the required twist was attained in all four blades.

Isothermal Forging: The isothermal forging dies and die set were installed in a 2,267,950 kg (2500 ton) hydraulic press as shown in Figure 5-52. Blades were located within the die by using a stainless steel root segment having holes drilled in the exact location as the locator holes in the root end of the block. The stainless steel root segment was bolted to the blade. When placed in the bottom die, no lateral or longitudinal movement could occur.



a. Cambered Blade

b. Airfoil Root Tearing

Figure 5-48 Blade 2 After Cambering

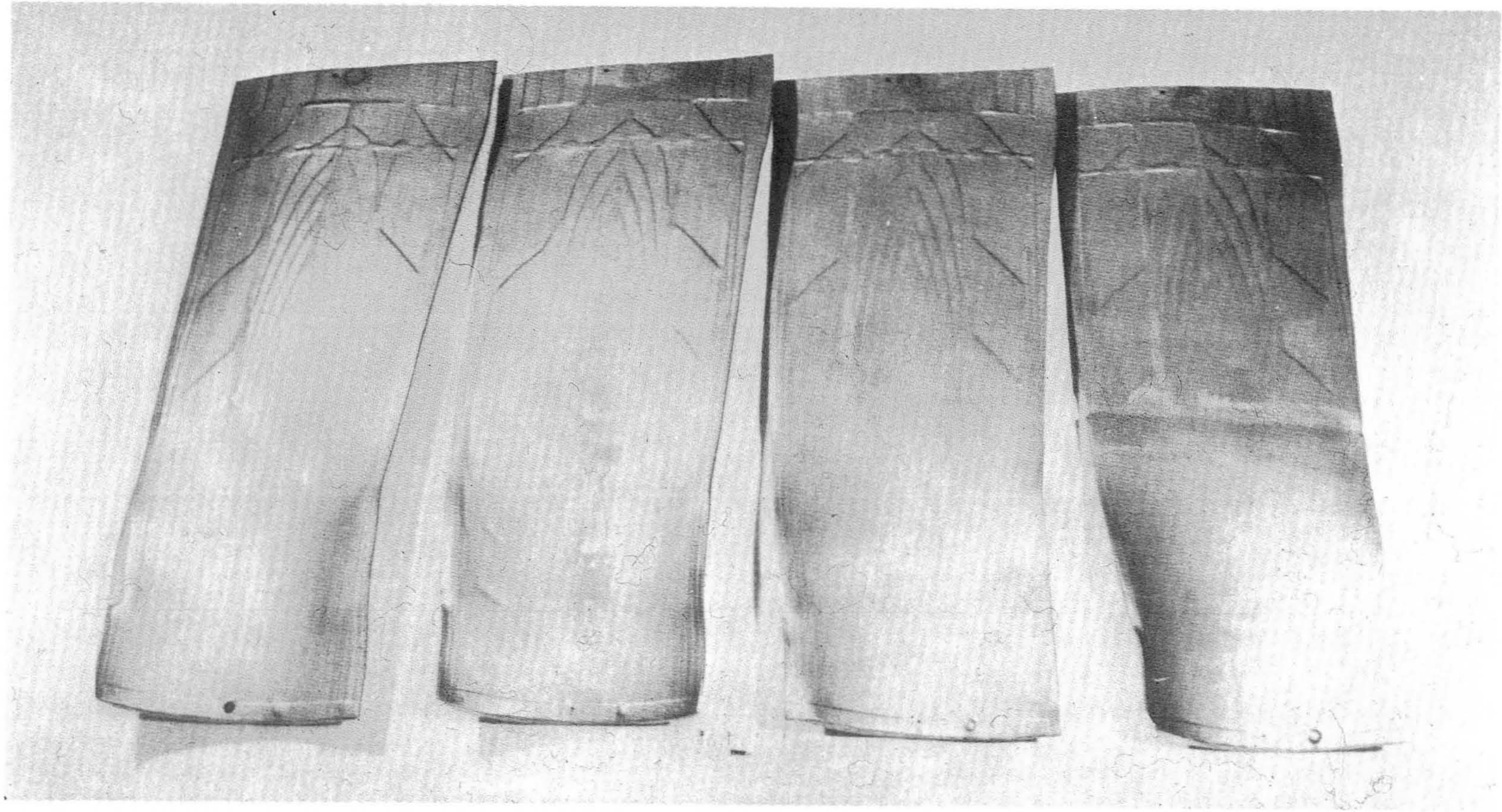


Figure 5-49   Blades 6 Through 9 After Cambering

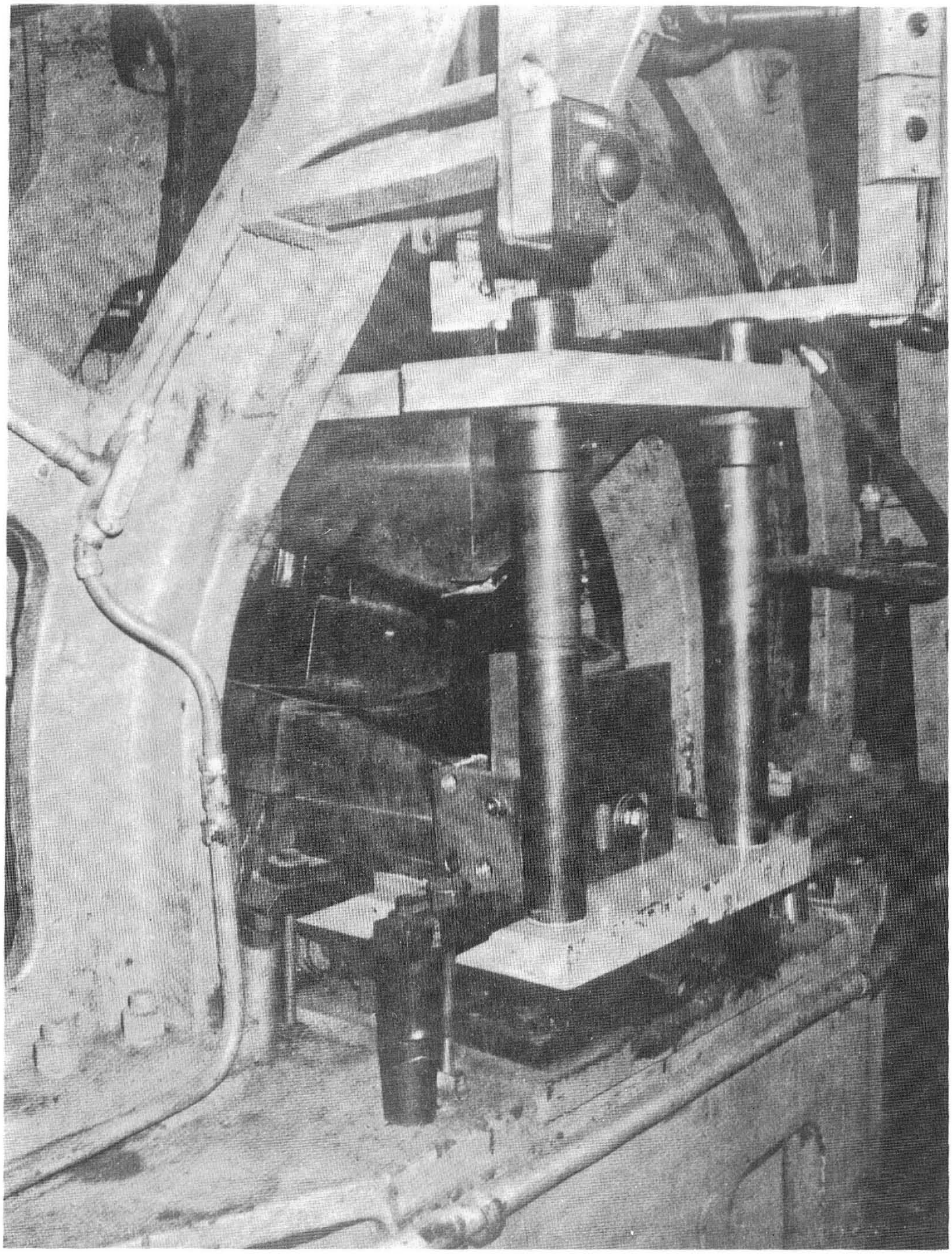


Figure 5-50 Twist Tooling Shown Installed In Ajax Crankpress Twister (Root and Center Dies Are Shown)

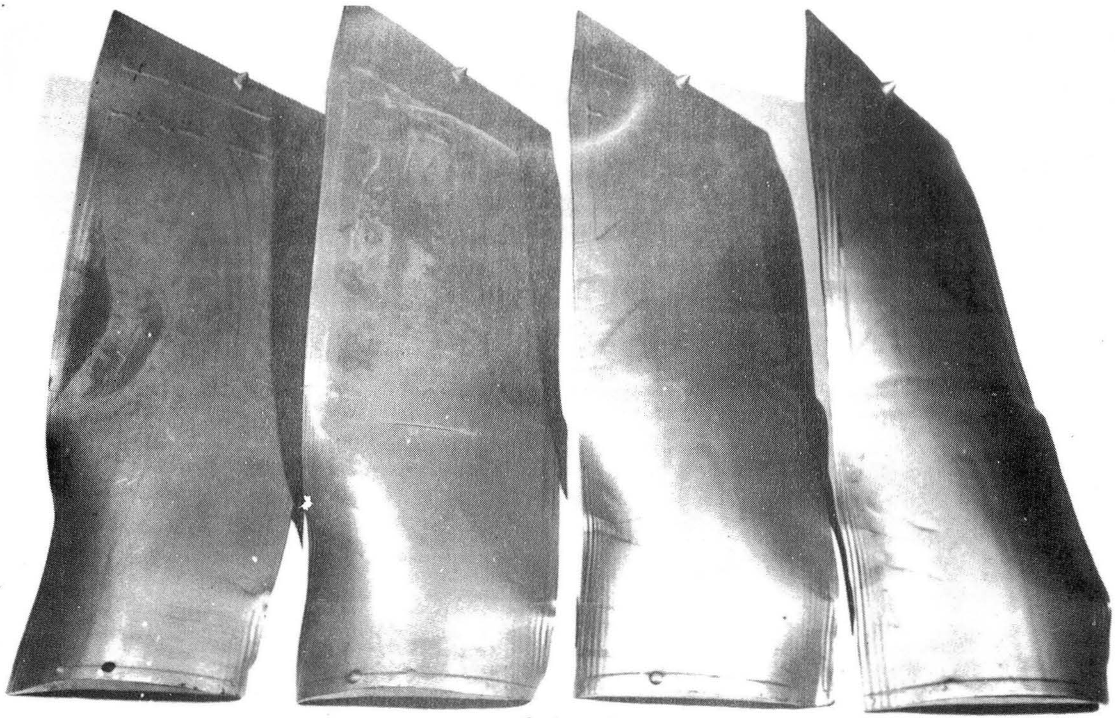


Figure 5-51 Blades 6 Through 9 After Twisting In Crankpress Twister

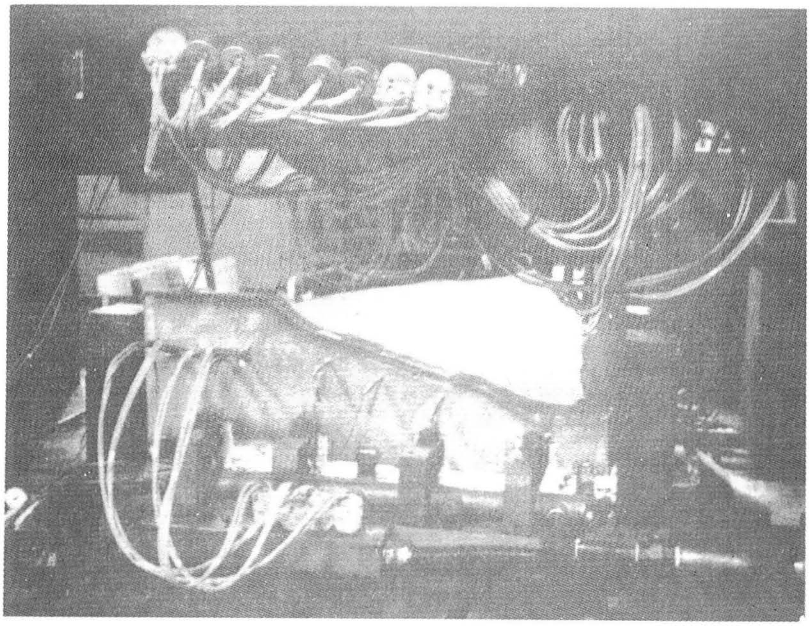


Figure 5-52 Isothermal Forge Tooling Shown Installed In 2,267,950 kg (2500 Ton) Hydraulic Press

Prior to forging, a protective coating was applied to all blades. Modifications evolving from a trial run using blade 4 resulted in the following isothermal forging procedure used for blades 6 through 9. The blades were placed in the die cold, the die was heated for 5 minutes at a temperature of 648°C (1200°F) and then clamped together using a 90,718- 181,436 kg (100-200 ton) load for 30 seconds. The part was then removed from the die and recoated with a protective lubricant and made ready for isothermal forging. The actual forging procedure required (1) external shimming of the die at the tip and root section to posture the die a maximum of 1.778 cm (0.700 in) from root to tip, (2) spray coating the blades, (3) preheating the part to 593°C (1100°F) for 10 minutes, (4) loading the part in the die and hold until temperature equilibrium is reached between part and die, (5) applying ramp pressure up to 1,632,924 kg (1800 tons) over a 5 minute period, and (6) holding under pressure for 10 minutes. Pressure was then released and the part was removed from the press and visually inspected. Blades 4, 6, and 9 were used to achieve the most desireable setup for forging blades 7 and 8 (see Figure 5-53) which were scheduled for delivery to NASA and Pratt & Whitney Aircraft. However, blade tip/die contact during forging remained minimal causing a very large oversize condition in the tip section as shown in Figure 5-54. This condition was expected because of the lack of contact at the tip section. In addition, the leading and trailing edges were found to be heavy in thickness. This heavy condition is attributed to excessive thermal expansion of the dies along the width of the blade during heating. The wider the chord the more significant the problem, and the hollow fan blade chord width is significantly larger than commercially produced blades. To produce an airfoil closer to blueprint specifications would require the forging dies to be redesigned incorporating revised thermal expansion data that evolved from this effort.

Blades 7, 8 and 9 were saved for machining while blades 4 and 6 were sectioned for internal cavity and cavity surface evaluations. Figure 5-55 shows a typical view of an airfoil section from blade 4 that meets the pitch thickness tolerance. It was determined that the wall thickness met blueprint requirements. Figure 5-56 shows the typical internal surface condition. Sections of blade 4 were also examined metallographically for disbonds and/or contaminates at the bond lines. No evidence of either was found on the sections evaluated. Figure 5-57 shows the typical microstructure observed for blade 4. Material for this photomicrograph was taken from the root. No evidence of 'micropores' was found at the bond lines using standard etching. Some evidence of 'micropores' was found when the material was given a heavy etch; however, this condition was observed in less than 5 percent of the bond lines examined.

All five blades were X-ray inspected. This inspection revealed that the cores at the leading and trailing edges flowed during the forging operation and followed the flash pattern (i.e., areas where more material flashing occurred resulted in more core flow in these areas). X-ray inspection also indicated that the cores had increased in length as a result of forging. Therefore, overall core dimensions did not meet blueprint requirements. It was determined that less titanium deformation during forging is required to control this core flow problem.

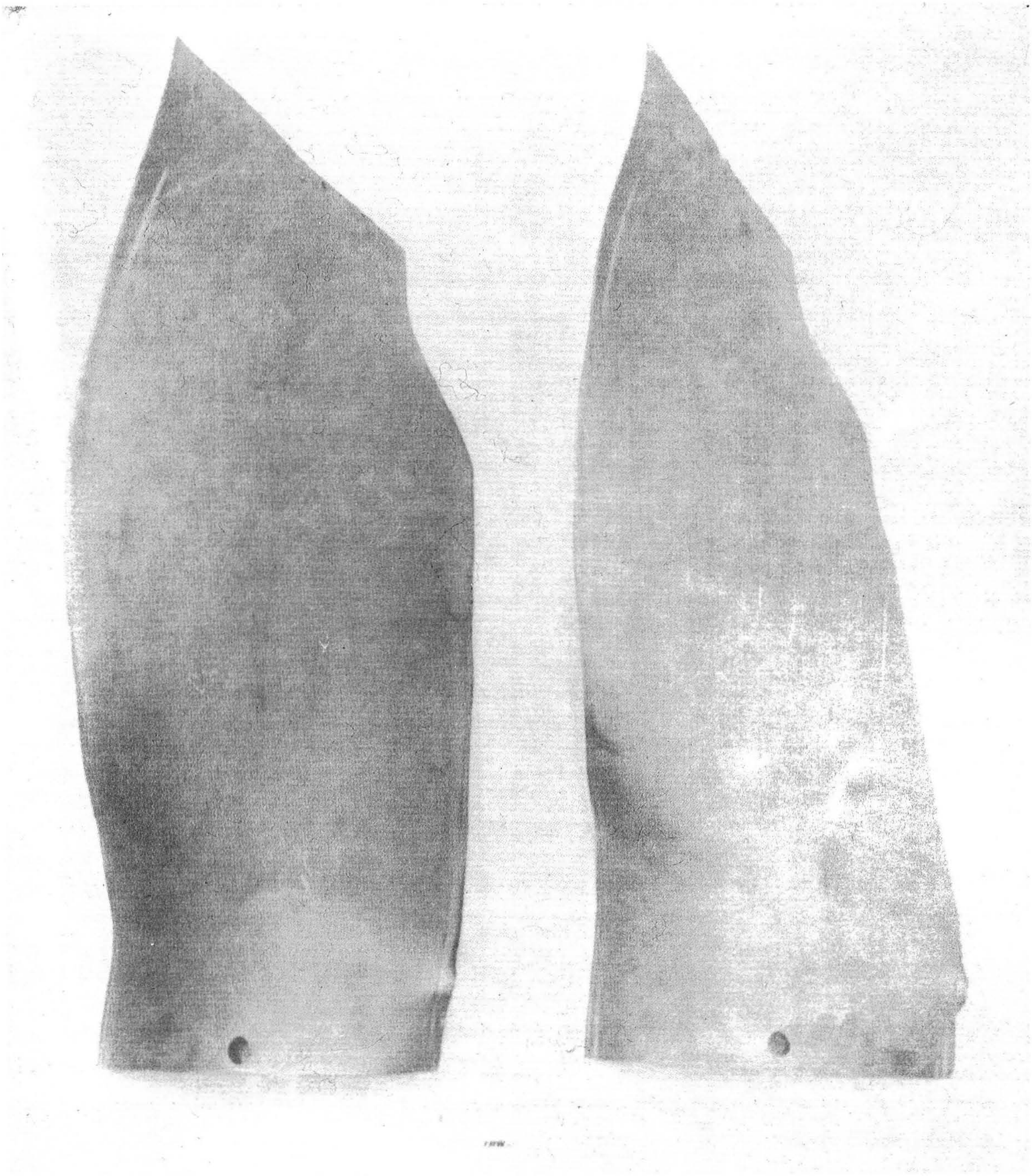


Figure 5-53   Blades 7 and 8 After Isothermal Forging

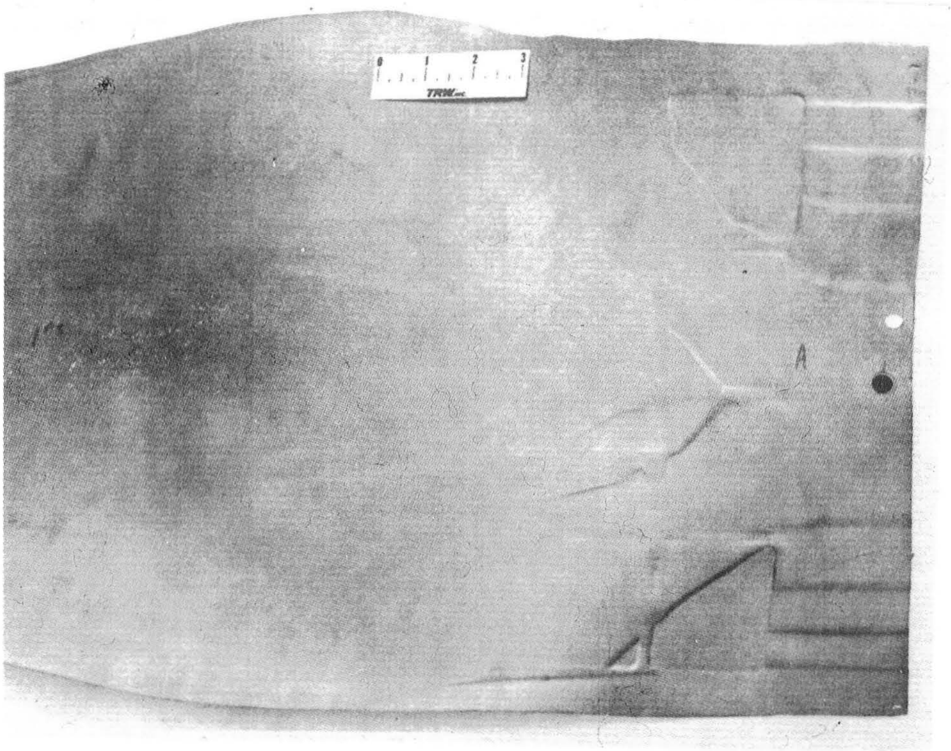

0 1 2 3
TRW inc
A

Figure 5-54 Tip Section of Blade 7 After Isothermal Forging Showing Lack of Contact In This Tip Section During Forging As Indicated By Ply Endings Present On The Surface

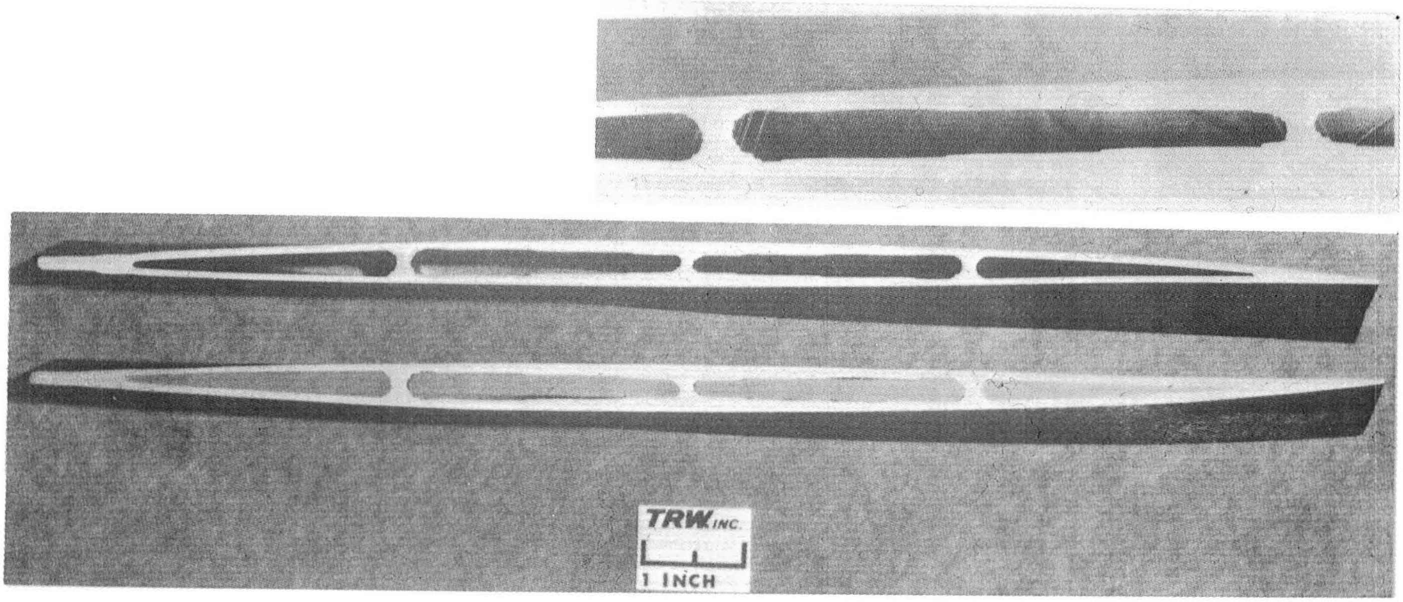

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Figure 5-55 Blade 4 Section AG-AG Top Piece Shown Has Core Removed

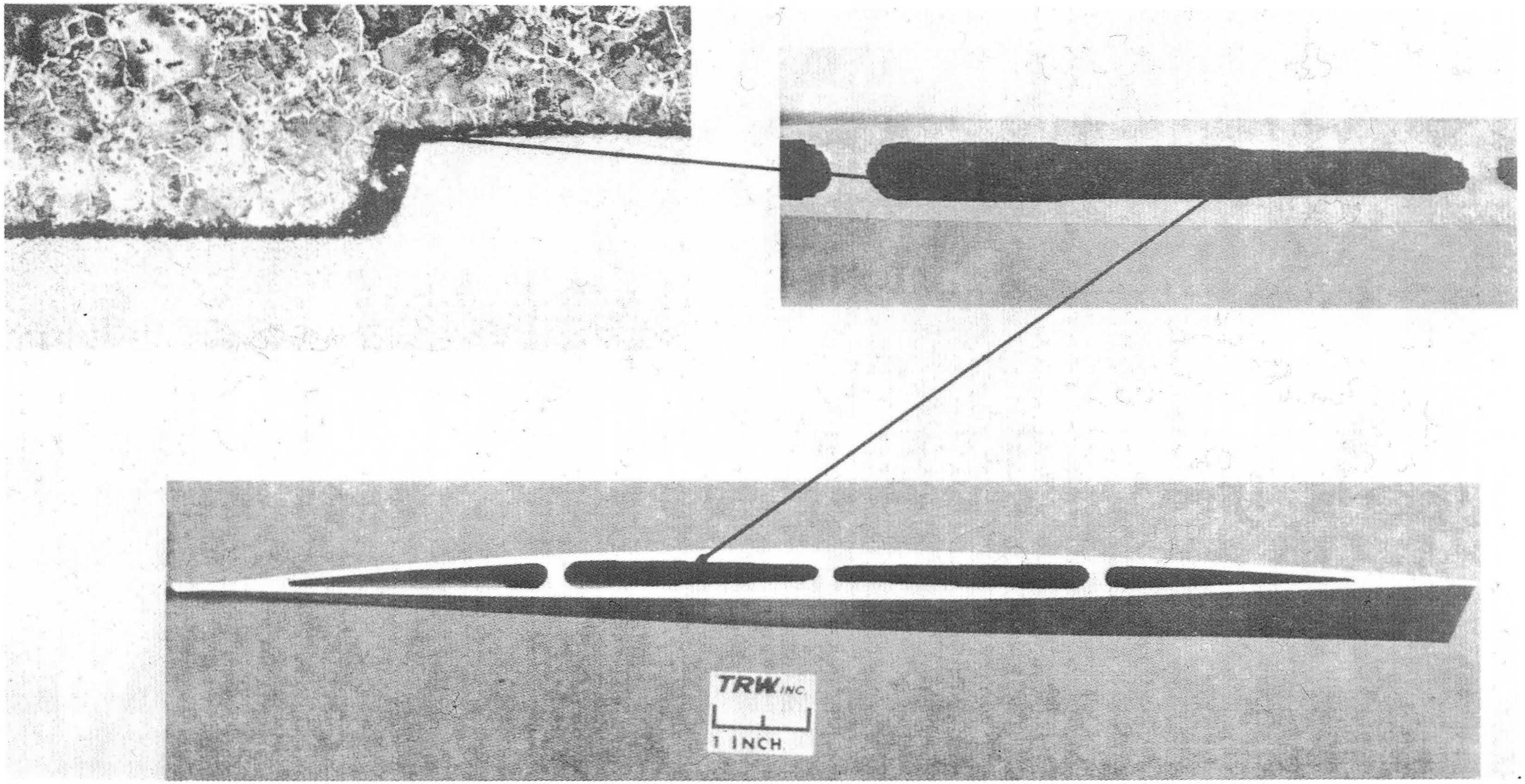
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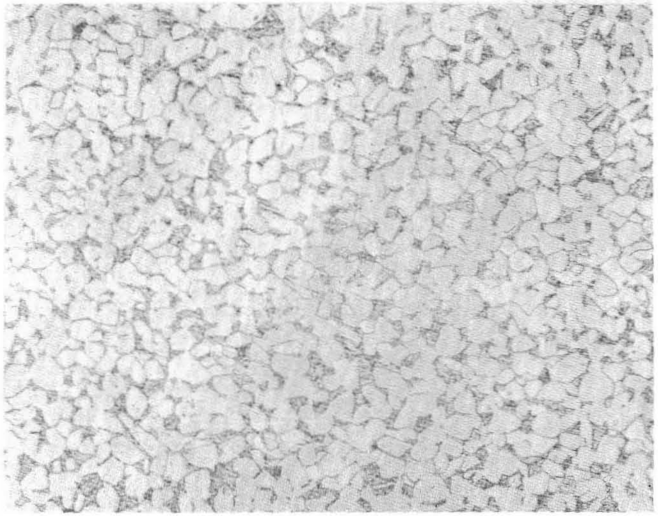
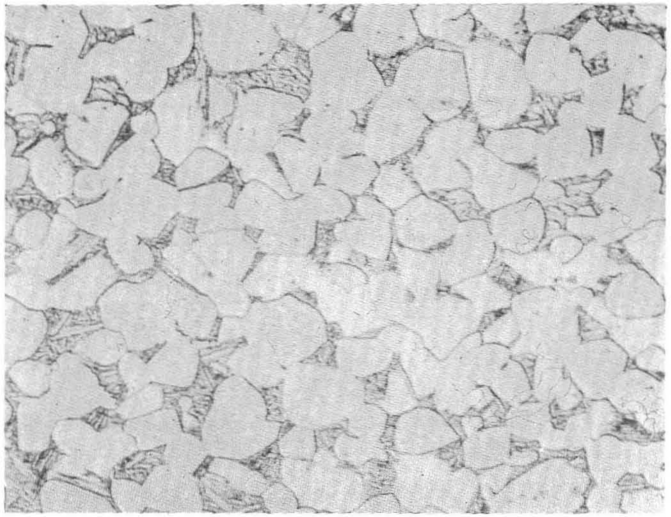
Figure 5-56 Blade 4 Section Af-AF With Core Removed and Typical Internal Wall Surface Condition



200X

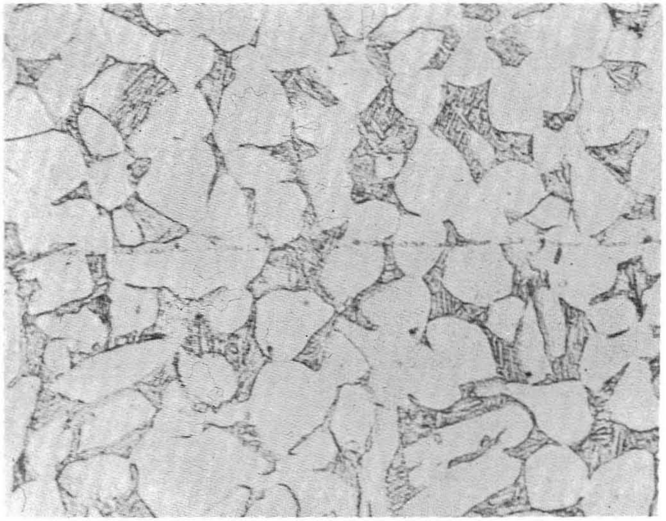
Etch

96 H_2O
2 HNO_3
2 HF



Bond Line

500X



Etch

60 H_2O
35 HNO_3
5 HF

Bond Line

500X

Figure 5-57 Microstructure Observed For Blade 4

Blades 7, 8, and 9 were finished machined (i.e., excess chord stock was removed, leading and trailing edge radii were incorporated, and the airfoils were cut to length) and the cores were leached through machined drilled racetrack holes (shown in Figure 5-58) in a hot 82°C (180°F) water/nitric acid (2:1) bath. Final blade preparation included acid stock removal (ASR) of 0.0002 cm (0.0001 in) material for each airfoil side and vapor blast the airfoil surfaces. The finished blades 7, 8, and 9 are shown in Figure 5-59. Blade 7 was delivered to NASA-Lewis Research Center, blade 8 was delivered to Pratt & Whitney Aircraft, and blade 9 was retained by TRW.

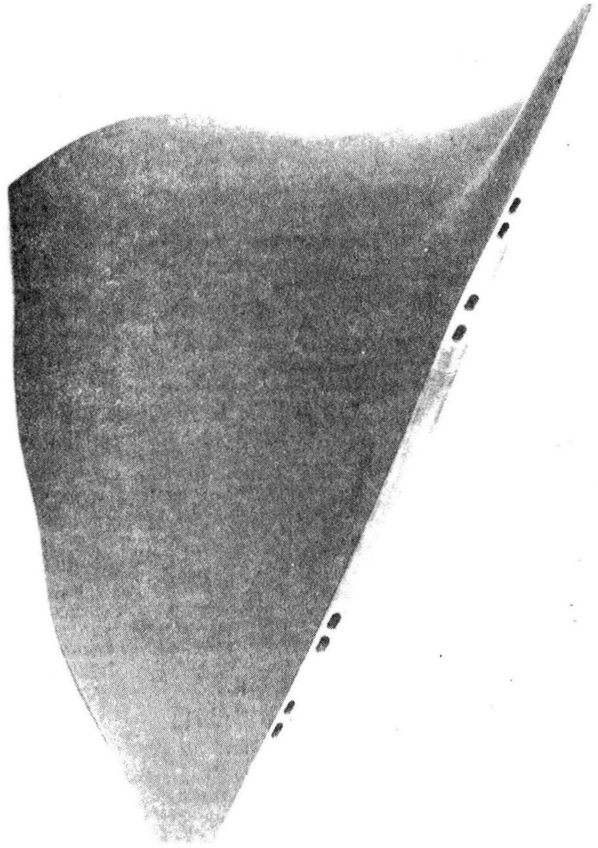


Figure 5-58 Racetrack Holes Machined Into The Blade Tip For Core Leaching

5.3.2.4 Summary of Results

Task 2 was successful in producing three full size shroudless, hollow fan blade airfoils in accordance with the design criteria specified by Pratt & Whitney Aircraft and by using the basic fabrication parameters established in Task 1.

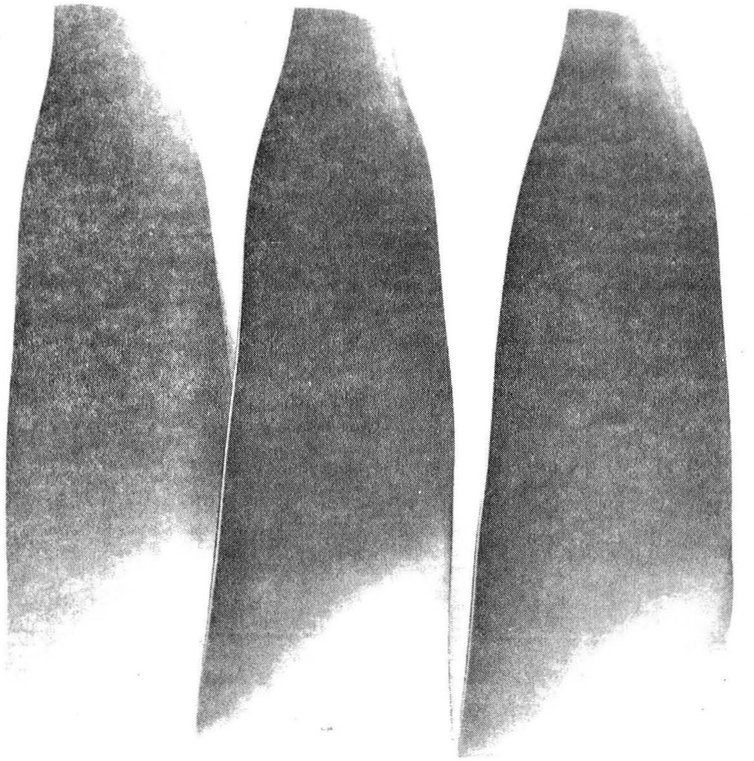


Figure 5-59 Blades 7, 8, and 9 After Finish Machining And Core Leaching

The approach used to produce these full size hollow fan blades required the cleaning of individual plies and cores, ply-core-can assembly, seam welding can periphery, hot isostatic pressing of the assembled package using the modified delayed pressurization approach, camber-twist-isothermal forging the HIP'ed blade, and finish machining of the edges and leaching out of the steel cores.

Some of the major accomplishments demonstrated under this program include (1) the development of a HIP cycle that produces a metallurgically bonded structure with grain growth across bond lines and no evidence of voids, (2) computer aided design and manufacture of plies and cores (ply stamping approach was determined to be less costly only in large quantities), and (3) the feasibility of isothermally forging a smooth airfoil finish in a laminated structure and demonstration of the potential technology for meeting blueprint dimensional specifications.

However, the Task 2 program effort was unsuccessful in demonstrating (1) the capability of forming smooth inner cavity surfaces, (2) the ability to produce a hollow blade with a properly bonded root attachment, (3) a suitable steel HIP container configuration, (4) exact duplication of blueprint requirements especially in the blade tip region, and (5) process repeatability. All of these areas would require extensive development prior to the release of this fabrication technique for production use.

Task 1 and Task 2 efforts revealed process difficulties that were not expected when the initial program was established. These difficulties included HIP containers that leaked, expensive tooling, soft core material, contaminated bonds, thermal distortion of the forge tooling, and unpredictable material flow during forging. These problems, combined with the escalating cost of titanium sheet resulted in a re-evaluation of the laminate/core fabrication approach. TRW concluded from this study that a more competitive fabrication technique for any follow-on hollow fan blade development work would be to forge two blade halves, machine the required core cavities in each half, incorporate steel cores and diffusion bond the assembled package. TRW believes this approach would be more cost effective, improve cavity definition and facilitate inspection with respect to bonding.

As previously mentioned, fabrication schedule delays and budgetary limitations resulted in cancellation of the blade test program. Hence, no test work was accomplished to address the impact of the inner cavity geometry and reduced material properties on blade operating characteristics.

SECTION 6.0 CONCLUDING REMARKS

Two manufacturing methods were used to fabricate titanium, hollow blade-like specimens. Subsequent evaluation of all fabrication iterations were made to determine the feasibility of each manufacturing method for possible application in the production of shroudless, hollow titanium fan blades. Based on the positive results evolving from TRW's specimen fabrication effort, a laminate-core/diffusion bonding and forging manufacturing approach was used to produce three final-shaped, full size, hollow fan blades.

As with other developmental programs, problems not initially defined in the scope of the program were encountered with each manufacturing method causing a detrimental impact on the overall success of the program. Problems such as poor secondary bonding, the inability to maintain proper hollow cavity dimensions, and unworkable tooling caused unforeseen slippages in schedule and exhausted the funding budgeted. This resulted in a premature termination of program efforts prior to completion of the planned work, including cancellation of the blade test program. Based on these unfavorable results, a determination was made to replace the hollow, shroudless blade with a conventional solid, shrouded blade for current use in the Energy Efficient Engine fan component.

However, the Shroudless, Hollow Fan Blade Technology program was successful in (1) demonstrating the fabricability of hollow titanium test specimens utilizing two separate manufacturing methods, (2) producing full size hollow fan blades employing the technology that evolved from the specimen fabrication effort, (3) identifying the problem areas that require further developmental work, and (4) establishing a technology data base for reference in developing a more competitive fabrication technique for any follow-on development work directed toward shroudless, hollow fan blades.

As a result of this program, it was determined that fabrication of hollow airfoil structures was possible utilizing either the superplastic forming/diffusion bonding fabrication technique or the laminate-core hot isostatic press/diffusion bond technique provided the necessary funding and time were made available. Further evaluation regarding the feasibility of these manufacturing methods would also be required to determine which method provided the best compromise between cost and performance.

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2. Toth, I.J.: 'TRW Energy Efficient Engine Hollow Fan Blades Final Technical Report,' ER-8050-F, 1981 (TRW Materials Technology, TRW Inc., 23555 Euclid Avenue, Cleveland, Ohio 44117)

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