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MATERIALS FOR ADVANCED TURBINE ENGINES

Project Completion Report
Project 3

ADVANCED BLADE TIP SEAL SYSTEM
Volume I

By

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16. Abstract

The overall objective of the Materials for Advanced Turbine Engines (MATE) program was the introduction of new materials technologies into advanced aircraft engines to achieve potential economic and operational-performance advantages.

Project 3, the subject of this technical report, was structured toward the successful engine demonstration of an improved-efficiency, long-life, tip-seal system for turbine blades. The advanced tip-seal system was designed to maintain close operating clearances between turbine blade tips and turbine shrouds and, at the same time, be resistant to environmental effects including high-temperature oxidation, hot corrosion, and thermal cycling. The turbine blade tip comprised an environmentally resistant, activated-difussion-bonded, monocrystal superalloy combined with a thin layer of aluminium oxide abrasive particles entrapped in an electroplated NiCr matrix. The project established the tip design and joint location, characterized the single-crystal tip alloy and abrasive tip treatment, and established the manufacturing and quality-control plans required to fully process the blades. A total of 171 blades were fully manufactured, and 100 were endurance and performance engine-tested.

Volume II of this report will describe the engine-testing and will include posttest analyses.

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Turbine Clearance
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PREFACE

This report was prepared for the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-20074. It presents the results of a 3-year project. The objective was to demonstrate the payoff of an advanced turbine-blade-tip/seal system designed to maintain close tolerance between blade tips and turbine shrouds and, at the same time, be resistant to environmental effects including high-temperature oxidation, hot corrosion, and thermal cycling. The shroud materials were Bradelloy, Genaseal, and vacuum plasma sprayed CoNiCrAlY. The turbine blade tip was a multicomponent construction consisting of an activated-diffusion-bonded (ADB), oxidation/corrosion/resistant, monocrystal-superalloy tip extension (capable of withstanding thermal cycling) combined with a thin layer of abrasive alumina (Al_2O_3) particles held in place by an environmentally resistant, electroplated matrix. The project goal was to demonstrate the increased efficency and increased blade life attainable by using the advanced blade tip-seal system.

The project was accomplished under the technical direction of Stan Young and Bob Bill of the NASA Lewis-Research Center. The project was conducted by the Material and Process Technology Laboratries of the General Electric Company, Evendale, Ohio under the overall direction of E.J. Kerzicnik, MATE Business Manager; L.G. Wilbers, Technical Manager; J.W. Zelahy, Project Manager; and N.P. Fairbanks, Principal Investigator. Appreciation is expressed for the contribution of T.K. Redden for his involvement in overall MATE Program Management and to A. Raeburn for his contributions to many of the bonding and machining operations. The invaluable assistance of J. Bauer in MATE 3 NASA presentations is also acknowledged.

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NOMENCLATURE

ADB	Activated Diffusion Bonding
CC	Conventionally Cast
DS	Directionally Solidified
EDM	Electrodischarge Machining
El	Elongation
FOD	Foreign Object Damage
HCF	High Cycle Fatigue
HPT	High Pressure Turbine
LCF	Low Cycle Fatigue
MATE	Materials for Advanced Turbine Engines
MPTL	Material and Process Technology Laboratories
PM	Powder Metallurgy
QC	Quality Control
RA	Reduction in Area
SETS	Simulated Engine Thermal Shock
SFC, sfc	Specific Fuel Consumption
SPLCF	Sustained-Peak, Low-Cycle Fatigue
UTS	Ultimate Tensile Strength
VPS	Vacuum-Plasma Sprayed
YS	Yield Strength

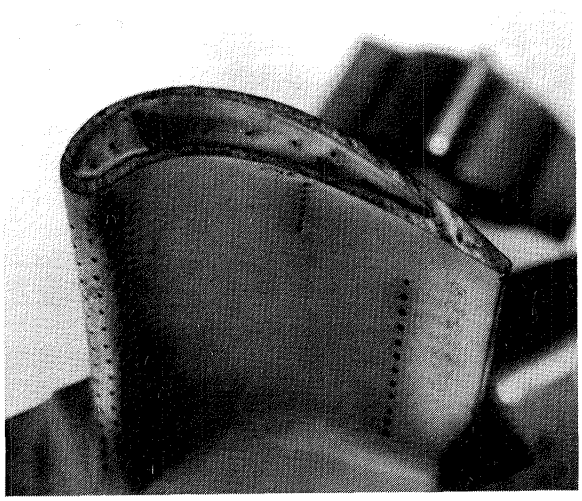
1.0 SUMMARY

To achieve maximum efficiency in today's advanced turbine engines, the clearances between the rotating blades and the stationary shrouds must be minimized. The target goal of the Materials for Advanced Turbine Engines (MATE) Project 3 was to demonstrate the increased efficiency and blade life attainable through an advanced blade-tip/seal system.

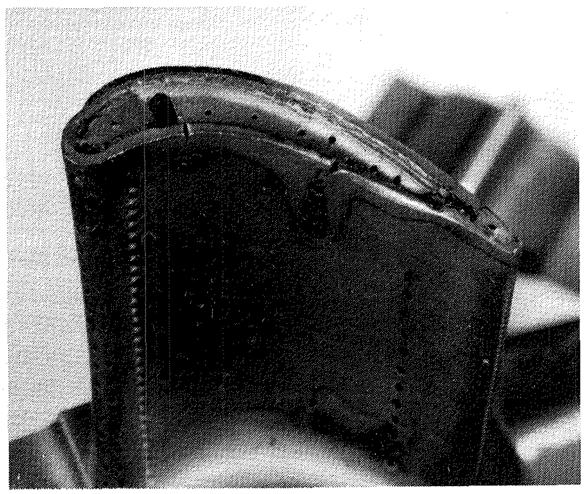
In spite of the designer's continuing efforts, engines typically become either out of round or out of concentricity. These conditions cause rubbing of the blade tips into the shroud resulting in loss of blade length and consequently loss in engine efficiency. In addition, the cyclic nature of the engine and the harsh environment at the blade tip subject the blade alloy to severe oxidation, hot corrosion, and thermal fatigue as shown below.

Problem:

Tip Wear



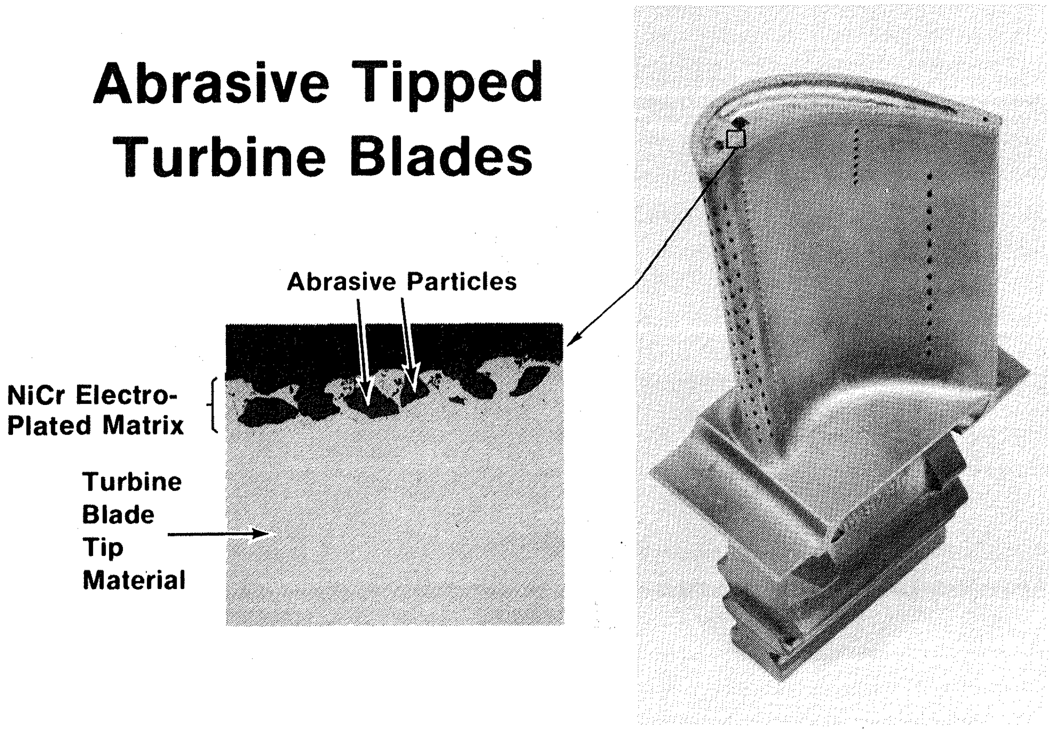
Oxidation/Cracking



Loss of Performance and Efficiency

In this project, the turbine blade tip treatment consisted of an activated-diffusion-bonded (ADB), oxidation/hot-corrosion-resistant, single-crystal-superalloy tip extension (capable of withstanding thermal cycling) plus a thin layer of abrasive alumina (Al_2O_3) particles held in place by an oxidation/corrosion-resistant matrix. The CF6-50 Stage 1 HPT blade was used as a demonstration vehicle in this project. The primary seal (shroud) material was Genaseal, but vacuum plasma sprayed (VPS) CoNiCrAlY and Bradelloy shrouds were also evaluated.

Abrasive Tipped Turbine Blades



The project established tip design and joint location, characterized the tip alloy, and defined the abrasive system. The project also defined the quality control plans and total manufacturing cycle required to fully process blades; 171 test blades were produced for component and engine test and evaluation.

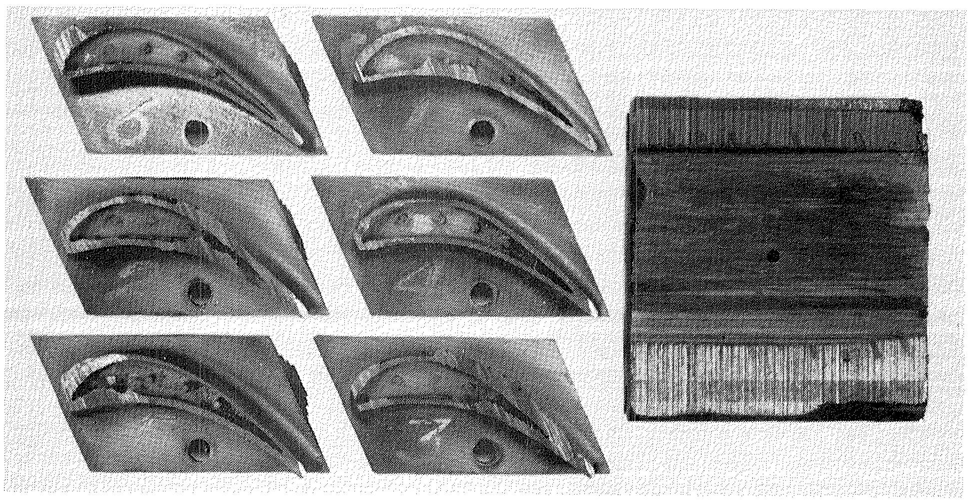
Initial blade tip design work defined a tip configuration conceived for maximum ease of manufacture, reliability, and reproducibility. The design eliminated stress concentrations by avoiding mismatch, located the joint in a low-stress region, and achieved total manufacturing acceptance.

Tip Design

A comprehensive evaluation of the mechanical and physical properties of both the tip material (single-crystal superalloy) and the tip-to-blade (René 80) bond joint was conducted. The testing was conducted both on standard specimens and on actual hardware and included tensile, stress rupture, fatigue, oxidation, hot corrosion, and simulated engine thermal shock (SETS). All of the test results met or exceeded the design requirements for CF6-50 engine operation.

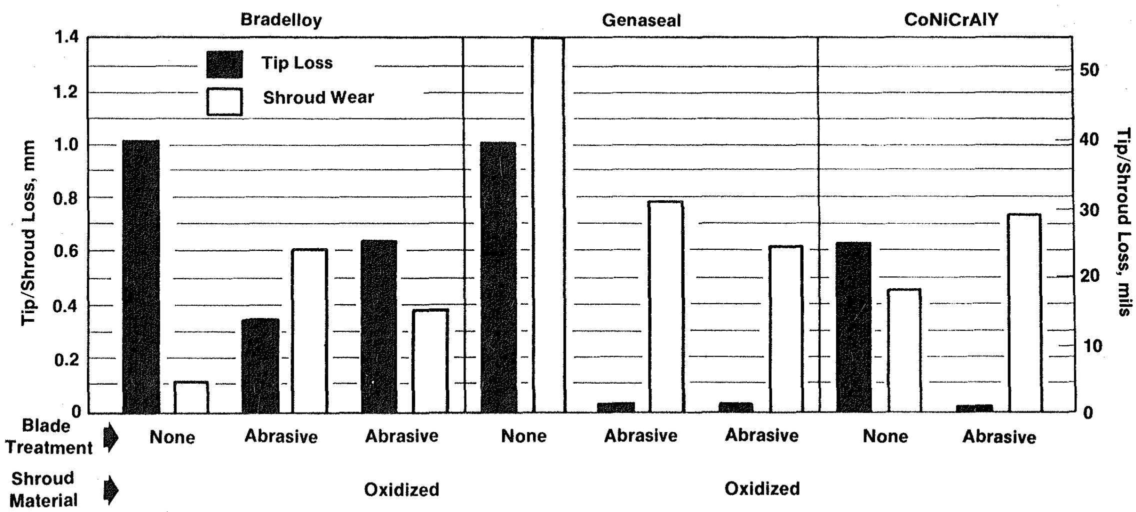
Abrasive tip treatments were evaluated through high-speed, high-temperature, wear testing at Solar (San Diego, California). Variations in particle size, type and relief, and incursion rate and variations in shroud materials were evaluated. In all cases, the method of particle attachment was an electroplate encapsulation technique. In all, more than 50 wear tests were conducted to fully define a suitable abrasive-tip system.

Solar Wear Test Specimen — After Test



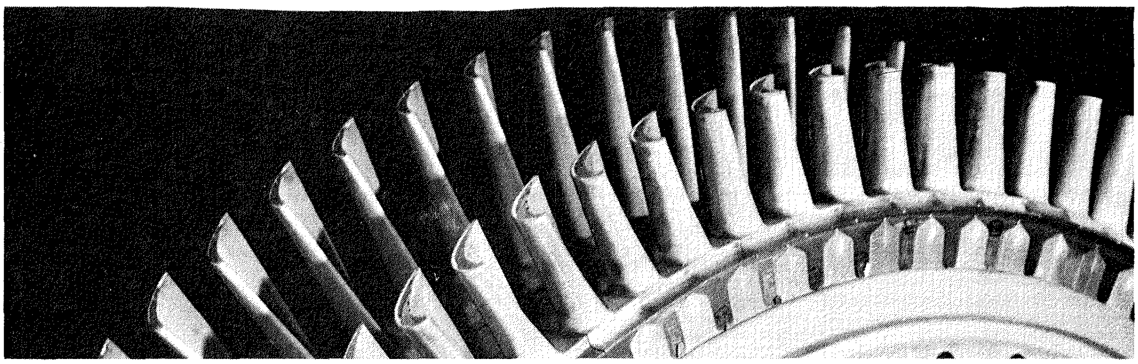
The results of the wear testing show that the abrasive tips successfully abraded both Genaseal and VPS CoNiCrAlY (both as-manufactured and with simulated engine exposure). The abrasive-tip system was marginally effective with new Bradelloy, but was not effective with oxidized Bradelloy. The finalized tip/seal system designated for engine test evaluation employed 127-178 μm (5-7 mil) Al_2O_3 particles in a 127-178 μm (5-7 mil) electroplated, diffusion-heat-treated and aluminide-coated NiCr matrix. The VPS CoNiCrAlY shroud material was identified as having the best overall compatibility with both the abrasive tip treatment and the engine environment.

Wear Test Results



The quality control and manufacturing process plans were established to fully define all related inspection and processing operations required to manufacture the environmentally resistant, abrasive-tipped blade. The quality plan included control over the tip material, the attachment process, the abrasive treatment, and any additional operations related to the advanced tip system. The process plan defined the blade casting preparation, the single-crystal tip configuration, the bonding process operations, the abrasive-tip treatment, and all nonstandard operations associated with the blade manufacture.

A total of 171 blades were subsequently fabricated using procedures established in earlier tasks. Of the 171 blades that were fabricated, only two parts (about 1%) were rejected because of tip-related discrepancies. For the most part, the blades were processed through the blade shop with no appreciable changes to the standard manufacturing operations; 100 of these blades were made available for engine testing, 20 for endurance testing, and 80 for performance testing. The engine testing and posttest analyses will be discussed in Volume II of this report.



2.0 INTRODUCTION

The primary objective of the Materials for Advanced Turbine Engines (MATE) project is the introduction of new materials technologies into advanced aircraft turbine engines to achieve potential economic and operational-performance advantages. The program encompasses accelerated transfer of selected material technologies by scaling them up from the laboratory-feasibility stage to engine demonstration as well as performing cost/benefit analyses to provide guidance in the selection of the candidate material technologies to be scaled up.

Project 3, the subject of this technical report, demonstrated the payoff of an advanced tip-seal system designed to maintain close tolerances between turbine blade tips and turbine shrouds and, at the same time, be resistant to environmental effects including high-temperature oxidation, hot corrosion, and thermal cycling. The project was structured toward the successful engine demonstration of an improved-efficiency, long-life, tip-seal system for turbine blades; the technical effort was divided into the nine principal tasks listed below:

- Task I - Turbine Blade Tip Seal System Design
- Task II - Monocrystal Tip Alloy Evaluation
- Task III - Abrasive Tip Evaluation
- Task IV - Seal System Verification
- Task V - Quality Control Plan
- Task VI - Manufacturing Process Plan
- Task VII - Seal System Manufacture and Component Test
- Task VIII - Engine Tests
- Task IX - Posttest Analysis

The goal of the project was to demonstrate the increased efficiency and increased blade life attainable through the advanced blade-tip-seal system. The turbine blade tip was comprised of an environmentally resistant, activated-diffusion-bonded (ADB), monocrystal superalloy combined with a thin layer of aluminum oxide abrasive particles entrapped in an electroplated NiCr matrix. The project established the tip design and joint location, characterized the single-crystal tip alloy and abrasive tip treatment, and established the manufacturing and quality control plans required to fully process the blades. A total of 171 blades were fabricated using the manufacturing sequences defined. Approximately 150 blades were fully manufactured, and 100 were made available for endurance and performance engine testing.

3.0 ADVANCED TURBINE BLADE TIP-SEAL SYSTEM

3.1 TASK I - TURBINE BLADE TIP-SEAL SYSTEM DESIGN

Theromechanical stress analyses were conducted on the advanced tip system to establish the tip design required to achieve the program goal of 2X René 80 life and 0.43% sfc improvement.

3.1.1 Monocrystal Tip

Stress levels and temperature profile at the blade tip were estimated from results of previously run CF6-50 test and field engines. This data was used to determine the correct tip/blade ADB joint location and to establish the best chordwise crystallographic orientation to provide optimum reliability and thermal fatigue resistance.

The region most susceptible to thermal fatigue cracking at the tip on the current CF6-50 Stage 1 HPT blade is on the concave side, approximately 15 mm (0.6 inch) from the trailing edge. A secondary location of tip distress is approximately 10 mm (0.4 inch) aft of the leading edge. Although the optimum thermal fatigue resistance of the monocrystal material was in the growth [001] direction, the best "compromised" orientation (shown in Figure 1) that could be achieved for both locations was to orient the [001] direction ±15° from each area of crack susceptibility. However, the 15° off-axis orientation, based on elastic modulus, was still considered sufficient to achieve the 2X René 80 life goal.

The location of the tip-to-blade ADB joint was determined by estimates of both radial (centrifugal) stresses and bending (rub induced) stresses at various radial tip lengths. Ideally, to achieve optimum tip life, the tip length above the tip cap should be at a maximum. However, with increased tip length, the stresses on the bond joint rapidy increase because of increased centrifugal and bending loads. Easily calculated, however, the bending stresses were estimated based on previously generated engine data. The centrifugal force, as a function of tip length, is shown in Figure 2 and was calculated at maximum engine rpm. As shown in Figure 2, the radial stresses in the expected range of tip height are between 5.5 MPa (0.8 ksi) and 8.5 MPa (1.2 ksi) which is well within the strength capabilities of both the monocrystal tip material and the tip-to-blade ADB joint.

Rub-induced bending stress levels were estimated based on previously generated factory test engines.

The maximmum bending stresses expected during a severe tip rub were estimated to be between 69 MPa (10 ksi) and 400 MPa (58 ksi) depending on tip thickness and tip height. The maximumn stress region was shown to be near the

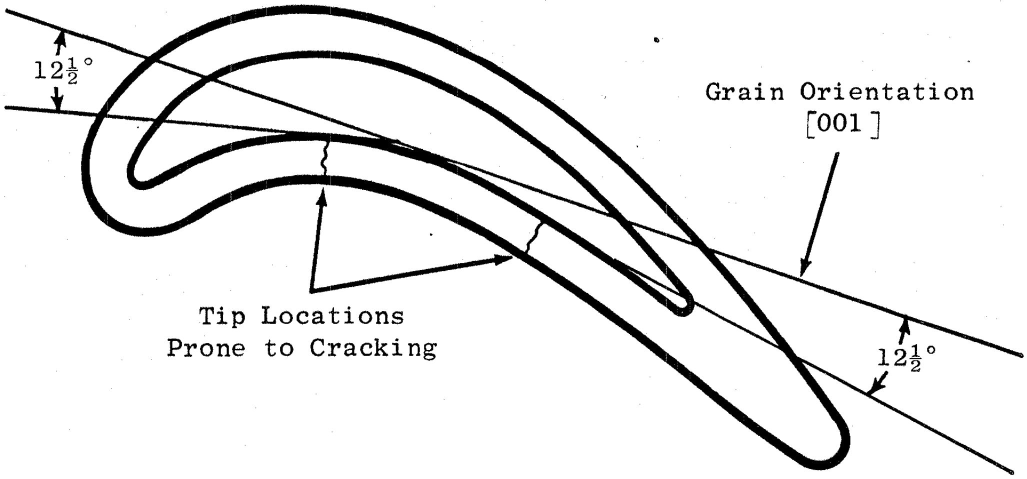


Figure 1. Crystallographic Orientation of the Monocrystal Normalloy Tip.

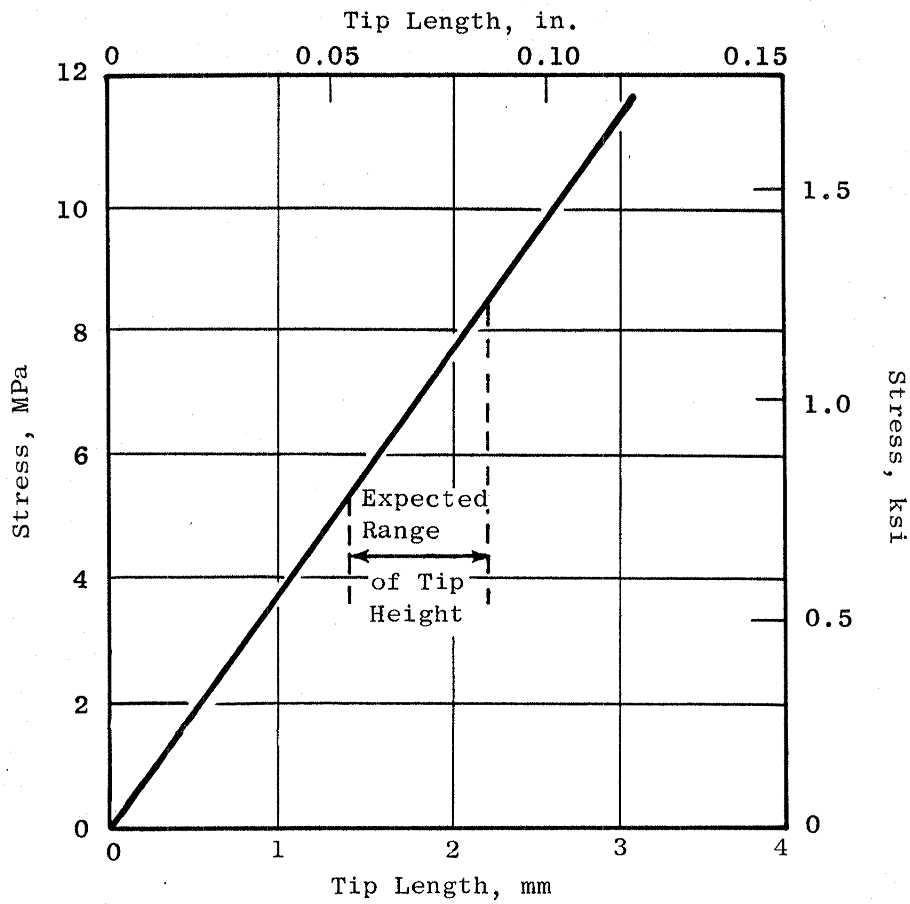


Figure 2. Radial Stress at ADB Joint as a Function of Tip Length at Maximum Engine Speed.

leading edge on the suction side of the airfoil with a peak estimated operating temperature of 1800° F. Since the rub force is not normal to the squealer tip at most locations, a stress correction factor shown in Figure 3 was used to establish stess levels at various locations around the tip. Using the above stress estimates combined with available strength data of the monocrystal tip material and ADB joint, the maximum allowable bending stress in the tip was set at 207 MPa (30 ksi) at 1800° F. The maximum squealer tip thickness, which was primarily dictated by manufacturing constraints, was set at 0.076 mm (0.030 inch) which subsequently limited the maximum tip height to 2.03 mm (0.080 inch). This height was estimated to be adequate for the LCF and oxidation requirements and was accepted as the final interaction on the design. The final tip configuration is shown in Figure 4.

3.1.2 Abrasive Tip

The abrasive tip treatment was applied to the blade just prior to Codep; it consisted of Al_2O_3 particles held in place by electroplated nickel and chromium (discussed in detail in Section 3.3) and was applied on the blade tip in the final radius-ground condition (Figure 5). The abrasive treatment is 127-178 μm (5-7 mil) thick and approximately 50% (by volume) Al_2O_3. Since it has a much lower density than the blade alloy, it presents no inordinate radial stresses on the blade. In addition, because the abrasive tip treatment cuts rather than rubs into the shroud, less resistance at the tip occurs; therefore, smaller vibratory responses occur in the airfoil.

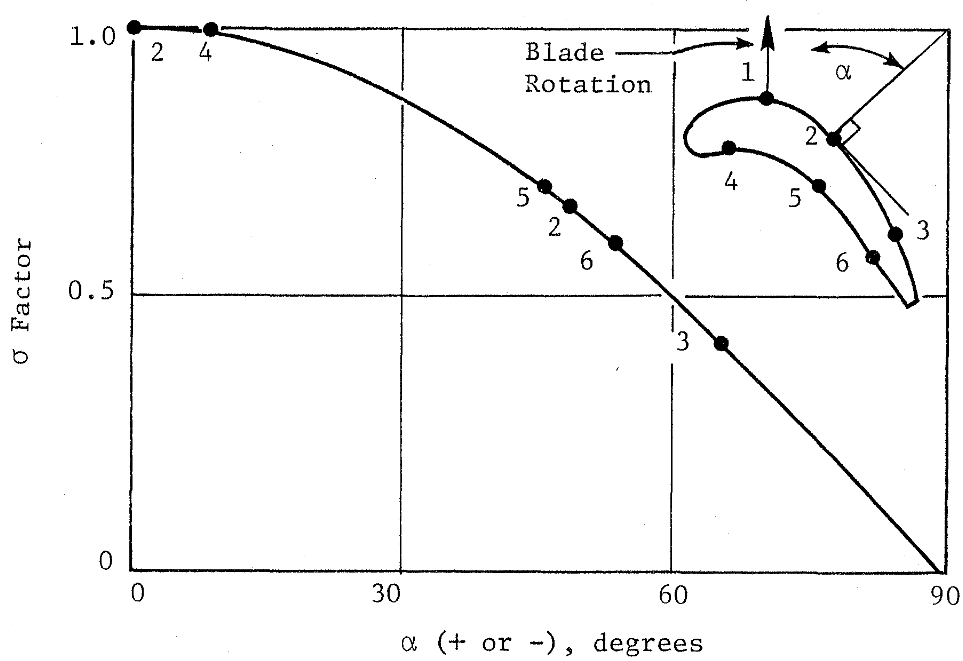


Figure 3. Stress Factor to Correct for Tip Contour. α = (Angle of a Line Normal to the Blade Contour to the Direction of Blade Rotation).

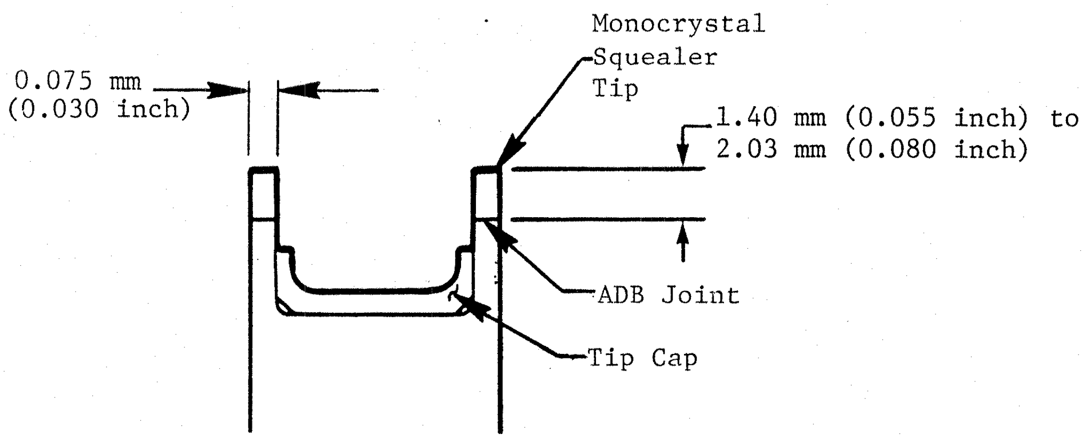


Figure 4. Advanced Blade Tip Design.

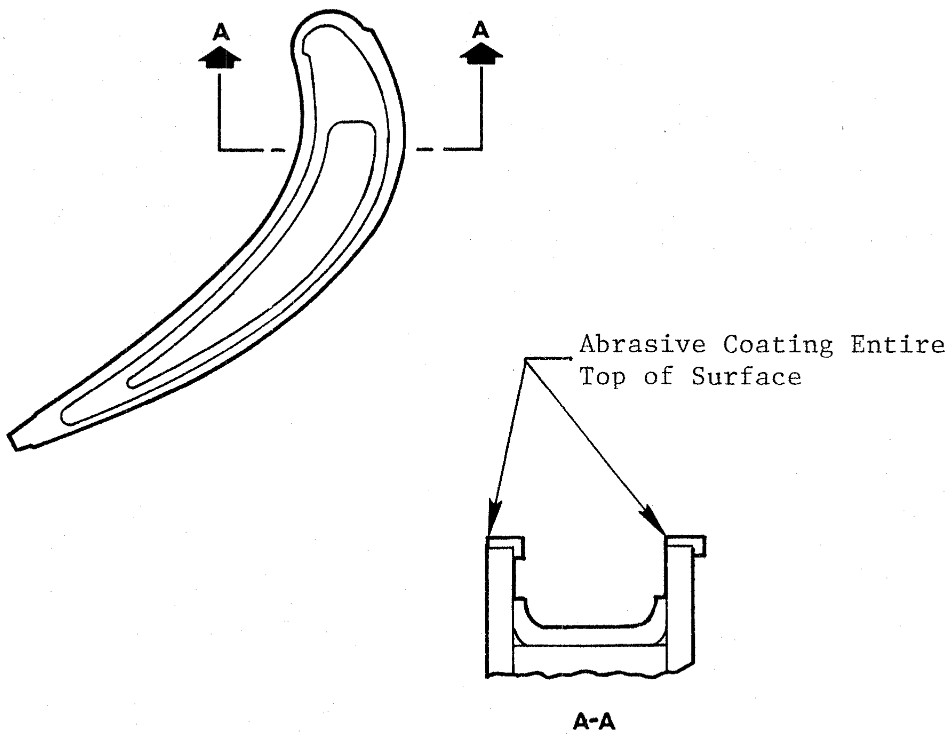


Figure 5. Abrasive Turbine Blade Tip Configuration.

The selected tip design, shown in Figure 4, provided the desired blade tip location and allowed processing through normal manufacturing operations with a minimum of additional operations. The internal tip squealer/blade mismatch (previously a problem) was alleviated by bonding the monocrystal tip to the blade prior to the tip-cap cavity electrodischarge machining (EDM) operation. By bonding prior to the tip-cap EDM, a smooth tip-to-blade internal surface was achieved when the tip-cap cavity was machined. The external tip squealer "overhang" was removed immediately after the tip-cap cavity EDM operation. This tip design allowed all standard manufacturing operations to be performed. Tip bonding and abrasive tip treatment, which were the only nonstandard shop operations; were performed in a laboratory environment.

Actual per part cost including the laboratory portion of the advanced, tip-treated blades was approximately 30% higher than for standard blades. However, it was estimated that in production, the cost increase of the advanced tip-seal system would be no greater than 15%.

3.1.3 System Benefits

The preliminary economic benefit analysis performed by CF6-50 Design Engineering indicated the following payoffs:

1. The predicted 2X increase in blade life from the monocrystal Normalloy oxidation/corrosion/thermal-fatigue-resistant tip in 1979 dollars would result in an $0.88/engine-hour savings.

2. A predicted 0.33 mm (0.013 inch) tip-clearance improvement resulting from the abrasive treatment to the tip would provide an 0.43% sfc improvement, as shown in Figure 6.

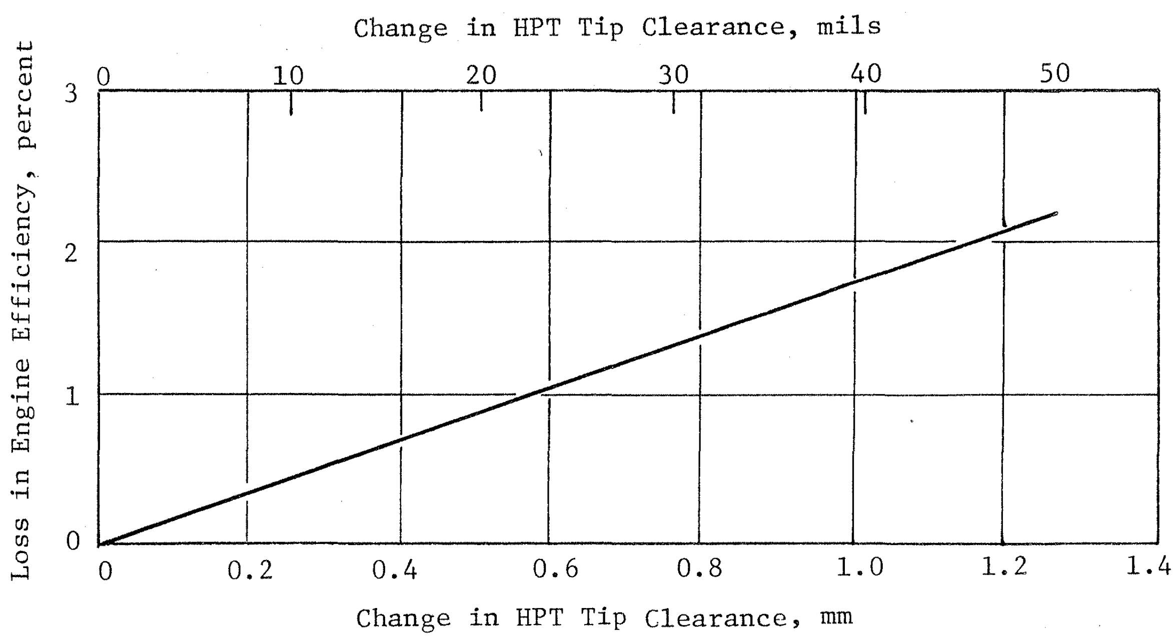


Figure 6. Effect of HPT Tip Clearance on Large-Turbofan Efficiency.

3.2 TASK II - MONOCRYSTAL TIP ALLOY EVALUATION

3.2.1 Alloy Selection

Normalloy, an alloy designed by General Electric, was selected as the tip alloy for the MATE Project 3 CF6-50 Stage 1 HPT blades. The tip requirements necessary to achieve the project goals of 0.4% sfc improvement and a twofold increase in blade life were determined by CF6-50 HPT blade design engineering personnel in Task I. These requirements included:

- Oxidation resistance - 2X improvement over René 80
- Corrosion resistance - equal to René 80
- Thermal fatigue resistance - 2X improvement over René 80 (all orientations)
- Tip material strength - 200 hours at 1093° C and 10.3 MPa (2000° F and 1.5 ksi)
- Joining - amenable to ADB process, joint strength of 5.5 MPa at 1093° C (0.8 ksi at 2000° F) for 200 hours
- Coating - compatible with standard Codep coating
- Casting - castable with monocrystal shapes.

Preliminary testing of Normalloy indicated that when produced as monocrystals, it met or exceeded the project goals.

The nominal composition for Normalloy in weight percent is:

Ni	Co	Cr	Al	W	Ta	Si	C	La
33.0	33.0	23.0	4.0	3.0	3.0	0.6	0.3	0.1

3.2.2 Alloy Manufacture

A 136 kg (300 lb) "master" heat of the nominal Normalloy composition was melted and cast into 7.62 cm (3 inch) diameter ingots by Teledyne Allvac Co., Monroe, North Carolina. This heat provided the feed stock for the monocrystal material required for mechanical-property evaluation and tip manufacture.

Ten 3.2 kg (7 lb) heats of the alloy were produced with variation in the critical elements (Al, Ta, W, Si, and C) to identify the acceptable chemistry range (Table I). These heats were cast into monocrystal rods, 1.3 cm (0.5 inch) in diameter, and machined into mechanical test bars and oxidation pins. Stress rupture bars of each compositional change were tested at 35.0, 28.0, 21.0, and 17.2 MPa, (5, 4, 3, and 21.5 ksi) at 1093° C (2000° F.) The data obtained are listed in Table II.

Table I. Alloy Compositional-Limits Study.

	Weight Percent									
	Ni	Co	Cr	Al	W	Ta	Si	C	La	B
Normalloy Aim Composition	33.0	33.0	23.0	4.0	3.0	3.0	0.7	0.5	0.1	0.001
Composition by Wet Chemistry	33.2	33.1	23.3	3.9	3.1	3.3	0.7	0.4	ND	0.001
Desired No. 1 Composition	33.0	32.75	23.0	4.25	3.0	3.0	0.7	0.5	0.1	0.001
Actual No. 1 Composition	34.0	33.6	23.4	4.0	3.1	3.2	0.7	0.5	ND	0.001
Desired No. 2 Composition	33.0	33.25	23.0	3.75	3.0	3.0	0.7	0.5	0.1	0.001
Actual No. 2 Composition	33.0	33.3	23.3	3.9	2.9	2.6	0.7	0.5	ND	0.001
Desired No. 3 Composition	33.0	32.5	23.0	4.0	3.0	3.5	0.7	0.5	0.1	0.001
Actual No. 3 Composition	33.3	32.9	23.1	4.7	3.1	3.5	0.7	0.5	ND	0.001
Desired No. 4 Composition	33.0	33.5	23.0	4.0	3.0	2.5	0.7	0.5	0.1	0.001
Actual No. 4 Composition	32.3	32.3	23.1	3.7	3.0	3.1	0.73	0.51	ND	0.001
Desired No. 5 Composition	33.0	32.5	23.0	4.0	3.5	3.0	0.7	0.5	0.1	0.001
Actual No. 5 Composition	33.3	32.7	23.4	3.9	3.5	3.4	0.72	0.56	ND	0.001
Desired No. 6 Composition	33.0	33.5	23.0	4.0	2.5	3.0	0.7	0.5	0.1	0.001
Actual No. 6 Composition	34.1	34.3	23.8	3.9	2.7	3.0	0.69	0.52	ND	0.001
Desired No. 7 Composition	33.0	32.7	23.0	4.0	3.0	3.0	1.0	0.5	0.1	0.001
Actual No. 7 Composition	32.8	31.7	23.3	4.6	3.1	3.2	1.01	0.49	ND	0.001
Desired No. 8 Composition	33.0	33.3	23.0	4.0	3.0	3.0	0.4	0.5	0.1	0.001
Actual No. 8 Composition	33.2	33.5	23.4	4.4	3.1	3.2	0.43	0.53	ND	0.001
Desired No. 9 Composition	33.0	32.9	23.0	4.0	3.0	3.0	0.7	0.6	0.1	0.001
Actual No. 9 Composition	32.4	32.3	23.2	3.8	3.0	3.1	0.73	0.6	ND	0.001
Desired No. 10 Composition	33.0	33.1	23.0	4.0	3.0	3.0	0.7	0.4	0.1	0.001
Actual No. 10 Composition	34.0	33.8	23.6	4.0	3.1	3.1	0.75	0.5	ND	0.001

ND = Not Detectable, % La Less Than 0.02.

The results of the stress rupture testing indicate that, within the compositional variations investigated, strength levels at 1093° C (2000° F) were virtually equivalent to the aim-composition results. Oxidation testing also indicated that equivalent oxidation properties were achieved with all compositional variations. Although lanthanum levels failed to meet the desired 0.1 Wt% (less than 0.01 Wt% was detected), the oxidation resistance was still twice that of René 80. Previously conducted oxidation and corrosion testing of monocrystal Normalloy with 0.05 Wt% lanthanum showed Normalloy to have a 6X oxidation improvement and a 3X improvement in hot corrosion compared to René 80. Subsequent casting of monocrystal 1.3 cm (0.5 inch) diameter bars from "master" heat material for use in the property test program (Section 3.2.3) produced material with acceptable lanthanum levels of 0.02 to 0.04 Wt%.

When the monocrystal bar size was increased to the 3.2 cm (1.25 inch) diameter needed for tip manufacture, both producibility and lanthanum retention became major concerns. Although the master heat had 0.063 Wt% lanthanum, and monocrystal remelt stock had 0.038 Wt% lanthanum, each 3.2 cm (1.25 inch) diameter bar had lanthanum levels below the detection range of 0.01 Wt%. Attempts to increase the lanthanum in the melting stock (to 0.15 to 0.20 Wt%) failed to provide detectable amounts in the large, monocrystal bars; nevertheless, it was decided to continue to use monocrystal Normalloy on the project since that alloy met the project oxidation goals even without detectable lanthanum.

Table II. Stress Rupture Results of Normalloy Compositional-Limits Study at 1093° C (2000° F).

MRAI No.	Specimen No.	Stress, MPa	Stress, ksi	Rupture Life, hr	Elongation, %	Reduction in Area (RA), %
SR-33593	0-1	34.5	5.0	25.3	38.0	52.0
SR-33594	0-2	27.6	4.0	123.8	38.7	39.2
SR-33595	0-3	20.7	3.0	586.7 (a)	21.5	28.0
SR-33598	0-4	17.2	2.5	1024.4 (b)	---	---
SR-33605	1-1	34.5	5.0	12.7	68.0	67.9
SR-33606	1-2	27.6	4.0	111.2	61.9 (c)	51.6 (c)
SR-33615	1-3	20.7	3.0	365.4	42.2	36.3
SR-33982	1-4	17.2	2.5	1001.8 (d)	---	---
SR-33607	2-1	34.5	5.0	57.3	43.3	49.5
SR-33616	2-2	27.6	4.0	176.4	35.8	37.6
SR-33621	2-3	20.7	3.0	959.7 (e)	(f)	17.9
SR-34113	2-4	17.2	2.5	1007.1 (d)	---	---
SR-33617	3-1	34.5	5.0	14.6	36.1	59.9
SR-33625	3-2	27.6	4.0	127.4	25.5 (c)	35.0 (c)
SR-33619	3-3	20.7	3.0	827.3 (g)	26.1	11.9
SR-33990	3-4	17.2	2.5	1005.3 (h)	---	---
SR-33620	4-1	34.5	5.0	25.8	43.9	54.9
SR-33672	4-2	27.6	4.0	91.7	37.2	44.4
SR-33972	4-3 (i)	44.1	6.4	2.5	64.2	72.0
SR-34022	4-4	20.7	3.0	533.3	33.7	31.8
SR-34120	4-5	17.2	2.5	1001.5 (j)	---	---
SR-33626	5-1	34.5	5.0	8.6	72.1	75.8
SR-33674	5-2	27.6	4.0	44.6	57.2	62.2
SR-33719	5-3	20.7	3.0	433.8 (k)	47.2	40.5
SR-33977	5-4	17.2	2.5	1029.2 (j)	---	---
SR-33628	6-1	34.5	5.0	24.5	55.3	61.0
SR-33686	6-2	27.6	4.0	76.1	32.8	62.9
SR-33726	6-3	20.7	3.0	1001.6 (j)	---	---
SR-34143	6-4	17.2	2.5	1005.6 (d)	---	---
SR-33629	7-1	34.5	5.0	45.3	47.9	53.1
SR-33689	7-2	27.6	4.0	156.2	39.2	36.4
SR-33978	7-3	20.7	3.0	776.4	26.6	12.2
SR-34159	7-4	17.2	2.5	1000.4 (d)	---	---
SR-33630	8-1	34.5	5.0	28.8	57.8	53.1
SR-33691	8-2	27.6	4.0	31.0	49.3	55.2
SR-33967	8-3	20.7	3.0	1012.9 (d)	---	---
SR-34176	8-4	17.2	2.5	1008.0 (d)	---	---
SR-33631	9-1	34.5	5.0	36.3	41.5	57.9
SR-33706	9-2	27.6	4.0	140.4	44.7	33.3
SR-33979	9-3	20.7	3.0	1000.8 (d)	---	---
SR-34342	9-4	17.2	2.5	1005.8 (d)	---	---
SR-33663	10-1	34.5	5.0	16.8	39.0	58.6
SR-33689	10-2	27.6	4.0	114.1	48.8	45.4
SR-33724	10-3	20.7	3.0	569.5 (l)	(f)	6.4
SR-33983	10-4	17.2	2.5	1000.1 (d)	---	---

Notes:

a. Control thermocouples replaced at 398.9 hours; test reloaded and run to failure
b. Specimen unloaded at time shown; control thermocouple replaced at 486.6 hours
c. Specimen broken in second location while removing from adapter; ductility values are best estimates
d. Specimen unloaded without failure at time shown
e. Control thermocouple replaced at 402.4 hours; specimen reloaded and run to failure
f. Ductility measurement not available due to condition of specimen after test
g. Control thermocouple replaced at 437.6 hours; specimen reloaded and run to failure
h. Furnace "burned out" at 143.7 hours; specimen reloaded in another frame and run to time shown without failure
i. Specimen loaded in error at stress shown
j. Specimen unloaded without failure; broke while removing from adapter
k. Control thermocouple replaced at 315.8 hours; specimen reloaded and run to failure
l. Pull-bar failure at 4.4 hours; reloaded and run to failure

Based on the results of the compositional-limits study, the target chemistry range for Normalloy is (in weight percent): Ni, 33 ± 0 5; Co, 33 ± 0.5; Cr, 23 ± 0.5; Al, 4 ± 0.25; W, 3 ± 0.5; Ta, 3 ± 0.5; Si, 0.7 ± 0.3; C, 0.5 ± 0.1; and La, 0.1 to 0.05. The La content of 0.05% to 0.1% was desired but was not achieved in large bar specimens. Subsequent oxidation testing showed a 2X improvement over René 80 could still be realized with a La level <0.05%. The low La Normalloy was therefore considered sufficient to meet the program goals.

3.2.3 Property Characterization

Elevated-temperature tensile, stress rupture, fatigue, thermal shock, oxidation, and hot-corrosion testing were conducted on monocrystal Normalloy in both the bare and the Codep-coated conditions. The monocrystal Normalloy stock material was procured as 3.2 cm (1-1/4 inch) diameter, 15.2 cm (6 inches) long bars. The growth direction [001] of each bar was established, and several 3.2 mm (1/8 inch) thick slices were removed from each bar. The slices were surface-ground to 215 mm (0.1 inch), and mechanical- and physical-property specimens were machined from the slices (Figure 7). Testing was conducted at Metcut Research Associates or the Materials and Process Technology Laboratory (MPTL) at General Electric.

3.2.3.1 Tensile Testing

The results of the tensile testing (Table III) show that the tensile properties of the Normalloy at 1093° C (2000° F) exceeded 70 MPa (10 ksi), well above the design requirements of the blade tip.

Table III. Tensile Strength of Monocrystal Normalloy at 1093° C (2000° F).

Condition	Ultimate Tensile Strength (UTS), MPa (ksi)	0.2% Yield Strength (0.2% YS) MPa (ksi)	Elongation (El), %
Bare	73.1 (10.6)	68.9 (10.0)	64.0
Codep Coated	74.5 (10.8)	45.5 (6.6)	69.0
Codep Coated	74.5 (10.8)	36.5 (5.3)	60.8
Codep Coated	73.1 (10.6)	40.0 (5.8)	61.0

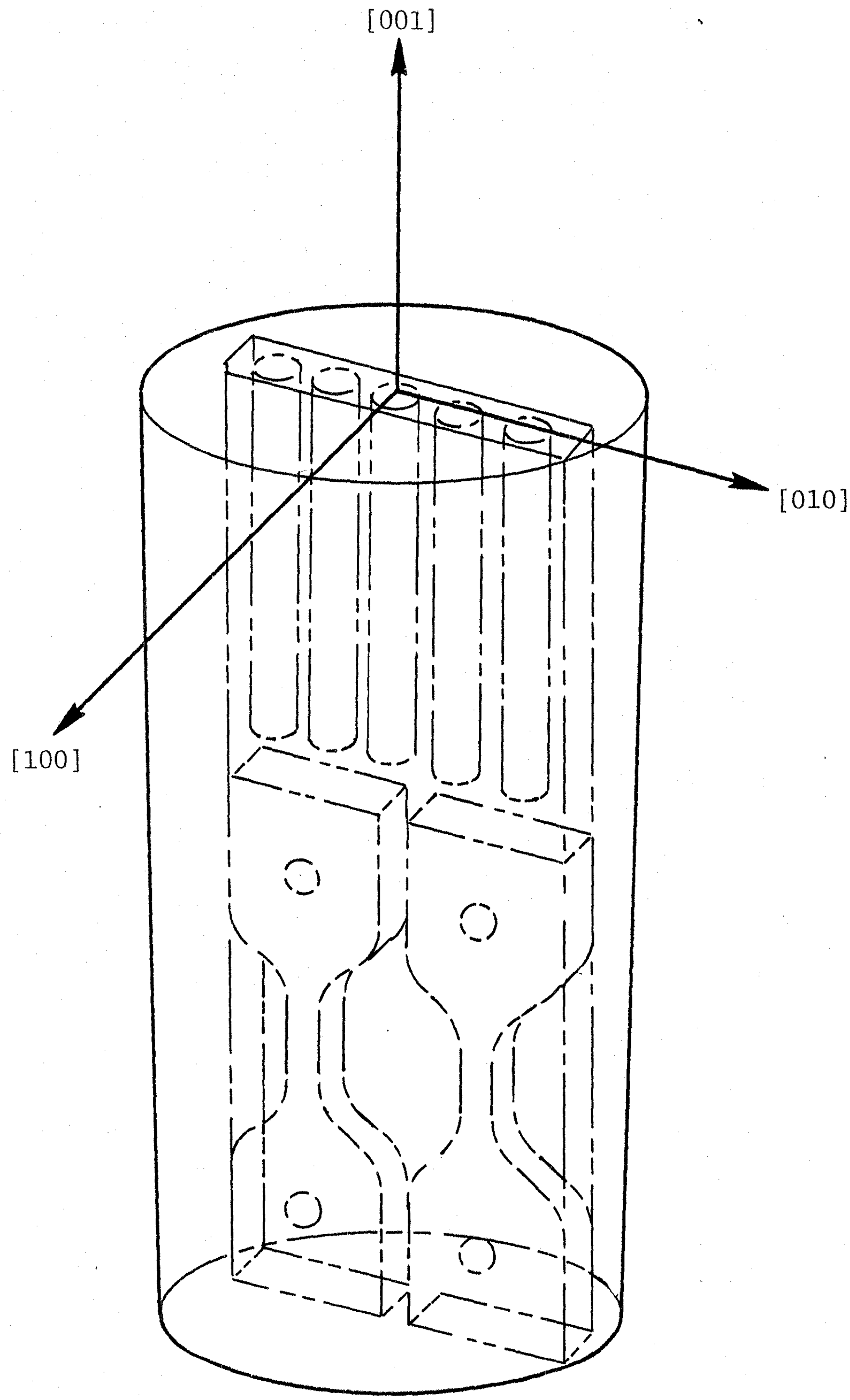


Figure 7. Method of Removal of Monocrystal Tips from Monocrystal Bar Stock.

3.2.3.2 Stress Rupture Testing

The results of the stress rupture testing at 1093° C (2000° F), listed in Table IV, show that the stress rupture strength, like tensile, is well above the design stress of the blade: 5.5 MPa (0.8 ksi). The Codep coating slightly reduced the stress rupture lives.

Table IV. Stress Rupture Strength of Monocrystal Normalloy at 1093° C (2000° F).

Condition	Stress MPa (ksi)	Life, hours	% El
Bare	34.5 (5.0)	3.0	65.4
Codep Coated	34.5 (5.0)	2.7	5.8
Bare	27.6 (4.0)	33.9	60.5
Codep Coated	27.6 (4.0)	34.2	54.9
Bare	20.7 (3.0)	175.7	---
Bare	20.7 (3.0)	163.1	59.1
Codep Coated	20.7 (3.0)	34.8	61.5

3.2.3.3 Sustained-Peak Low Cycle Fatigue

Sustained-peak low cycle fatigue (SPLCF) testing was conducted on the monocrystal Normalloy at conditions that were judged closest to those of actual engine operation. The testing was conducted with alternating tensile stresses at 17.2 and 27.6 MPa (2.5 and 4 ksi), at 1093° C (2000° F), with a hold time of 1-1/2 minutes. The results (Figure 8) show that the SPLCF properties of the Normalloy are approximately equal to those of the blade alloy, René 80, at this high stress range, and considerably better in the medium-to-low stress range.

3.2.3.4 Simulated Engine Thermal Shock

SETS testing was conducted on standard wedge specimens (Figure 9) of both monocrystal Normalloy and conventionally cast (CC) René 80 in the MPTL thermal-shock rig (SETS II). The temperature/time cycle is shown in Figure 10. At the first inspection (at 120 cycles), both the bare and the Codep-coated René 80 specimens exhibited several cracks; the monocrystal Normalloy specimens were unaffected. At 200 cycles, the bare monocrystal Normalloy specimens exhibited tiny surface "eruptions," and, at 300 cycles, these "eruptions" initiated tiny surface cracks. At 740 cycles, the René 80 specimens were severely cracked, and the bare Normalloy specimens exhibited several small cracks; however, the Codep-coated monocrystal Normalloy specimens were crack-free (although the coating was somewhat wrinkled). The testing was terminated at 2000 cycles; only one of the three Codep-coated Normalloy specimens was

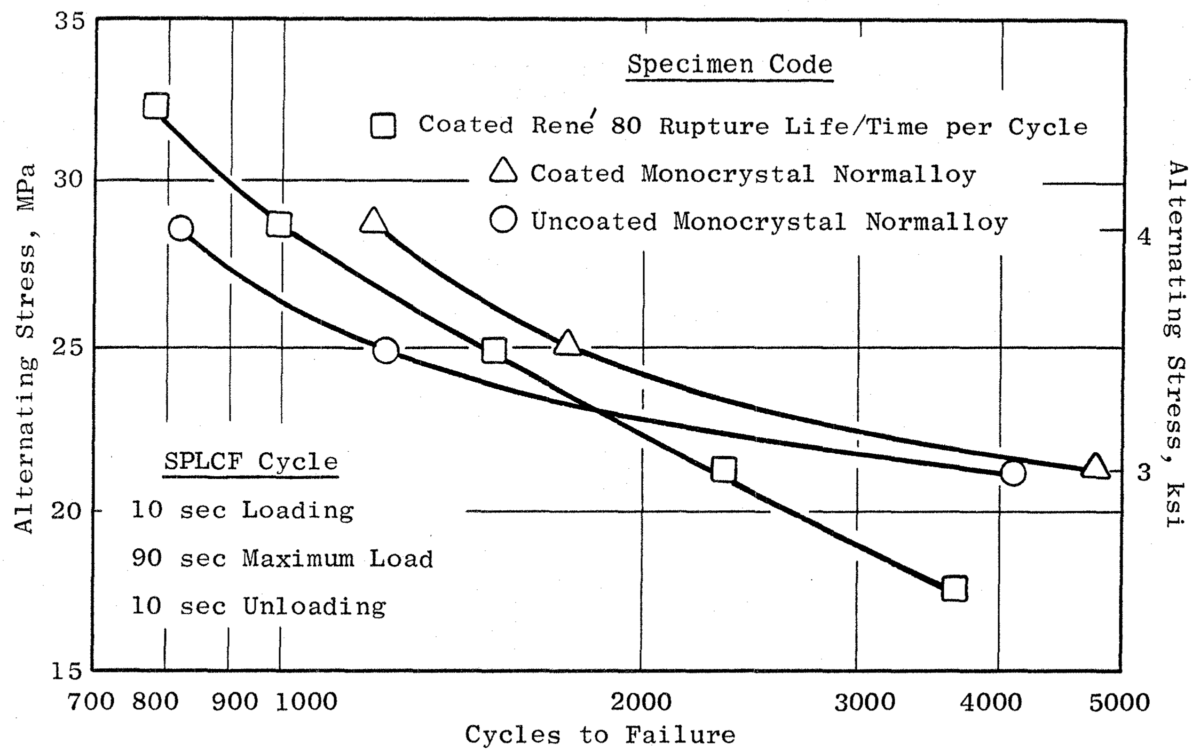


Figure 8. SPLCF Results for Bare and Codep-Coated Monocrystal Normalloy Compared to René 80.

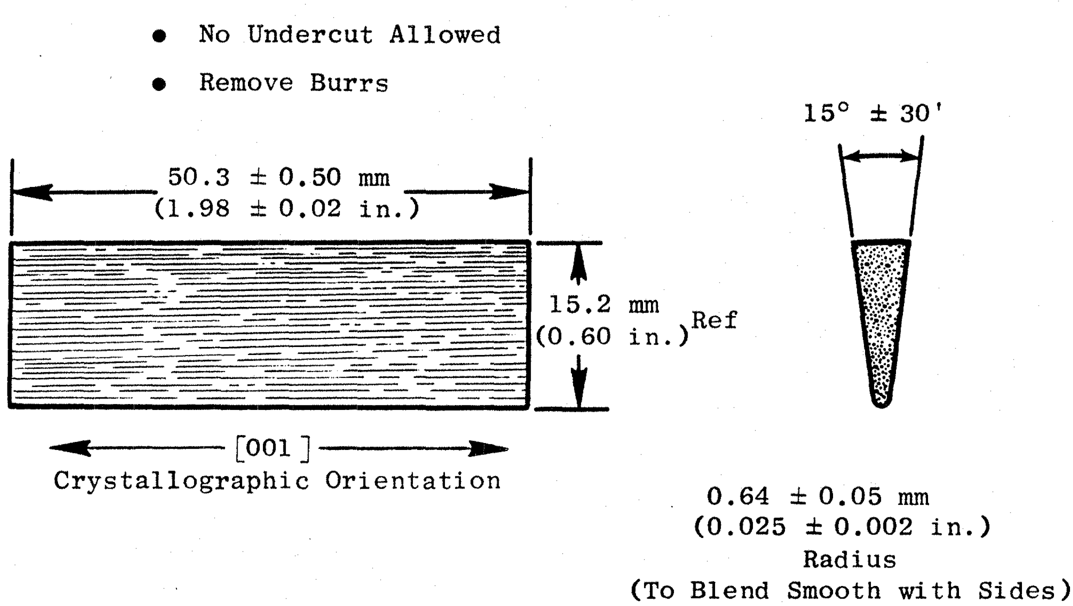


Figure 9. SETS Thermal-Fatigue Specimen.

cracked. All of the uncoated Normalloy specimens exhibited several small cracks. The René 80 specimens had several large cracks extending well into the specimen. Photographs showing the condition of the SETS specimens at 740 cycles are shown in Figure 11.

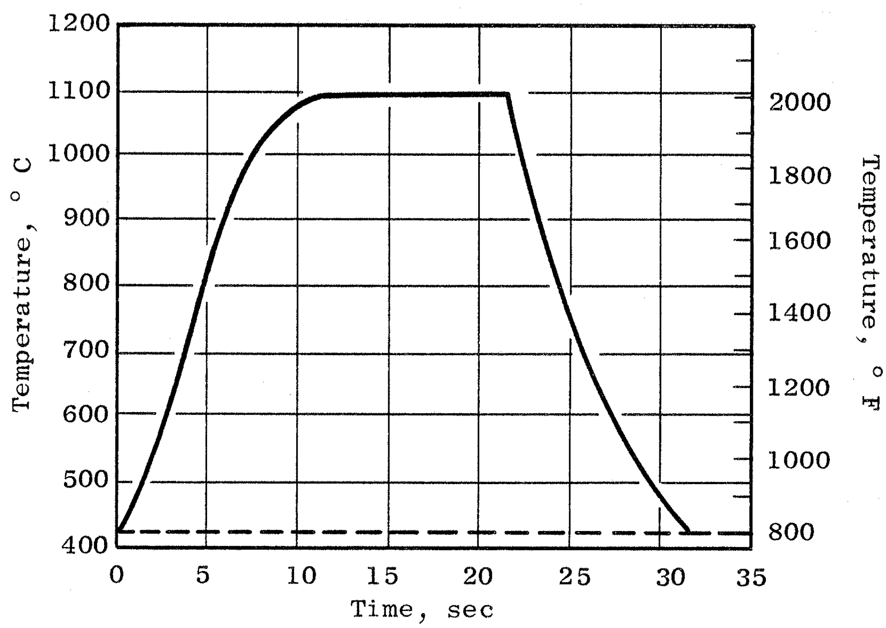


Figure 10. SETS Testing Cycle.

The results of the SETS testing clearly demonstrated the increased resistance of the monocrystal Normalloy to thermal fatigue relative to René 80.

3.2.3.5 Modulus of Elasticity

The modulus of elasticity for monocrystal Normalloy (uncoated) in the [001] crystallographic direction was measured at temperatures from room temperature to 1093° C (2000° F). The modulus data are compared with those of conventionally cast René 80 in Figure 12 and show that the modulus of monocrystal Normalloy is considerably lower than that of CC René 80.

The modulus difference is approximately 68.9 GPa (10,000 ksi) throughout the temperature range. Therefore, at typical engine operating temperatures 870°-1090° C (1600°-2000° F), the modulus of monocrystal Normalloy is approximately 50% that of René 80. The lower modulus will result in lower stresses from monocrystal Normalloy thermal expansion and contraction during engine operation.

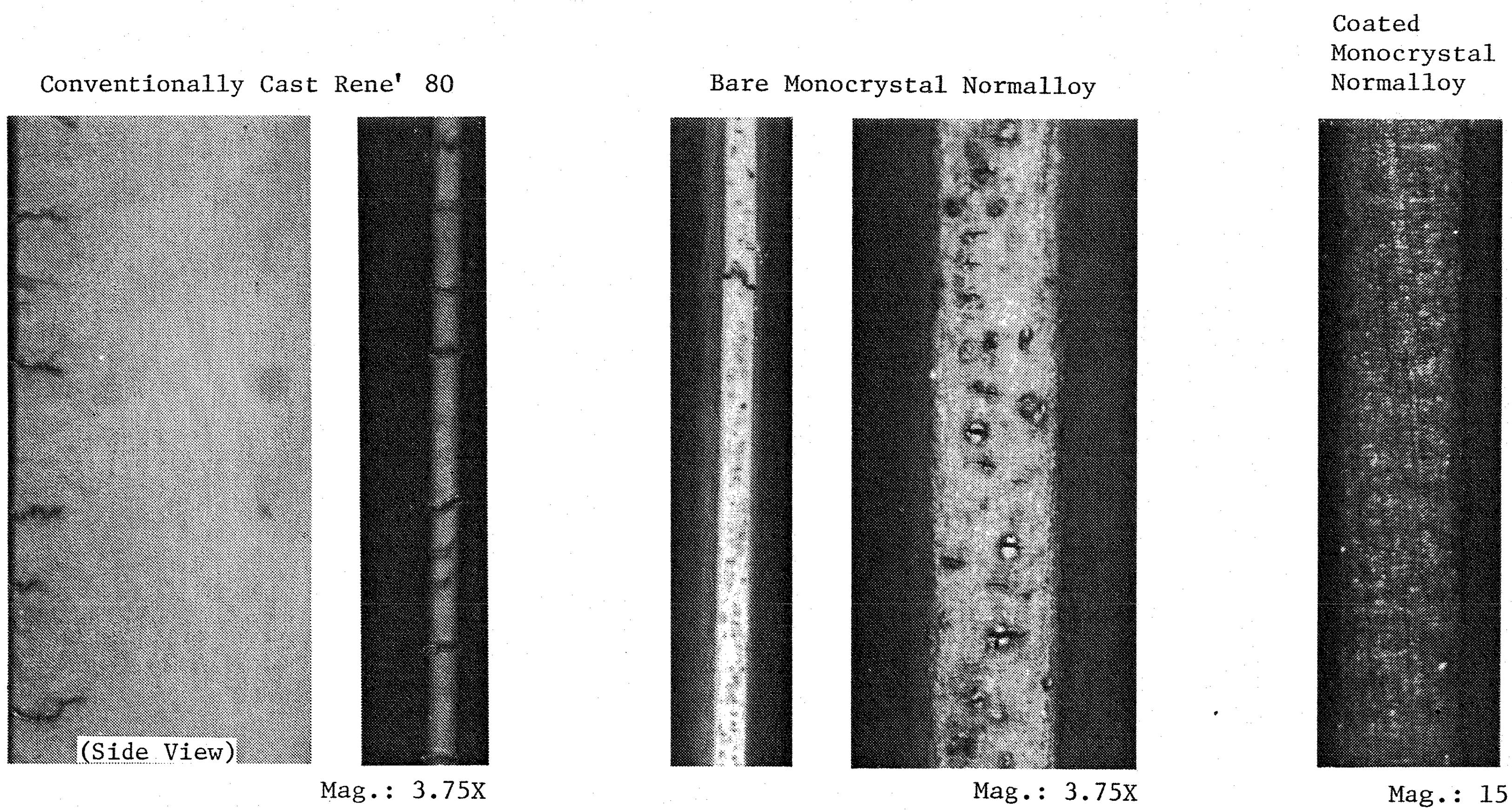


Figure 11. SETS Specimens at 740 Cycles.

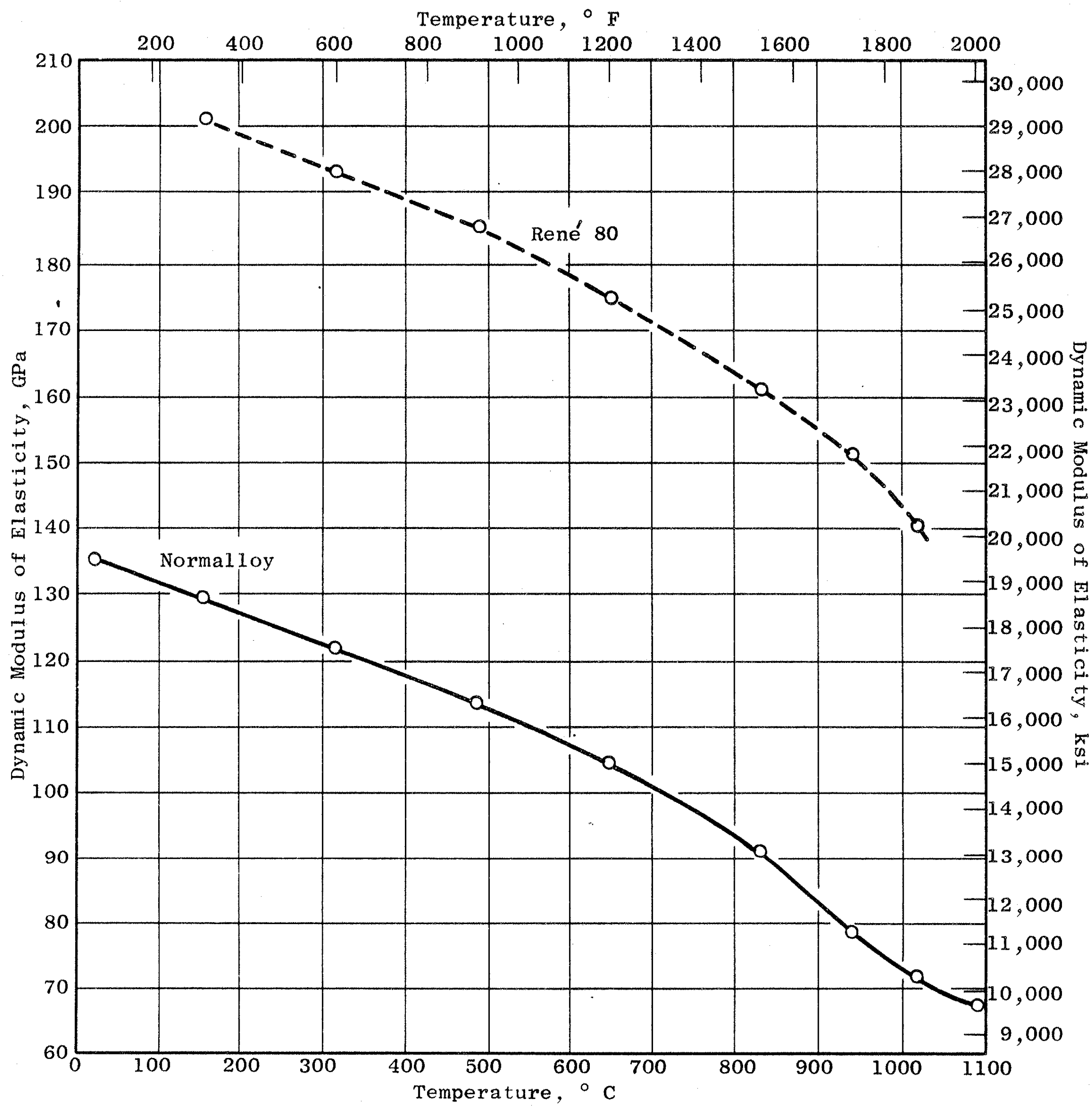


Figure 12. Dynamic Modulus of Elasticity of Monocrystal Normalloy Compared to CC René 80.

3.2.3.6 Coefficient of Thermal Expansion

Thermal-expansion characteristics for monocrystal Normalloy in the [001] crystallographic direction were determined from room temperature through 982° C (1800° F). The data are compared to thermal expansion data for CC René 80 in Figure 13; the coefficient of expansion of monocrystal Normalloy is between 10% to 15% higher than that of René 80. The effect of the difference in expansion coefficients could, under certain conditions of temperature gradient and blade tip configuration, result in high chordwise stresses in the squealer tip and/or the ADB joint. The temperature profile for the CF6-50 HPT blade was not expected to produce a temperature gradient high enough to cause a problem in factory engine testing.

3.2.3.7 Oxidation Testing

Dynamic oxidation testing was conducted on uncoated specimens of both monocrystal Normalloy and CC René 80. The testing was conducted at 1093° C (2000° F) in the MPTL Mach 0.5 oxidation tester and was run for 500 hours. The metallographic results in Figure 14 show that the Normalloy was considerably more oxidation resistant than the René 80. The depth of oxide penetration into the René 80 was about 0.8 mm (0.03 inch), but penetration into the Normalloy was only about 0.1 mm (0.005 inch) or a 6X increase in oxidation resistance. The project goal of a 2X increase was exceeded.

3.2.3.8 Hot-Corrosion Testing

Hot-corrosion testing was conducted on uncoated specimens of both monocrystal Normalloy and CC René 80. The testing was run at 927° C (1700° F) with 5 ppm sea salt for 700 hours. The results, shown in Figure 15, were obtained metallographically and show that compared to René 80, the Normalloy is about four times more resistant to hot corrosion. Depth of corrosion for René 80 was about 0.30 mm (0.012 inch), and penetration into the Normalloy was about 0.08 mm (0.003 in.). Again, the project goal of 2X was exceeded.

3.2.4 Joining Evaluation

Activated diffusion bonding was selected as the process for joining the monocrystal tip to the blades. Tensile, stress rupture, SETS, and high cycle fatigue (HCF) properties of ADB joints of monocrystal Normalloy to René 80 were generated. With the exception of fatigue, all testing of the ADB joints was conducted identically (and in some cases concurrently) with that of the monocrystal Normalloy.

3.2.4.1 Tensile Testing

Tensile testing was conducted at 1093° C (2000° F) on specimens of monocrystal Normalloy activated diffusion bonded to René 80. Each specimen contained two ADB joints (Figure 16) and oriented the [001] crystallographic

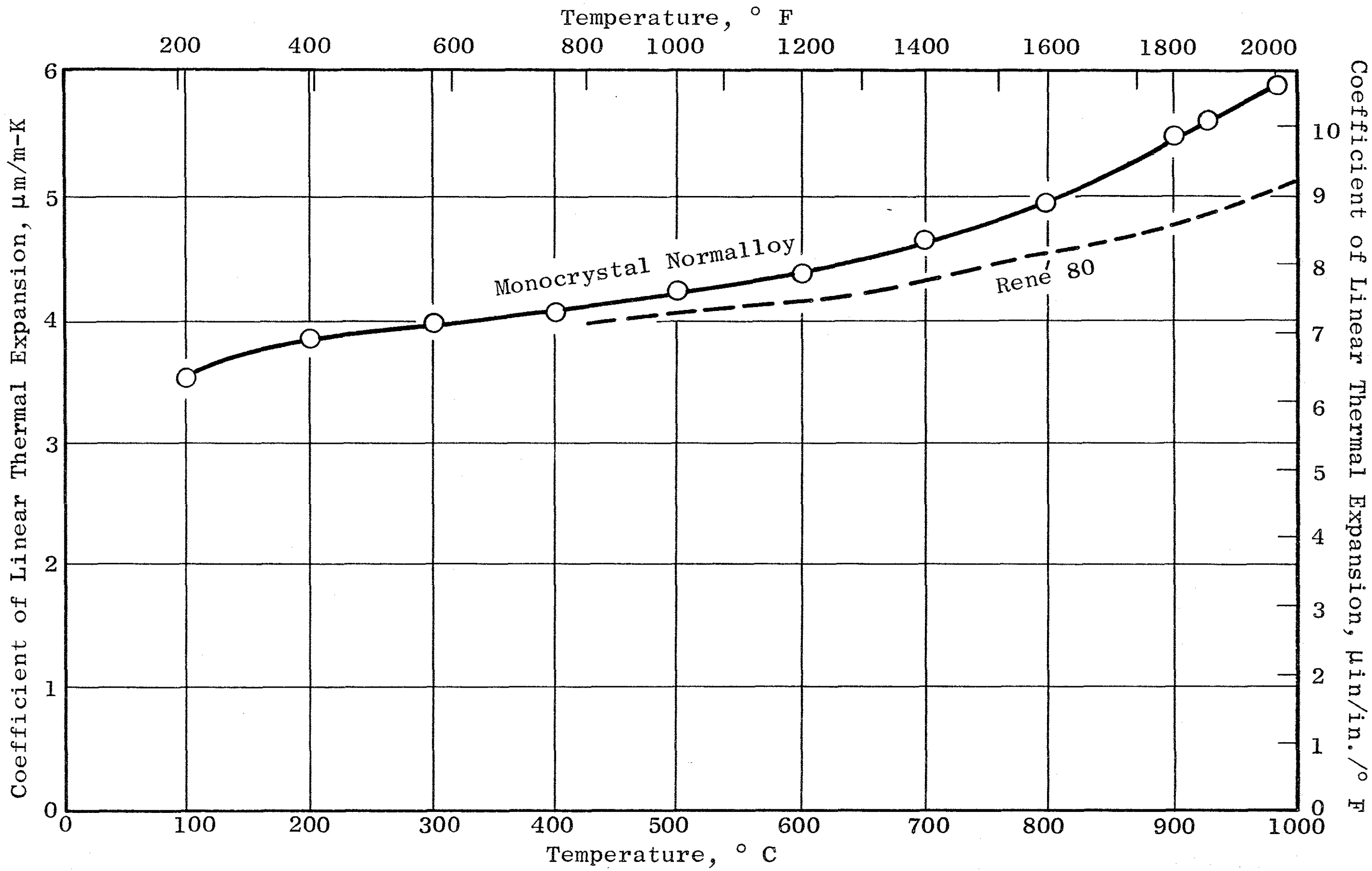


Figure 13. Coefficients of Thermal Expansion; Monocrystal Normalloy [001] Compared to René 80.

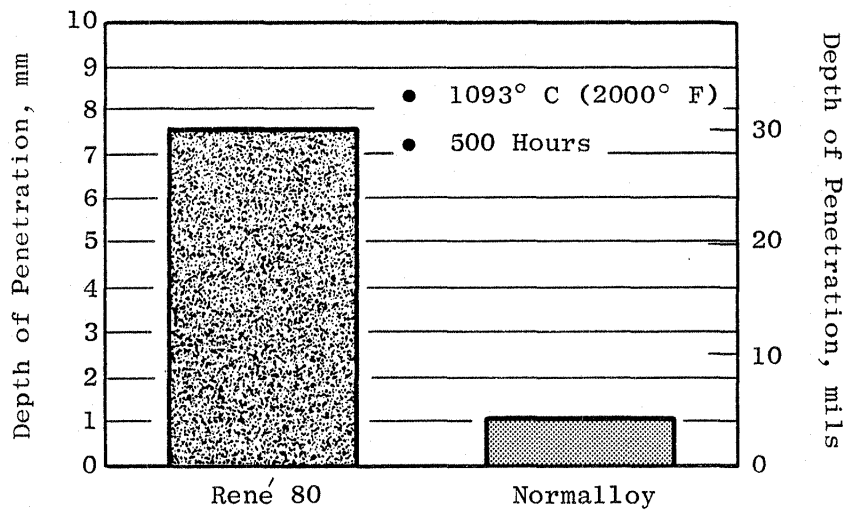


Figure 14. Static Oxidation Resistance of Monocrystal Normalloy and René 80.

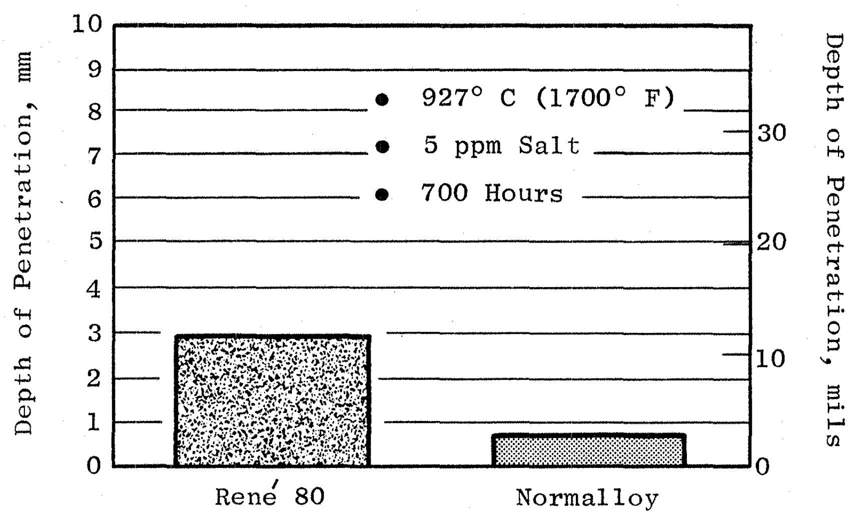


Figure 15. Hot-Corrosion Resistance of Monocrystal Normalloy and René 80.

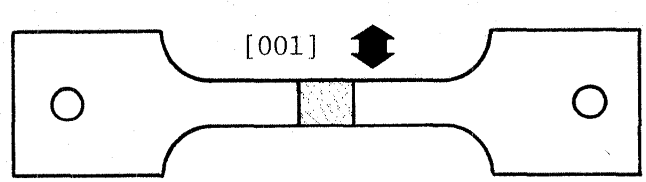


Figure 16. Specimen Configuration for Tensile and Stress Rupture Testing of Normalloy-to-René 80 ADB Joints.

direction of the Normalloy transverse to the specimen axis. The results are tabulated in Table V and show that the tensile strengths of the ADB joints were virtually the same as those of the parent material. Thirteen out of twenty specimens failed outside of the joint region, graphically demonstrating the reliability of the ADB joint.

Table V. Tensile Testing at 1093° C (2000° F) of Monocrystal Normalloy Bonded to René 80.

Bare UTS, MPa (ksi)	Codep-Coated UTS, MPa (ksi)
89.6 (13.0)	102.7 (14.9)
75.8 (11.0)*	91.7 (13.3)*
82.7 (12.0)*	89.6 (13.0)*
90.3 (13.1)	97.2 (14.1)
83.4 (12.1)*	103.4 (15.0)
87.6 (12.7)	97.2 (14.1)
87.6 (12.7)	97.9 (14.2)*
86.2 (12.5)*	91.0 (13.2)
83.4 (12.1)	111.7 (16.2)
82.0 (11.9)	89.6 (13.0)

*Parent Metal Failure

3.2.4.2 Stress Rupture Testing

Stress rupture testing was conducted at 1093° C (2000° F) on specimens of monocrystal Normalloy activated diffusion bonded to René 80. This specimen configuration was the same as that for the tensile evaluation (Figure 15). The testing was conducted at 5.5, 13.8, 17.2, 20.7, and 27.6 MPa (0.8, 2.0, 2.5, 3.0, and 4.0 ksi) on both bare and Codep-coated specimens. The test results (Table VI) show that the stress rupture strength of the Normalloy-to-René 80 ADB joints was well above the 5.5 MPa (0.8 ksi)/200 hour design requirement and approached that of Normalloy parent-metal strength.

3.2.4.3 High Cycle Fatigue Testing

The HCF testing was conducted on a Baldwin Lima Hamilton SF-2 cantilever-bend, load-control machine with a frequency of 1800 cpm. The testing was conducted at 1093° C (2000° F) with an A-ratio of ∞ using a constant-stress specimen configuration as shown in Figure 17. For all HCF testing, 12 million cycles constituted a nonfailure "run-out." Initial stress (load) was established through the earlier stress rupture data. The first specimen (Codep coated) was run at 13.8 MPa (2.0) ksi and resulted in a failure in the René 80 outside of the

Table VI. Monocrystal Normalloy Bonded to René 80; Stress Rupture at 1093° C (2000° F).

Specimen Configuration	Stress, MPa (ksi)	Life, Hours	%El
Bare	5.5 (0.8)	1056 Terminated	0.34
Codep Coated	5.5 (0.8)	1052 Terminated	2.2
Bare	13.8 (2.0)	88.4	1.8
Bare	13.8 (2.0)	100.9	2.3
Bare	13.8 (2.0)	100.8	1.9
Bare	13.8 (2.0)	128.1	3.5
Bare	13.8 (2.0)	89.2	2.3
Codep Coated	13.8 (2.0)	631.0	---
Codep Coated	13.8 (2.0)	550.6	14.3
Codep Coated	13.8 (2.0)	899.3	11.8
Bare	17.2 (2.5)	130.9	3.6
Bare	17.2 (2.5)	22.0	1.7
Bare	17.2 (2.5)	110.0	1.7
Bare	17.2 (2.5)	101.9	2.4
Bare	17.2 (2.5)	94.4	4.7
Bare	17.2 (2.5)	0.3	0.32
Bare	17.2 (2.5)	92.3	2.4
Bare	17.2 (2.5)	9.1	1.8
Codep Coated	17.2 (2.5)	128.9	22.1
Codep Coated	17.2 (2.5)	237.4	7.8
Codep Coated	17.2 (2.5)	314.0	9.5
Codep Coated	17.2 (2.5)	434.5	8.6
Codep Coated	17.2 (2.5)	130.5	---
Codep Coated	17.2 (2.5)	7.8	0.87
Codep Coated	17.2 (2.5)	10.3	3.0
Codep Coated	17.2 (2.5)	1.5	7.6
Codep Coated	17.2 (2.5)	170.7	12.5
Bare	20.7 (3.0)	62.7	3.7
Bare	20.7 (3.0)	59.7	4.9
Bare	20.7 (3.0)	72.4	3.0
Bare	20.7 (3.0)	38.2	6.6
Codep Coated	20.7 (3.0)	54.0	25.5
Codep Coated	20.7 (3.0)	87.6	2.9
Codep Coated	20.7 (3.0)	93.6	17.4
Codep Coated	20.7 (3.0)	5.3	3.0
Codep Coated	27.6 (4.0)	2.2	4.1
Codep Coated	27.6 (4.0)	21.9	31.5

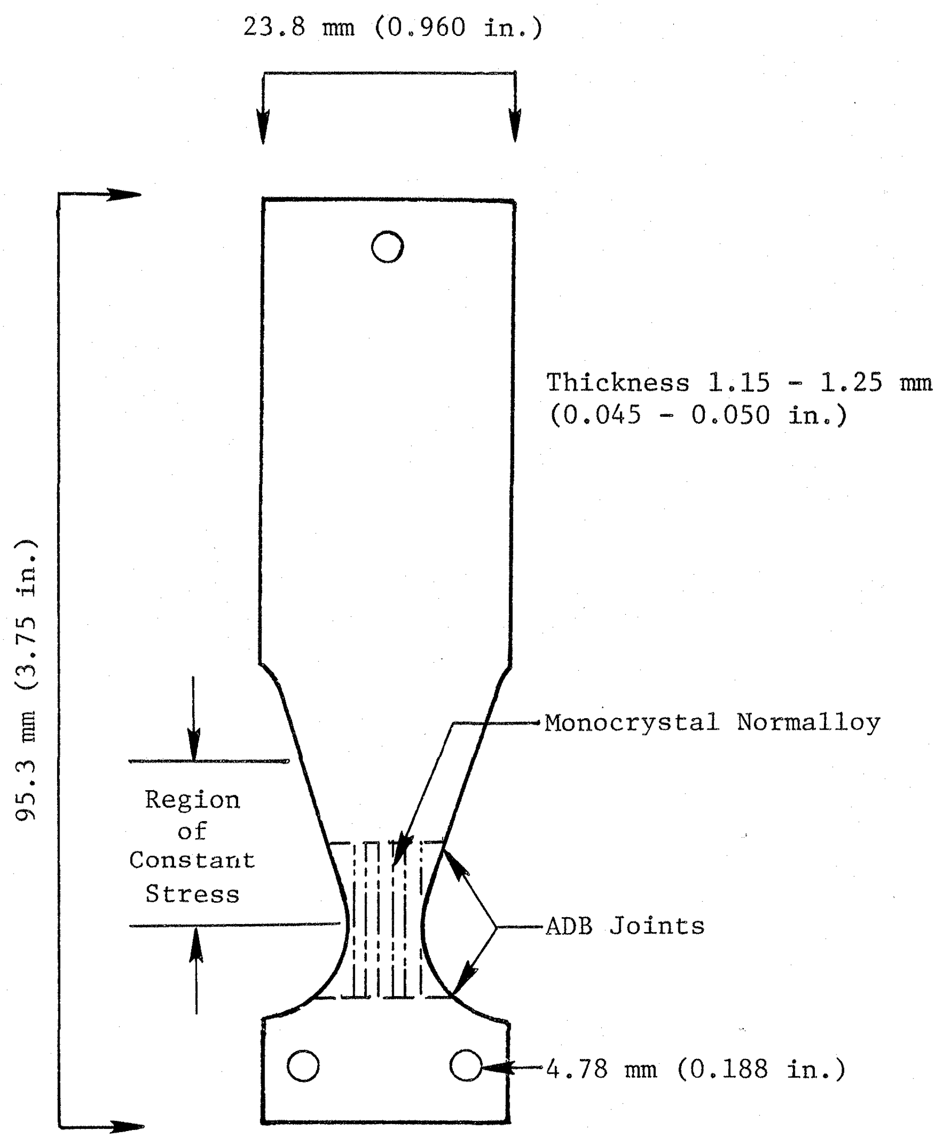


Figure 17. HCF Specimen Configuration.

constant-stress area at 3.6 million cycles. The next specimen was tested at 10.3 MPa (1.5 ksi); however, it ran out at 12 million cycles. The same specimen was subsequently step loaded as high as 220.6 MPa (32 ksi) with no failure. Testing of this specimen was discontinued, and another was run with similar results. At this point it was presumed that the specimen "design," and not the testing procedures or material properties, was responsible for the erroneous results. The bimetal specimen comprised of materials with large differences in properties was not exhibiting characteristics typical of monolythic specimens; therefore, additional HCF testing in that mode was discontinued. Since HCF properties of the tip-to-blade ADB joint were not considered critical to safe engine operation, CF6-50 Design Engineering waived the requirements.

3.2.4.4 Simulated Engine Thermal Shock Testing

SETS testing was conducted on standard René 80 "wedge" specimens with monocrystal Normalloy activated diffusion bonded to the leading edge (Figure 18). The testing was conducted on baseline René 80 and on fabricated specimens, both bare and Codep coated. Maximum/minimum temperatures during the test were 1093° C (2000° F) and 427° C (800° F) respectively at approximately 30 seconds per cycle.

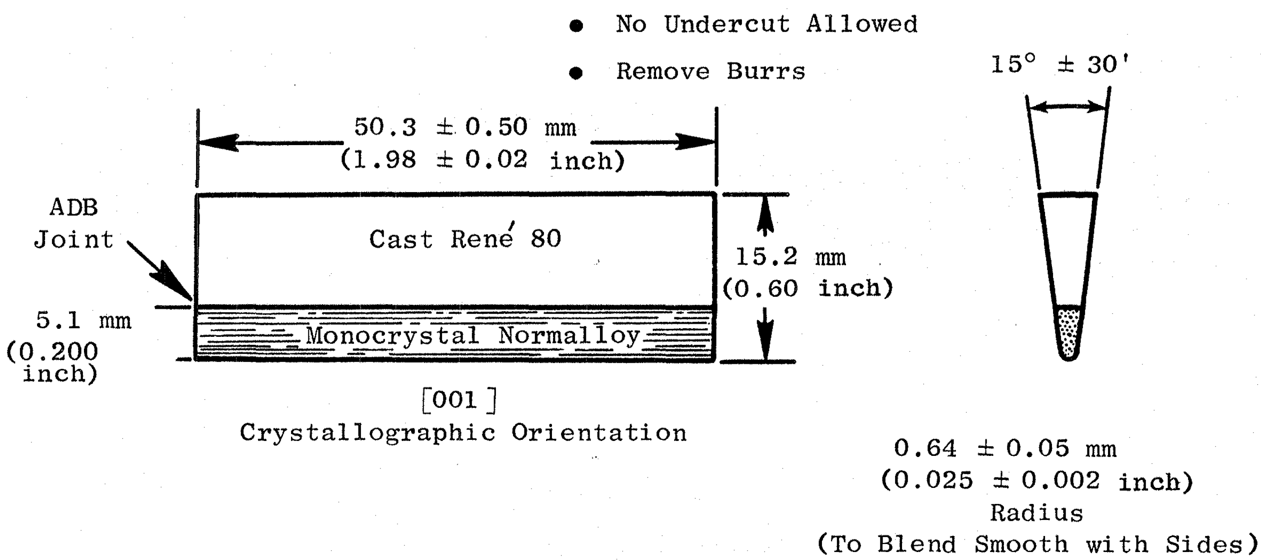
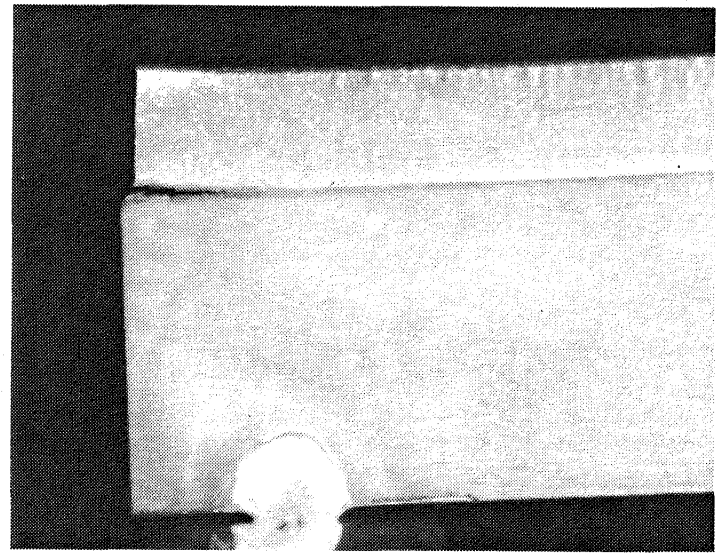


Figure 18. Thermal-Fatigue Specimen of Monocrystal Normalloy Bonded to Rene' 80.

Unlike the Normalloy parent-metal specimens tested earlier (Section 3.2.3.3), the bonded specimens failed at the Normalloy-to-René 80 ADB joint and not in the Normalloy material (Figure 19). Three of the five specimens failed at the bond line at 265, 500, and 750 cycles. No cracking was observed in the two remaining specimens after 2000 cycles, at which point the testing was terminated (also shown in Figure 19).

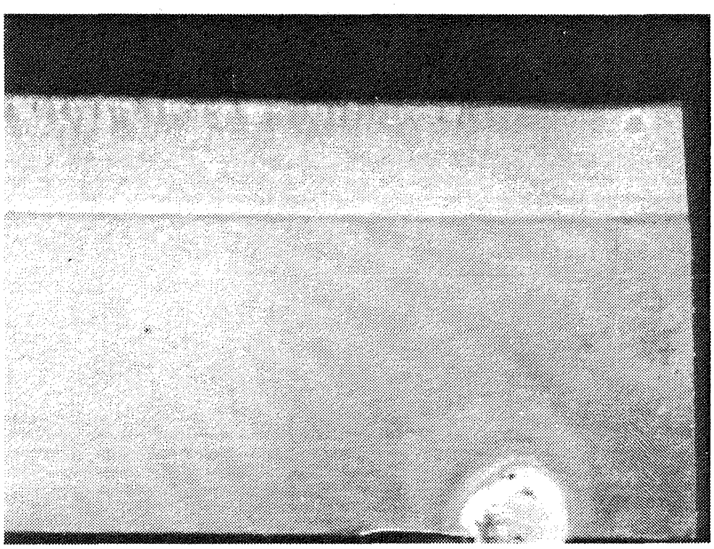
Monocrystal/Rene' 80 Joint Separation

500 Cycles



3.75X

Monocrystal/Rene' 80 Joint - No Cracking



1300 Cycles

Figure 19. Thermal-Fatigue Specimens after Testing.

Analysis of the results indicated that the joint failures resulted from a combination of specimen configuration, and the mismatch in thermal-expansion coefficients. In the SETS configuration, there existed a considerable volume of material mismatch between the Normalloy and the more rigid René 80. In engine conditions, the René 80 blade wall and the monocrystal top wall would be of identical thicknesses. Therefore, this condition was not expected to be a major problem in the actual turbine blade configuration.

Although failures occurred earlier than expected, the joined specimens ran considerably longer compared to the previously tested René 80 material. Increasing the thermal-fatigue life by a factor of two continued to be a realistic goal.

3.2.5 Task II Summary

Review of the mechanical and physical properties of the monocrystal Normalloy tip material and the Normalloy-to-René 80 ADB joints indicated that all properties exceeded the engine stress/environmental requirements for the blade tip.

3.3 TASK III - ABRASIVE-TIP EVALUATION

The one characteristic of the advanced blade tip/seal system most responsible for improving engine performance is the abrasive-tip treatment. This system must be capable of abrading shroud surfaces that are several times the area of the blade tip.

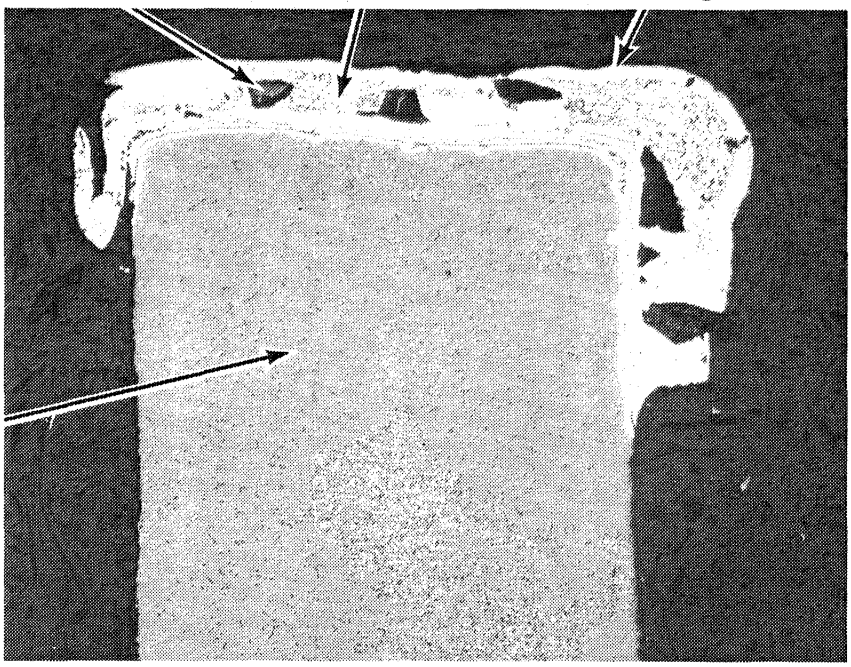
3.3.1 Application Process

Preliminary engine testing at General Electric, with HPT blade tips, indicated that an abrasive treatment consisting of particles entrapment-plated to the blade tip was capable of removing varying amounts of shroud material in early engine life. The basic system selected for this program (shown in Figure 20) consisted of Al_2O_3 particles, about 152 μm (0.006 inch) in size, entrapment-plated to the blade tips in a nickel/chromium matrix. A subsequent aluminide coating was applied to enhance environmental resistance.

3.3.2 Evaluation

The test plan shown in Table VII was formulated to evaluate and quantitatively rank factors affecting characteristics of the abrasive-tip treatment system. Factors evaluated were particle size 102 - 279 μm (0.004 - 0.011 inch), particle relief, matrix composition, shroud material and condition (new or oxidized), rub rate, test temperature, and tip speed. The selected system was further evaluated to ascertain the resistance to thermal shock, foreign object damage (FOD), and corrosion and oxidation. In the course of this investigation, more than 50 high-speed [427 m/sec (1400 ft/sec) tip speed],

Top View
35X



Cross Section
100X

Figure 20. Abrasive-Tip Treatment.

Table VII. Abrasive-Tip Test Plan.

Abrasive	Particle Mesh Size	Matrix	Coating	Incursion Rate µm/sec	Incursion Rate mil/sec	No. of Blades	Shroud Material	Depth of Incursion mm	Depth of Incursion in.
Al_2O_3, 38 x	100	Ni/Cr	Codep	50.8	2	6	New Bradelloy	1.02	0.040
Al_2O_3, 38 x	100	Ni/Cr	Codep	50.8	2	6	New Genaseal	1.02	0.040
Al_2O_3, 38 x	100	Ni/Cr	Codep	50.8	2	6	Oxidized Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codep	50.8	2	6	Oxidized Genaseal	0.76	0.030
Borazon I	100	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
Borazon I	100	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
Borazon I	100	Ni/Cr	Codep	50.8	2	6	Oxidized Bradelloy	0.76	0.030
Borazon 500	100	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
Borazon 500	100	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
Borazon 500	100	Ni/Cr	Codep	50.8	2	6	Oxidized Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codep	25.4	1	6	New Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codep	25.4	1	6	New Genaseal	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codep	101.6	4	6	New Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codep	101.6	4	6	New Genaseal	0.76	0.030
Al_2O_3, 38 x	150	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
Al_2O_3, 38 x	150	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
Al_2O_3, 38 x	60	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
Al_2O_3, 38 x	60	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
Al_2O_3, 32 x	150	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
Al_2O_3, 32 x	150	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
Al_2O_3, 32 x	60	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
Al_2O_3, 32 x	60	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
* Al_2O_3, 38 x	100	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
* Al_2O_3, 38 x	100	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
* Borazon I, 500	100	Ni/Cr	Codep	50.8	2	6	New Bradelloy	0.76	0.030
* Borazon I, 500	100	Ni/Cr	Codep	50.8	2	6	New Genaseal	0.76	0.030
** None	-	-	Codep	50.8	2	4	New Bradelloy	0.76	0.030
** None	-	-	Codep	50.8	2	4	New Genaseal	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Genaseal	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Genaseal	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	100 hr, Oxidized Bradelloy	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	100 hr, Oxidized Genaseal	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Bradelloy	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Bradelloy	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Bradelloy	0.25	0.010
*** Al_2O_3, 38 X	100	Ni/Cr	Codal	50.8	2	6	New Genaseal	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	4	New Bradelloy	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	4	New Bradelloy	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	4	New Genaseal	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	4	New Genaseal	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	4	New CoNiCrAlY	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	4	New CoNiCrAlY	0.76	0.030
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Genaseal	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New Genaseal	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Bradelloy	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Bradelloy	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Bradelloy	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Genaseal	0.25	0.010
*** Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized Genaseal	0.25	0.010
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New CoNiCrAlY	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	New CoNiCrAlY	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized CoNiCrAlY	0.76	0.030
Al_2O_3, 38 x	100	Ni/Cr	Codal	50.8	2	6	Oxidized CoNiCrAlY	0.76	0.030

* NiCr Plated Flush With Particles
** Monocrystal Normalloy Tipped Blades
*** Interrupted and Inspected at 0.25 mm (0.01 in.), final depth of 0.76 mm (0.03 in.)

high-temperature [1093° C (2000° F) shroud surface temperature] rubs were made into selected shroud materials using various abrasive-tip treatments. Testing was accomplished at Solar Turbine International in San Diego, California. A schematic of the Solar rub tester is shown in Figure 21.

The rub-test blade specimens (Figure 22) used in this program were machined to produce tip walls similar to those of the CF6-50 Stage 1 HPT blade. Test blade specimen material was MAR-M-421, a cast nickel-base superalloy with a a chemistry similar to that of Rene' 80. Six blades in groups of three, 180° apart, were used in each rub test. Both aluminum oxide (Al_2O_3) and Borazon (cubic boron material) particles in various grades and particle sizes were evaluated. In all cases, the abrasive particles were attached to the tip by the entrapment-plating process. The plated matrix consisted of a layer of nickel, plated to a depth which covered about 60% of the abrasive-particle height, followed by a chromium overplate of 7.6 - 12.7 μm (0.0003 - 0.0005 inch). All blades were subjected to a 1093° C (2000° F), 1-hour, vacuum-diffusion cycle that allowed the chromium to diffuse into the nickel and also enhanced the plating-to-blade bond (shown previously in Figure 19). Some tests were performed with blades in which the matrix had been plated to a depth which completely encapsulated the abrasive particles. This "flush" plating was done to increase the capability of the system for particle retention. Some later rub tests also had the abrasive treatment applied on the convex side of the blade for a distance of 0.6 mm (0.025 inch) from the tip. This technique provided additional abrasive capability in the event the particles on the tip were removed during a severe rub. All blades were aluminide coated (after the diffusion cycle) to optimize the oxidation resistance of the plated matrix. The standard GE Codep process was utilized in most earlier tests, and Codal patch coating (provides more aluminide) was used in later tests.

The shroud specimens for each test were machined from actual, engine-quality, shroud segments. Each shroud specimen had two thermocouples installed through the back into holes drilled in the shroud material. One thermocouple was located 1.27 mm (0.050 inch) below the surface and was used to measure and record shroud temperature. The other thermocouple was installed flush with the rub surface and was used to indicate the actual start of the rub.

When the tip speed reached 427 m/sec (1400 ft/sec), and the thermocouples read 1093° C (2000° F), the shroud was moved into the blade at a controlled rate. When the blade abraded the surface thermocouple (opening the circuit), incursion was timed to achieve 0.76 mm (0.030 inch) depth, then reversed to withdraw the shroud piece from rubbing contact. Figure 23 shows the blade specimens and the shroud specimen after wear testing.

Constant test conditions of the Solar rub testing were as follows: 427 m/sec (1400 surface-ft/sec) specimen tip speed, 1093° C (2000° F) surface temperature, 45/55 particle/matrix density (volume fraction). Variable test conditions are listed in Table VII.

Facility of Solar Turbines International, a Division of Caterpillar Tractor Company

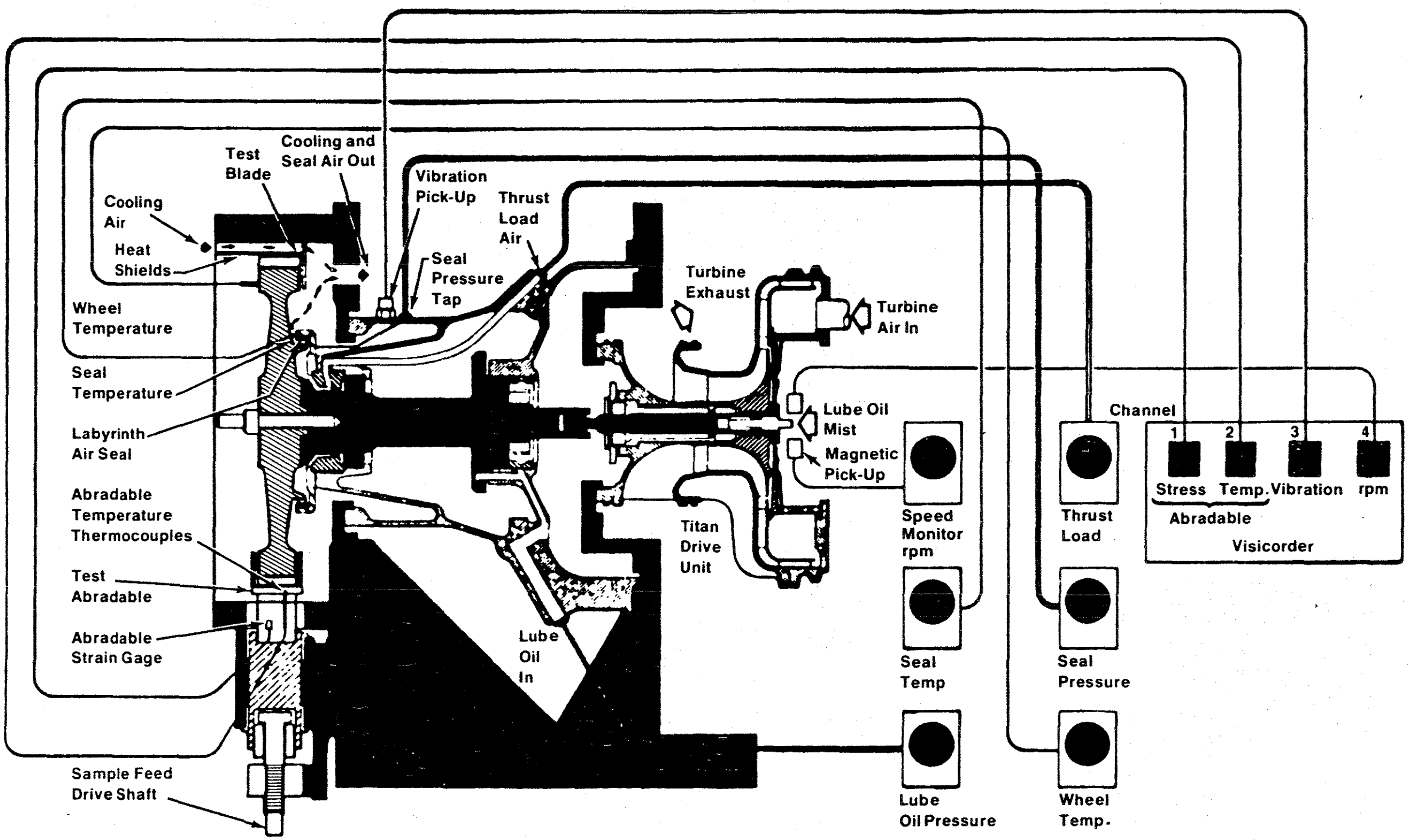


Figure 21. High Temperature Rub Tester.

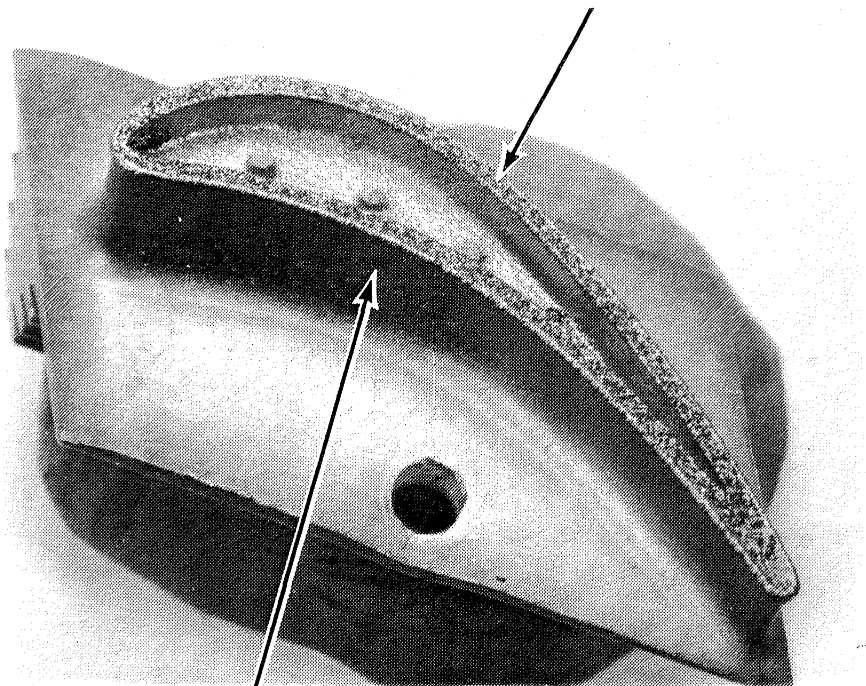


Figure 22. Wear-Test Specimen Machined to Simulate the CF6-50 Tip Configuration.

3.3.3 <u>Test Results</u>

The test results, presented in Figure 24 and summarized in Figure 25, show that (as expected) untreated blade tips could not remove sufficient shroud material. The aluminum oxide (Al_2O_3) system in all combinations of particle size, type, and extent of encapsulation was effective in removing Genaseal (Figure 26), both new and preoxidized. The Al_2O_3 system, however, was only marginally effective when rubbing into new Bradelloy and could not abrade oxidized Bradelloy (Figure 27). The Al_2O_3 system was also tested into VPS CoNiCrAlY and shown to be extremely effective in removing this shroud material (Figure 28).

Even though Borazon was not a prime candidate for a long-life abrasive system due to potential oxidation problems, it was evaluated because it has superior abrasive qualities. It was shown to be the most effective system for abrading Bradelloy.

As shown in Figures 26 and 27, rubs made into either Genaseal or CoNiCrAlY resulted in only slight blade tip loss, and in each case most of the abrasive system remained on the blade tip.

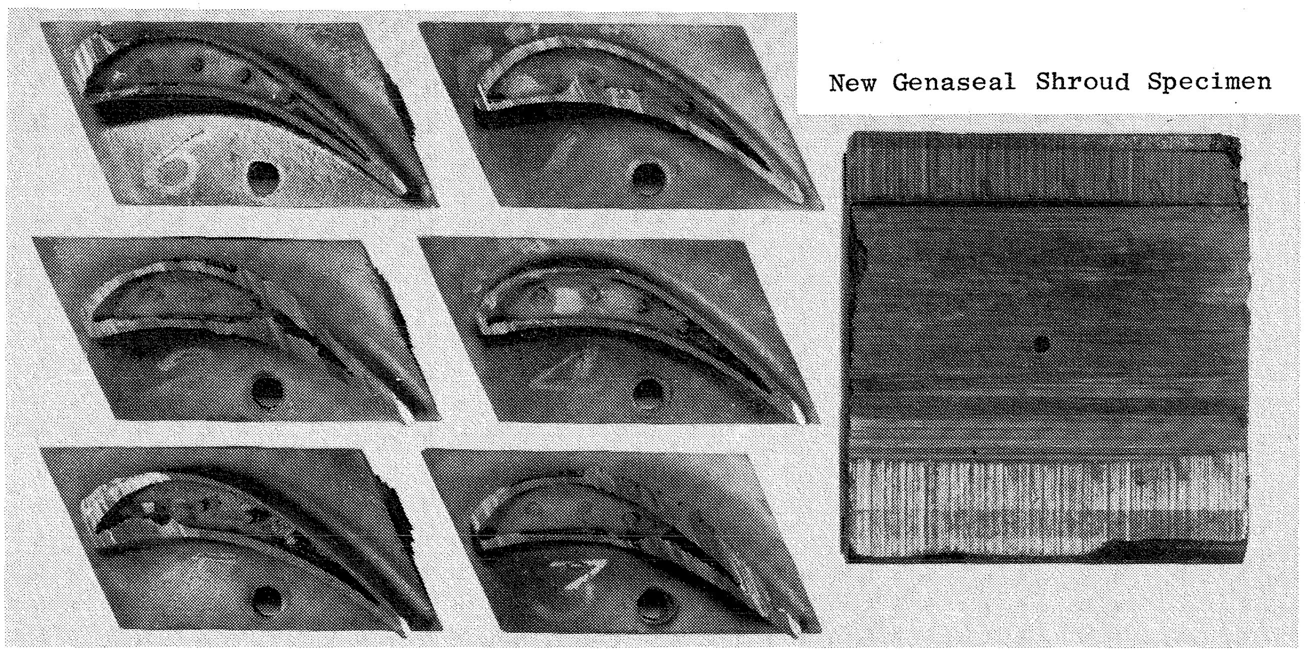


Figure 23. Specimens After High-Speed, High-Temperature Wear Testing.

- Results are the Average of 1 to 8 Tests
- 1093° C (2000° F)
- 427 m/sec (1400 ft/sec)

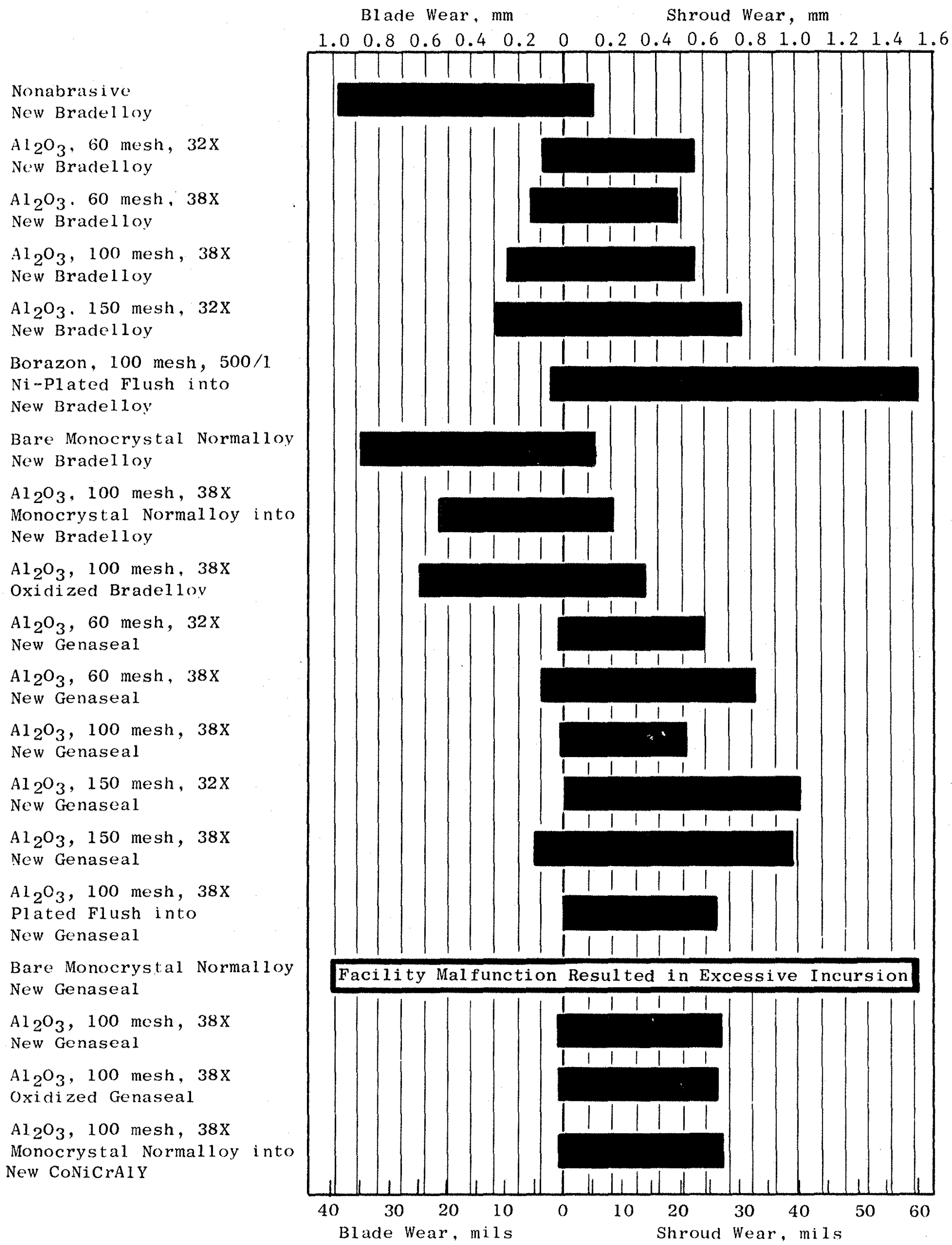


Figure 24. Rub Testing at Solar.

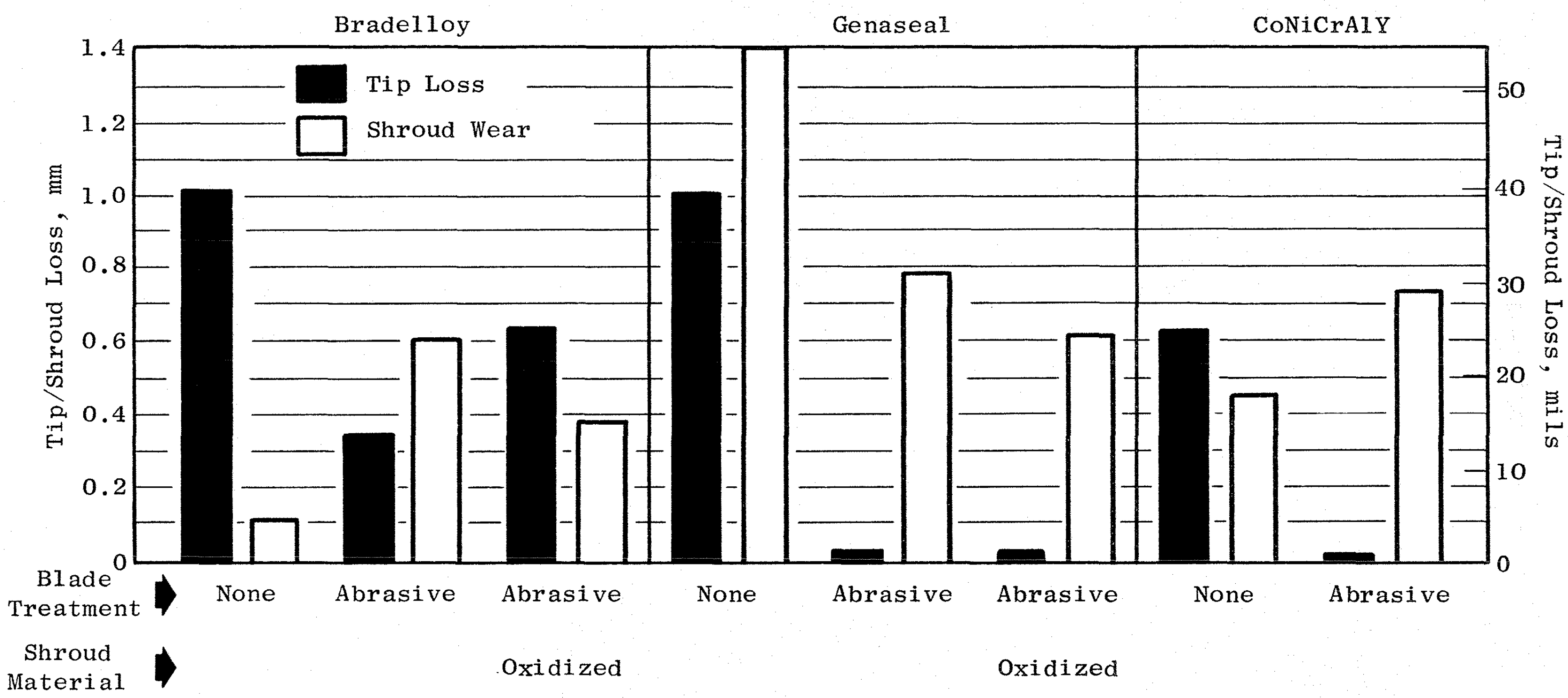


Figure 25. Summary of Wear-Test Results (About 60 Tests).

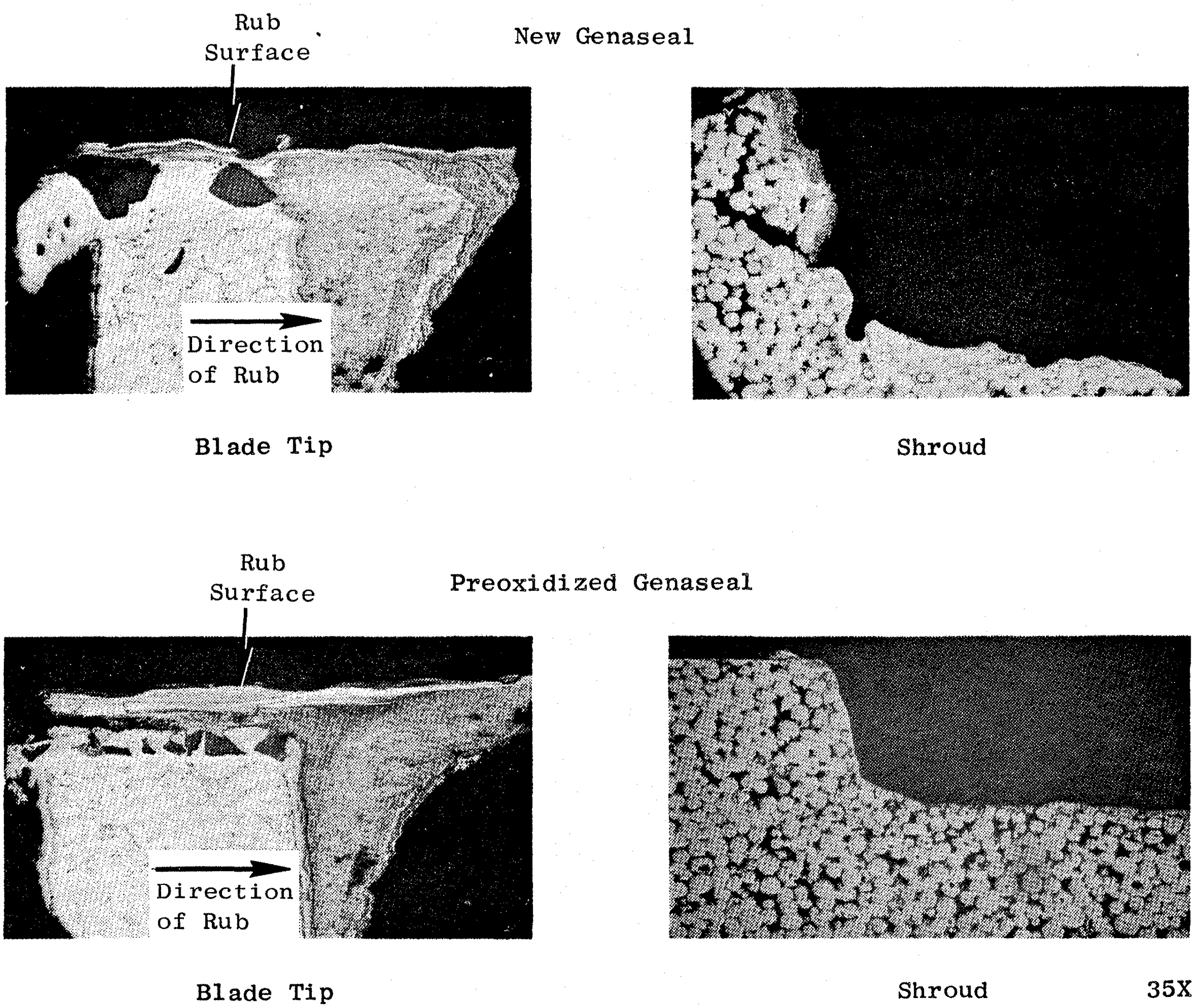
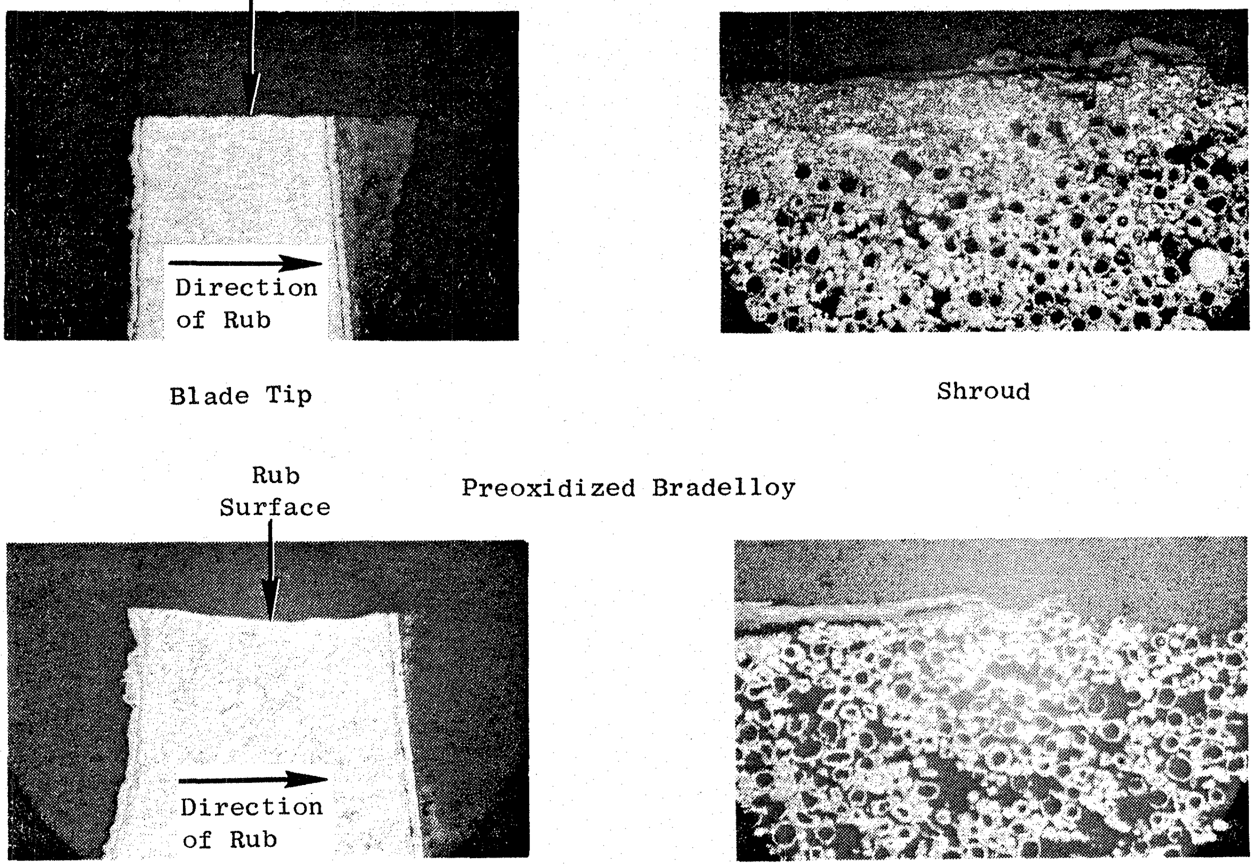


Figure 26. Wear-Test Results of Al_2O_3 Abrasive-Tip Treatment into New and Preoxidized Genaseal.

Rub Surface

New Bradelloy



Blade Tip

Shroud

Rub Surface

Preoxidized Bradelloy

Blade Tip

Shroud

40X

Figure 27. Wear-Test Results of Al_2O_3 Abrasive-Tip Treatment into New and Preoxidized Bradelloy.

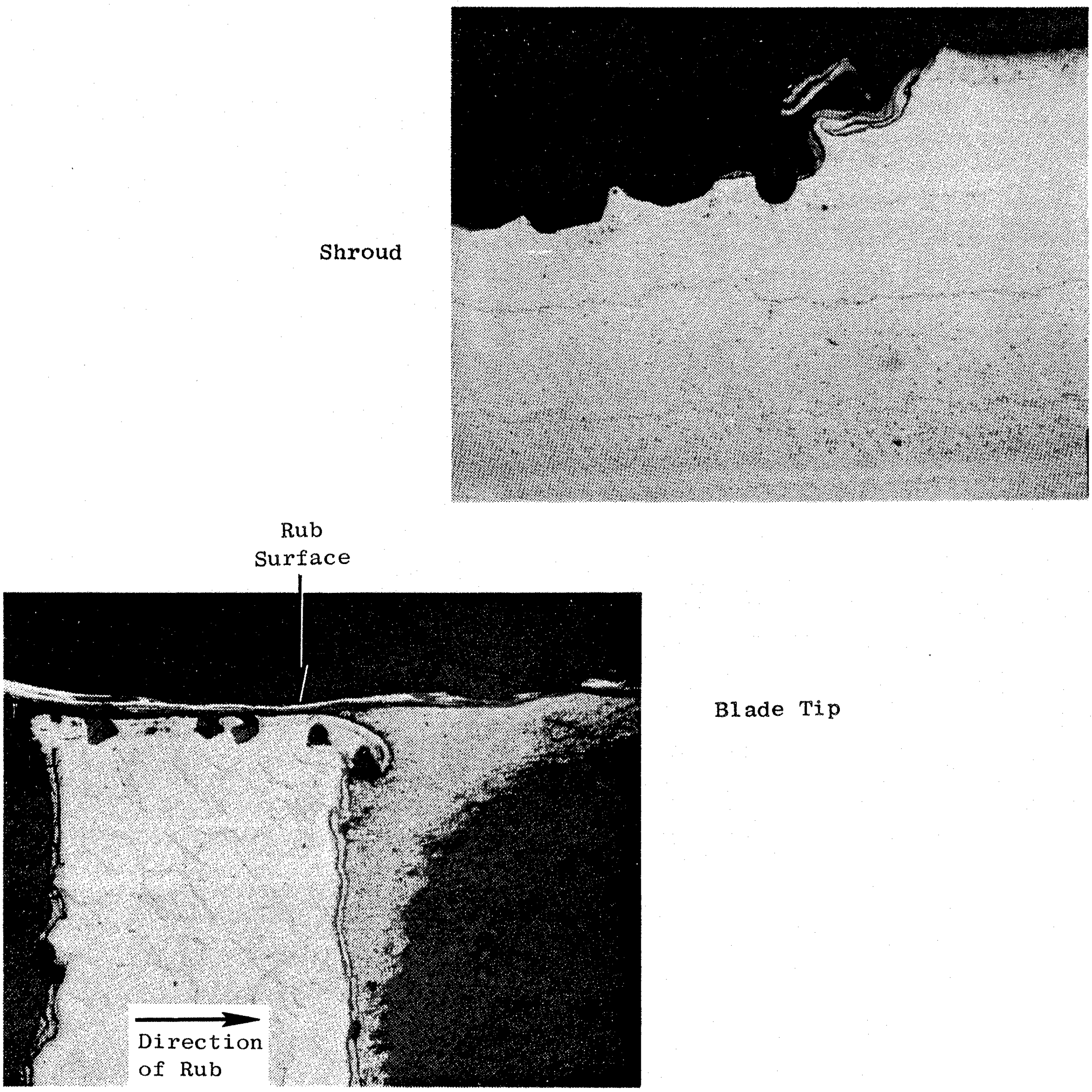


Figure 28. Wear-Test Results of Al_2O_3 Abrasive-Tip Treatment into New VPS CoNiCrAlY.

The goal of this project was to achieve a 0.38 mm (0.015 inch) improvement in blade-tip-to-shroud-clearance. The test results generated in this task clearly demonstrated the capability of the selected tip treatment to achieve the program goal when combined with either Genaseal or CoNiCrAlY shrouds.

As a result of the wear testing, the following abrasive-particle/matrix combination was selected for factory engine-test evaluation:

- Particle: 164.7 μm (0.0065 inch) Norton Grade 38 x Al_2O_3.
- Matrix: 152 μm (0.006 inch) electroplated nickel plus 10.2 - 15.2 μm (0.0004 - 0.0006 inch) chromium electroplate.

3.3.3.1 Additional High Temperature Rub Testing

Twelve additional rub tests were performed at Solar utilizing improved abrasive tip treatments as shown in Table VIII. Eight tests were performed with rub test blades having a long life abrasive tip system. The tips for these blades had Al_2O_3 particle dispersed throughout a superalloy matrix which had been hot isostatically pressed to full density. Airfoil shaped tips were removed and bonded to the Solar rub test blades, and the center removed by EDM to provide 0.76 mm (0.030 inch) thick walls to simulate the HPT blade configuration. Tests AO-1, AO-4, AO-9, and AO-10 all suffered abrasive tip damage, breaking off in areas at the original load line. Tests AO-3 and AO-11 rubbed into oxidized Bradelloy (previously determined to be the most difficult to remove) with some degree of success. In test AO-3, 0.76 mm (0.030 inch) of Bradelloy was removed, and 0.51 mm (0.025 inch) of tip material lost. No fracture or distress of the tip was noted on either of these oxidized Bradelloy rubs. Tests AO-2 and AO-8 rubbed into new Geneseal and new Bradelloy with a minimum of wear on the blade and moderate shroud removal, however one blade in each test had a piece broken off at the joint interface.

Rub test AO-12 had blades with a proprietary brazing/particle entrapment process with CBN 500 particles being the abrasive media. This test had just completed the rub cycle when the Solar rub test machine lost a bearing, and the resultant damage ruined the test blade and shroud, and required complete overhaul of the Solar rub tester. Afer facility repair, tests AO-5 and AO-6 were rubs made into oxidized Bradelloy and AO-7 into oxidized CoNiCrAlY shroud segments. The blades were provided with a newly developed CBN particle, Borazon 570, which was electrolytically entrapment plated identical to the previous rub tests. In all three tests, the abrasive system removed the shroud material to a depth of 0.76 mm (0.030 inch) without loss of the abrasive particles on the rub test blades. This is the first time an abrasive system has been totally successful in rubbing into oxidized Bradelloy and removing Bradelloy without removing the abrasive from the blades. Also, these tests were performed with four rub test blades per test instead of the six blades used for previous testing.

Table VIII. Additional Abrasive Tip Tests.

	Abrasive	Particle Mesh Size	Matrix	Coating	Incursion Rate		Number of Blades	Shroud Material	Depth of Incursion	
					μm/sec	mil/sec			mm	inch
AO-1	Al_2O_3	100	T-24	Codep	50.8	2	4	New Bradelloy	0.76	0.030
AO-2	Al_2O_3	100	T-24	Codep	50.8	2	4	New Geneseal	0.76	0.030
AO-3	Al_2O_3	100	T-24	Codep	50.8	2	4	Oxidized Bradelloy	0.76	0.030
AO-4	Al_2O_3	100	T-24	Codep	50.8	2	4	Oxidized Geneseal	0.76	0.030
AO-5	CBN 570	100	Ni/Cr	Codep	50.8	2	4	Oxidized Bradelloy	0.76	0.030
AO-6	CBN 570	100	Ni/Cr	Codep	50.8	2	4	Oxidized Bradelloy	0.76	0.030
AO-7	CBN 570	100	Ni/Cr	Codep	50.8	2	4	Oxidized CoNiCrAlY	0.76	0.030
AO-8	Al_2O_3	100	T-24	Codep	50.8	2	4	New Bradelloy	0.76	0.030
AO-9	Al_2O_3	100	T-24	Codep	50.8	2	4	Oxidized Geneseal	0.76	0.030
AO-10	Al_2O_3	100	T-24	Codep	50.8	2	4	Oxidized CoNiCrAlY	0.76	0.030
AO-11	Al_2O_3	100	T-24	Codep	50.8	2	4	Oxidized Bradelloy	0.76	0.030
AO-12	CBN 500	100	*	Codep	50.8	2	4	Oxidized Bradelloy	0.76	0.030 **

*Particles Entrapped in a Proprietary Braze Media
**Solar Rub Test Rig Failure - Test Results Eradicated.

T-24 Composition - Nominal

Ni	Cr	Al	W	Ta	Ti	C	Y
68.3	15.0	5.5	8.0	1.0	2.0	0.05	0.2

3.3.3.2 Conclusions of the Additional Rub Test

The Al_2O_3/T-24 hot isostatically compacts for long time wear application were somewhat encouraging in that some success in shroud removal was attained, however the structure must be strengthened to withstand the rub generated forces without fracturing. Some withstood severe rubbing without fracture, indicating that with more effort, the fracturing can be eliminated (Figure 29).

The CBN 570 abrasive particle is particularly promising for short-term shroud removal. Initial oxidation testing indicates the particles have a limited effective life (~5-15 hours at 2000° F); however, if clearances can be set closer to take advantage of the superior rub characteristics of CBN 570, significant clearance improvements can be obtained.

3.4 TASK IV - SEAL SYSTEM VERIFICATION

The objective of this task was to verify that the tip/seal system defined in Tasks I, II, and III would demonstrate the required physical and mechanical properties and be considered safe for factory engine testing. The system verification was accomplished according to the plan described in Figure 30.

3.4.1 Blade Tip Treatment

Blades for the rub-test portion of this task were fabricated to simulate the actual engine-blade tip configuration. The MAR-M-421 Solar rub test blades were ground flat to the blade root. Airfoil-shaped René 80, 4.0 mm (0.160 inch) thick, and monocrystal Normalloy, 1.85 mm (0.075 inch) thick, pieces were machined to airfoil shapes, ground flat and parallel, and activation diffusion bonded to the MAR-M-421 test blades. The specimens (blades) were finish-machined to a configuration similar to that of the CF6-50 HPT blade tip (Figure 31). The blades were then returned to General Electric for abrasive tip treatment and aluminide coating. Figure 32 shows an actual blade after rub testing.

3.4.1.1 High-Speed, Elevated-Temperature Wear Testing

Eight rub tests were performed at Solar, six tests with Al_2O_3 abrasive and two tests without abrasive treatment. The abrasive-tip-treated blades were tested (in duplicate) into new Bradelloy, new Genaseal, and new CoNiCrAlY shroud specimens. The rubs of untreated tips into new Bradelloy and new Genaseal resulted in minimal shroud removal and considerable blade wear. In all abrasive-tipped-blade rubs into shroud specimens (new Genaseal and new CoNiCrAlY), the shroud material was removed to the depth of incursion, and the abrasive remained on the blade tips. Rubs into new Bradelloy were marginal, as evidened earlier in the Task III testing.

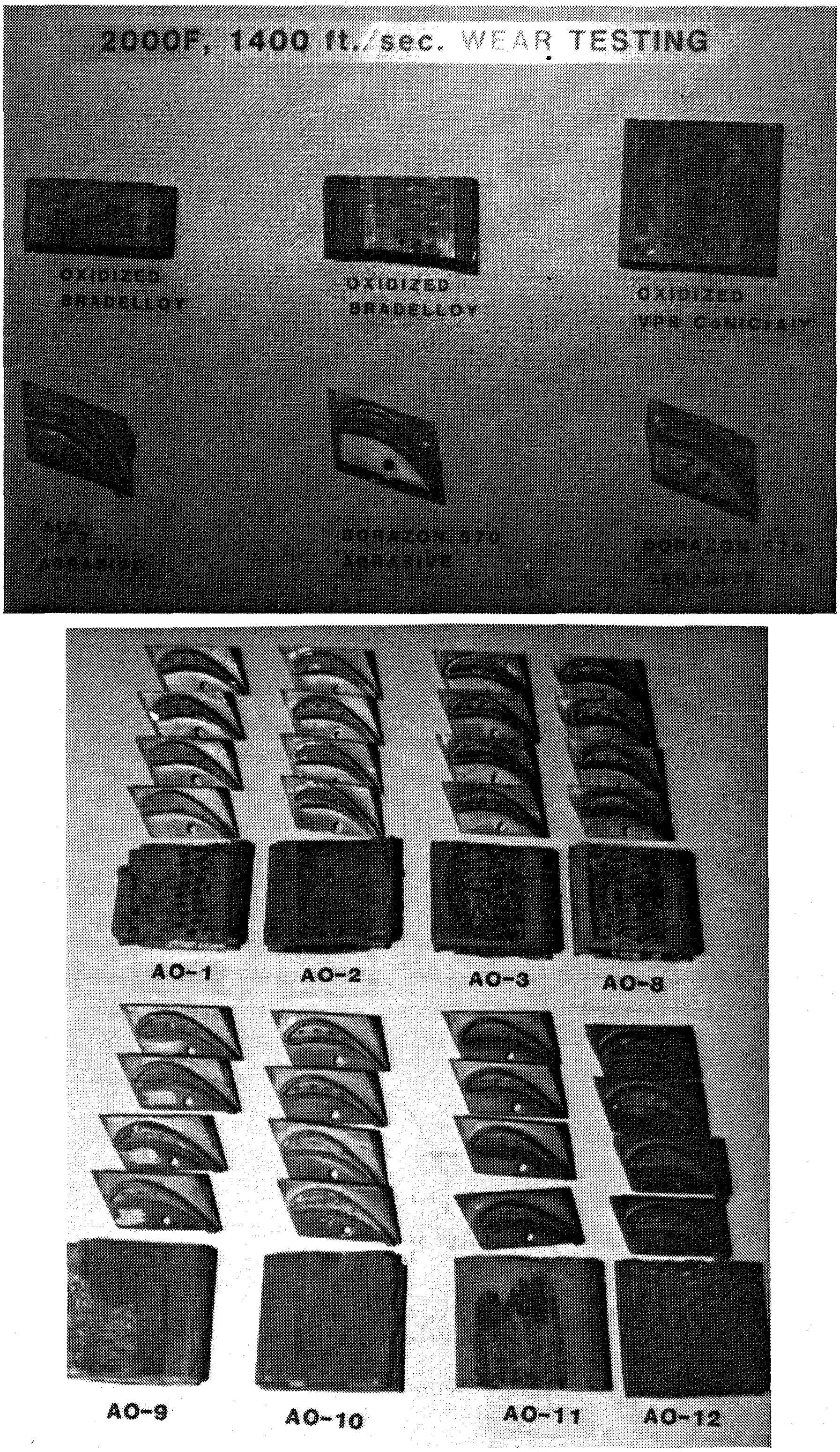


Figure 29. Additional Testing After 2000° F.

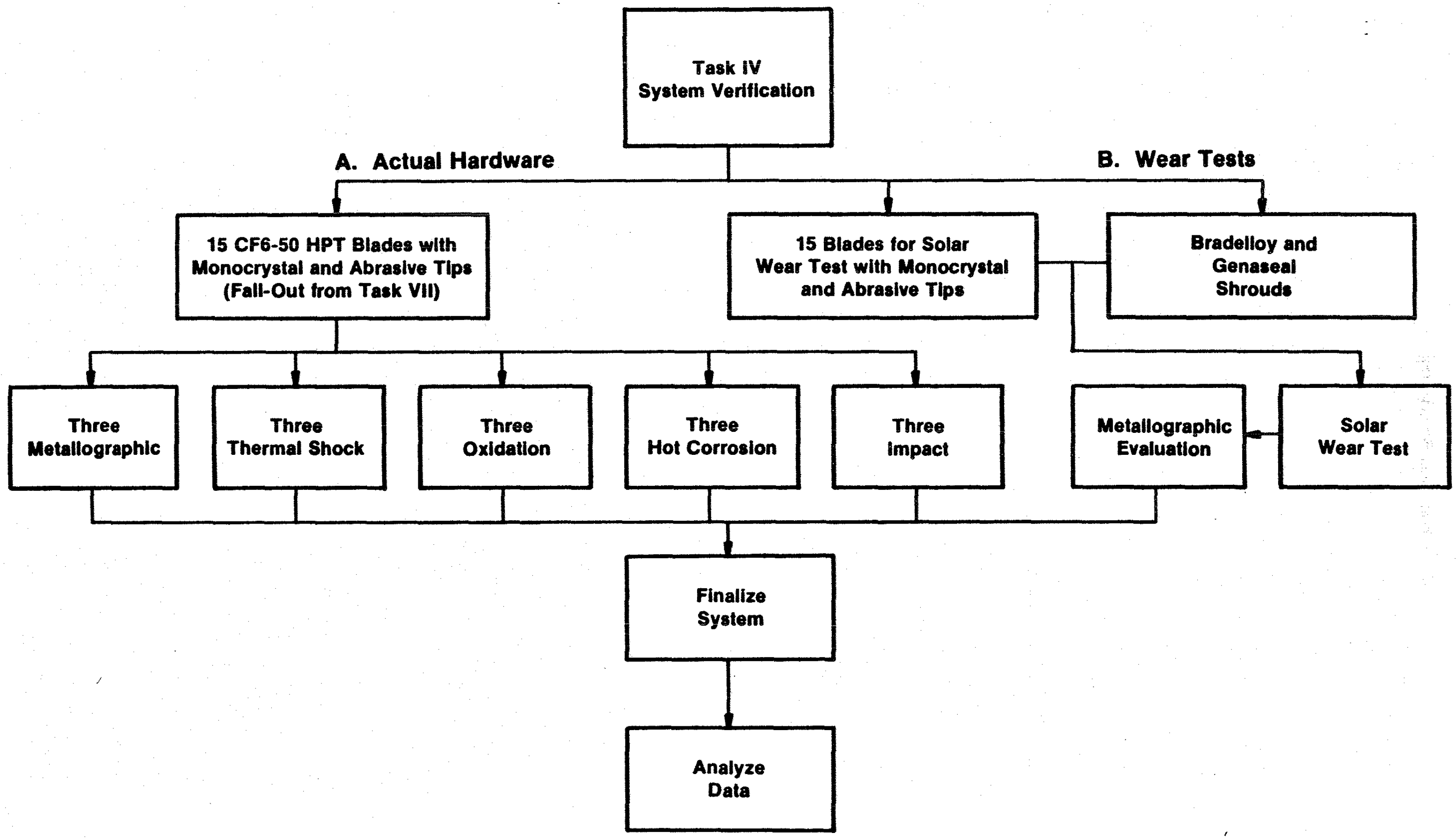


Figure 30. Test Plan for Seal System Verification.

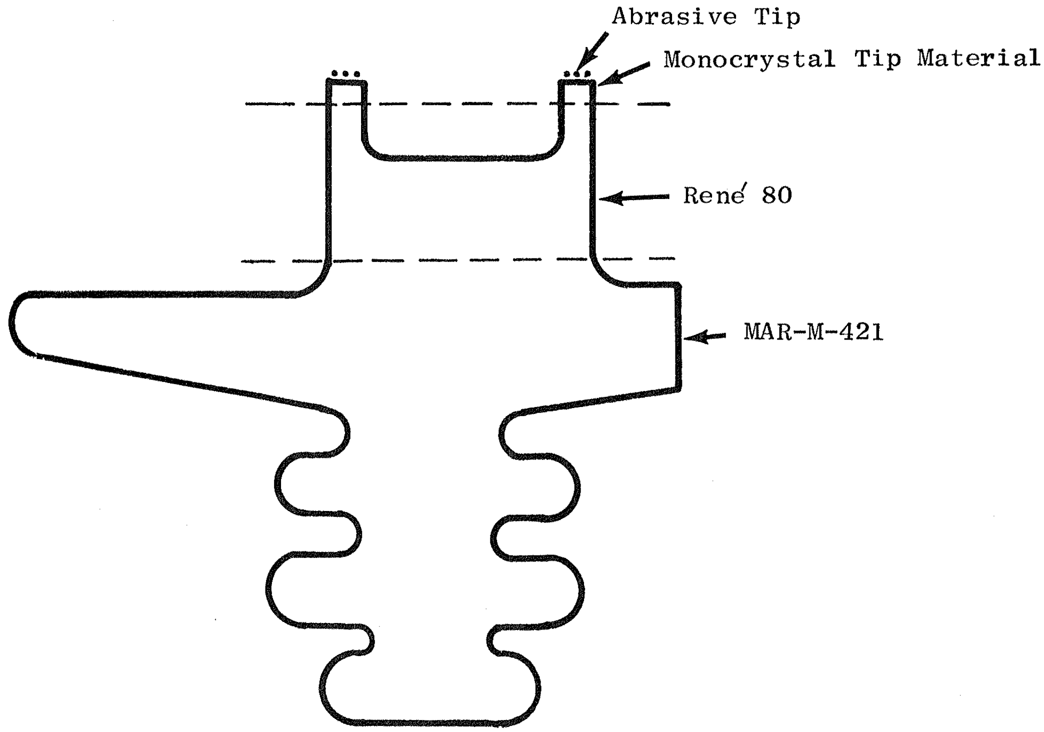


Figure 31. Specimen Configuration for Wear Testing of Advanced Tip-Seal System.

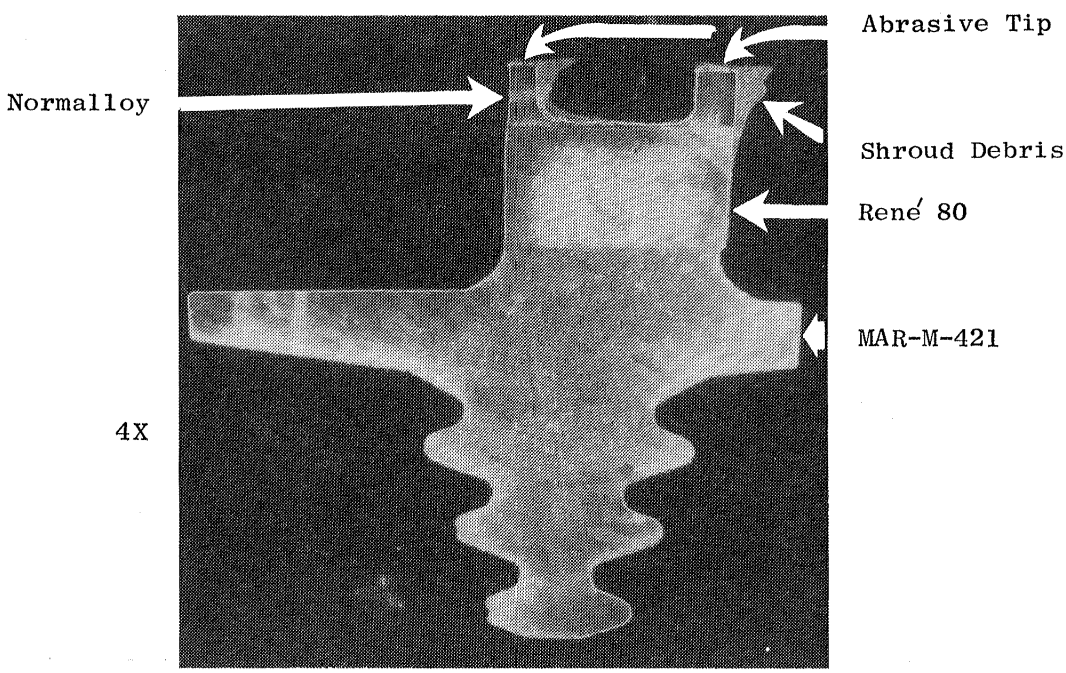


Figure 32. Wear-Test Blade with Advanced Tip System After Wear Testing.

There were no indications of ADB joint distress in any of the tests. Moreover, during the bare blade rub into Genaseal, the depth of incursion inadvertently reached about 2.3 mm (0.090 inch), removing most of the monocrystal tip, but no evidence of tip/joint distress was noted.

Additional wear testing (at NASA's request) is currently being conducted to evaluate the rub capability of an improved abrasive system into Bradelloy and an advanced shroud system comprised of VPS CoNiCrAlY on MM509. Two potential long-life systems are also being evaluated and are being rubbed into Bradelloy, Genaseal, and VPS CoNiCrAlY. The testing is being conducted with both as-manufactured and preoxidized shroud materials. The results will be compared to those generated in Task III and will be published as an addendum to this technical report.

3.4.1.2 Ballistic Impact Testing

Ballistic impact testing of fully manufactured CF6-50 blades with the advanced tip system was conducted to verify the ability of the ADB Joint to withstand FOD. Testing was conducted at 1093° C (2000° F), 360 m/sec (1180 ft/sec), and 23 J (17 ft-lb). This impact target area was located at or just below the tip-to-blade ADB joint. Two tests were conducted; neither test resulted in failures in the ADB joint even though considerable deformation occurred (Figure 33). In one test, the projectile went through one side of the blade and stuck the underside of the tip cap, driving it upward, yet the adjacent ADB joint region remained intact.

3.4.1.3 Thermal Shock Testing

SETS testing was conducted on fully manufactured CF6-50 blades with the advanced blade-tip system. Two conventionally cast René 80 blades and one weld-repaired (with Inco 625) blade were tested concurrently to serve as a baseline for comparison. The advanced-tip system was tested in the following configurations:

- Abrasive treated and Codep coated (two specimens)
- Codep coated with abrasive removed at tip (to simulate a rub sufficient to just remove the abrasive treatment (two specimens)
- Codep coated with abrasive removed such that only 0.51 mm (0.020 inch) of monocrystal tip remained (to simulate a severe rub condition) (one specimen).

The temperature/time cycle is shown in Figure 34. The burners of the SETS rig were adjusted to impinge on the blade tips in a manner simulating the temperature profile experienced during actual engine operation.

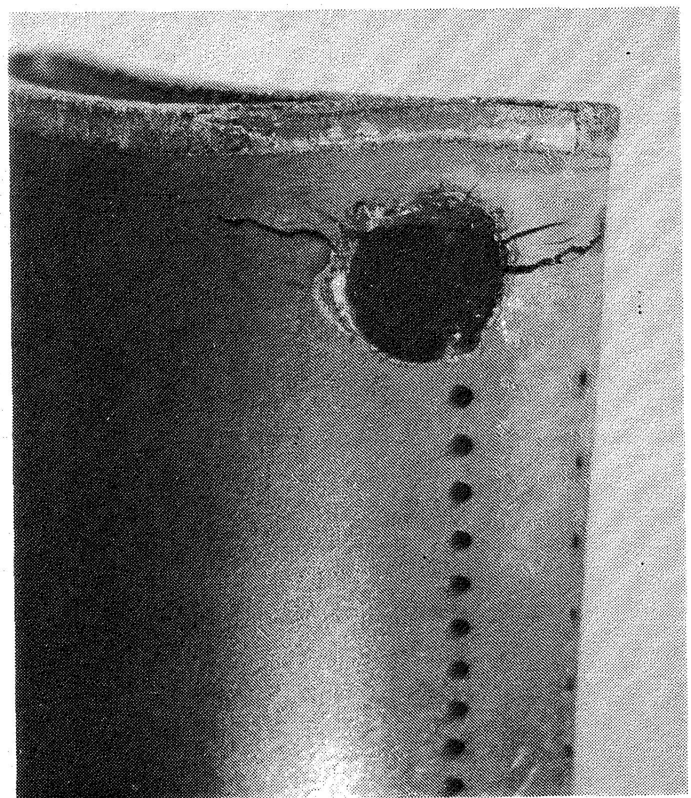


Figure 33. Advanced Tip System after Ballistic Impact Testing.

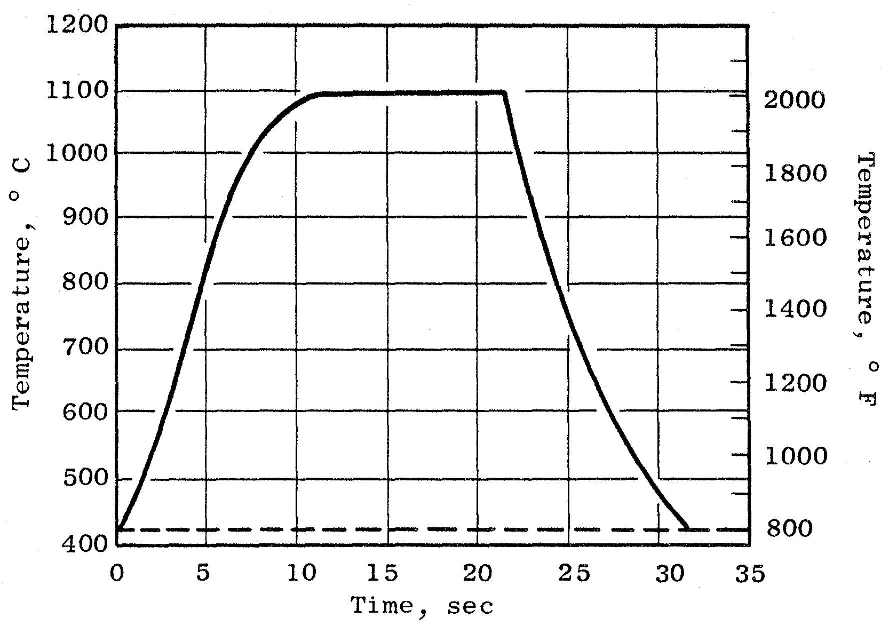


Figure 34. SETS Temperature/Time Cycle.

Unlike earlier testing (funded separately) where only minor tip cracking and no joint distress were evidenced after as many as 6000 cycles in this testing, cracking (primarily in the bond joint) occurred as early as 500 cycles (Figure 35). The reason for the differences in system behavior is believed to be a combination of thermal gradient and squealer-tip configuration. The earlier testing was conducted in a SETS facility that produced a much shallower gradient than the facility used for the latter testing. Also, the earlier testing was conducted on blades with unmachined tips (that is, radial height) that resulted in lower temperature at the joint.

All but one monocrystal-tipped blade cracked in the joint at the trailing edge at approximately 500 cycles. The one blade that did not show trailing-edge bond distress was the blade that had been ground short prior to test. It, however, exhibited a radial crack in the Normalloy.

The weld-repaired blade (Figure 35) began to crack between 50 and 150 cycles and continued to exhibit more and deeper cracks throughout the test. One of the René 80 blades cracked between 150 and 500 cycles; the other René 80 blade didn't crack until after 1000 cycles (Figure 33). In both of the René 80 blades, the cracks propagated rapidly after initiation.

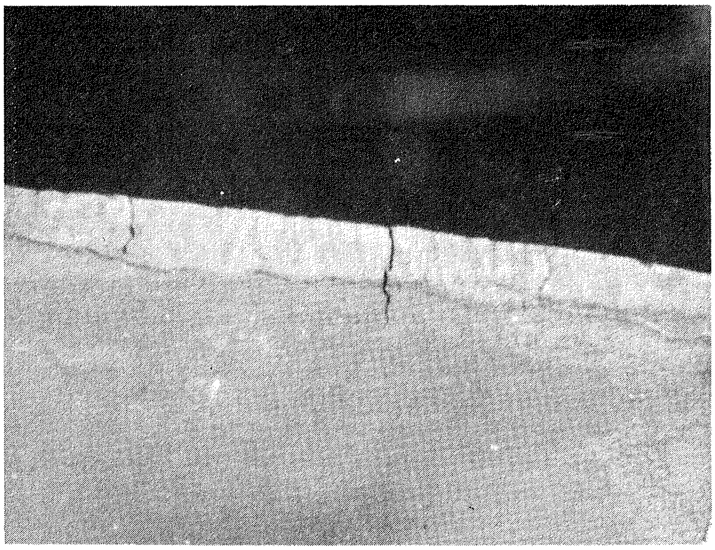
Generally, the results were unanticipated and were attributed to the combination of high thermal gradient, specimen configuration, and the differences in the thermal-expansion coefficients of Normalloy and René 80. These factors could have caused inordinate shear stresses in the joint region, especially at the trailing edge, which resulted in bond failure. The specimen which was radius-ground very short had no cracks initiating at this joint because the tip material was thin enough to yield rather than produce high shear stresses at the joint.

It was concluded that the failure modes and test conditions present in the latter SETS test were unrepresentative of those observed in actual engine operation. These test results, although unfavorable, were not sufficient to prevent engine test evaluation of the advanced tip system.

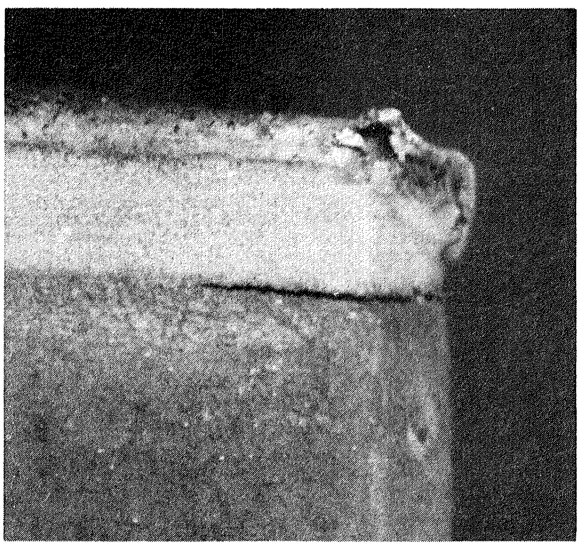
3.4.1.4 Oxidation Testing

Fully manufactured, monocrystal-tipped, abrasive-treated, CF6-50 HPT Stage 1 blades were currently being oxidation tested at 1095° C (2000° F) in air for 1000 hours. Three configurations were evaluated; one blade was abrasive coated, one had the abrasive removed to expose bare monocrystal, and one was standard René 80 blade for comparison. After 1000 hours of testing, minor Codep spallation on the monocrystal tip occurred; however, the superior oxidation resistance of the tip prevented further oxidation.

Weld-Repaired Tip Cracks, 8X



Monocrystal Tip with Abrasive, Trailing-Edge Joint Separation



13X

Monocrystal Tip without Abrasive, Trailing-Edge Joint Separation

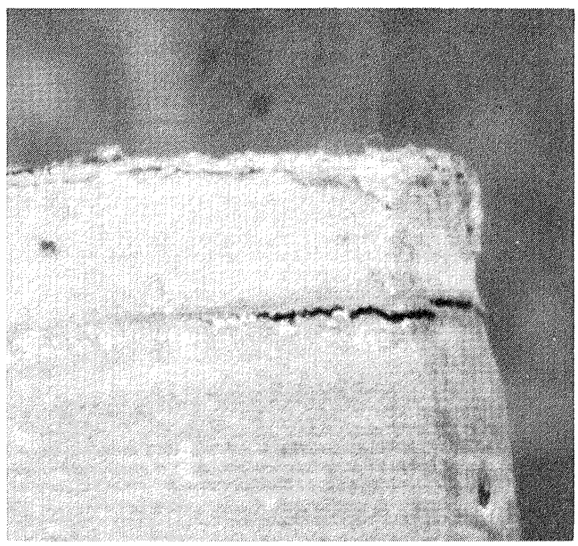


Figure 35. SETS Specimens After 500 Cycles.

3.4.1.5 Corrosion Testing

Fully manufactured blades, similar to those used in oxidation testing, were being corrosion tested at 927° C (1700° F) in 5 ppm salt. One fully coated blade, one blade with abrasive removed and monocrystal exposed, and one standard René 80 blade were tested. The results of these tests indicated that the salt corrosion atmosphere had no deleterious affects on the advanced turbine blade tip system as compared to the standard René 80 specimen.

3.4.2 Shroud Segments

Genaseal and CoNiCrAlY shrouds of engine quality were used to make the test specimens used in Solar rub testing. The shrouds had completed the required inspections for standard shroud manufacturing, according to General Electric Specification F50TF41-S2. The erosion requirements of that specification were as follows.

Filled and sintered parts were erosion tested and conformed to the weight-loss requirements specified on the applicable part drawing. If no limits were specified, the erosion weight loss did not exceed 0.3 kg/m^2 (0.2 g/in^2). Visual evidence of nonuniformly eroded areas exceeding 0.51 mm (0.02 in.) in depth were cause for rejection even though the weight loss was within the requirements.

3.4.3 Analysis of Component Test Results

The results of the component testing conducted in this task indicate that the advanced tip-seal system will have sufficient durability to achieve the goals of this project. The testing demonstrated the capability of the monocrystal abrasive tip system to abrade Genaseal and VPS CoNiCrAlY and to withstand the rigors of severe rub and FOD conditions. Although the recent thermal-shock (SETS) results on the monocrystal material were inconclusive, strength, modulus, and SETS data indicated that a 2X improvement in crack resistance could be achieved. The thermal shock (SETS) results of both actual finished blades and of wedge specimens proved inconclusive because of variations in specimen configurations and testing modes and conditions. However, strength and elastic modules data generated in Task II and SETS data generated prior to the start of the contract indicated that the monocrystal Normalloy could achieve the 2X improvement in crack resistance. Since the abrasive-tip system will, in service, undoubtedly rub heavily within the first 25 hours and be consumed, the oxidation and hot-corrosion properties (currently being generated) are expected to be adequate. Based upon the data generated in this task, combined with data generated in Tasks II and III, the advanced tip/seal system was judged safe for factory engine-test evaluation.

3.5 TASK V - QUALITY CONTROL PLAN

Throughout the manufacture of the environmental/abrasive-tipped turbine blades, quality control (QC) requirements for raw material and nonstandard, in-house and outside-vendor processing were established. The following QC plan was defined to assure the reproducibility and reliability of the finished blade with respect to all operations relating to the environmental-resistant/abrasive-tipped turbine blade.

3.5.1 Materials

3.5.1.1 Tip Materials

Vendor certification for the master heat of Normalloy was required, and supplemental confirmation was obtained by internal (General Electric) chemical analysis. Each monocrystal cast bar produced was analyzed for lanthanum content and crystallographic orientation.

3.5.1.2 Bonding Alloy

The ADB alloy foil (D15) was purchased to a General Electric specification for bonding foils.

3.5.1.3 Blade Castings

The blades were cast to the current CF6-50 Stage 1 HPT blade production configuration. The blade alloy was René 80 and conformed to General Electric specification for cast, nickel-base superalloy components.

3.5.2 Processes

3.5.2.1 Tip Manufacture

Squealer tips were machined from monocrystal Normalloy bars furnished by General Electric. These tips were electrodischarge machined to the CF6-50 blade airfoil configuration by an outside source. Certificates of conformance were supplied.

3.5.2.2 Tip Grind

The blade tip grind-to-length operation was accomplished at the General Electric Aviation Service Overhaul Shop utilizing a modified blade-repair operation (Appendix A).

3.5.2.3 Dimensional Inspection

Each blade was measured for overall length, prior to tip bonding, in the fixture shown in Figure 36. Dimensions were recorded on the blade bonding record sheet (Figure 37). The actual measuring procedures are discussed under Task VI.

3.5.2.4 Bonding Process

The blade/squealer bonding process (discussed in Section 3.6) was conducted in a cold-wall, high-vacuum furnace. The furnace instrumentation was certified to standards required for "P" (flight engine) quality parts. The temperature was strip chart recorded (two thermocouples) for each bonding cycle (12 blades/run).

3.5.2.5 Joint Quality

After bonding, the blade lengths were redimensioned in the measuring fixture and recorded on the blade bonding sheet (Figures 34 and 35). The initial readings were subtracted from the as-bonded measurements, and a maximum of +63.5 μm (0.0025 inch) was allowed on any reading. A "standard" blade was measured after each 10 blades dimensioned in order to verify fixture reproducibility. The bond line was also 100% visually inspected in white light at 30X magnification; no voids in the fillet were allowed.

3.5.2.6 Finishing Operations

Excess stock on the outside contour of the tip was removed by belt grinding following EDM of the tip-cap cavity. Outside-contour benching, a standard blade operation, was performed by the General Electric Aviation Service Shop.

Prior to application of the abrasive treatment, the blades were radius-ground to final rotor dimensions (Appendix B) at an outside machining source. A certification of compliance (Appendix C) was required from the vendor to assure that proper procedures had been followed.

3.5.2.7 Abrasive Tip Treatment

The abrasives were applied to the blade in accordance with General Electric specifications for abrasive tip treatments and Drawing 9218M91G10EAD (Appendix D). A vendor compliance certificate was required (Appendix E). The blades were 10X visually inspected after abrasive coating and then heat treated at General Electric per specification for abrasive tip treatment.

All remaining blade operations were standard shop operations and conformed to standard blade-manufacturing procedures.

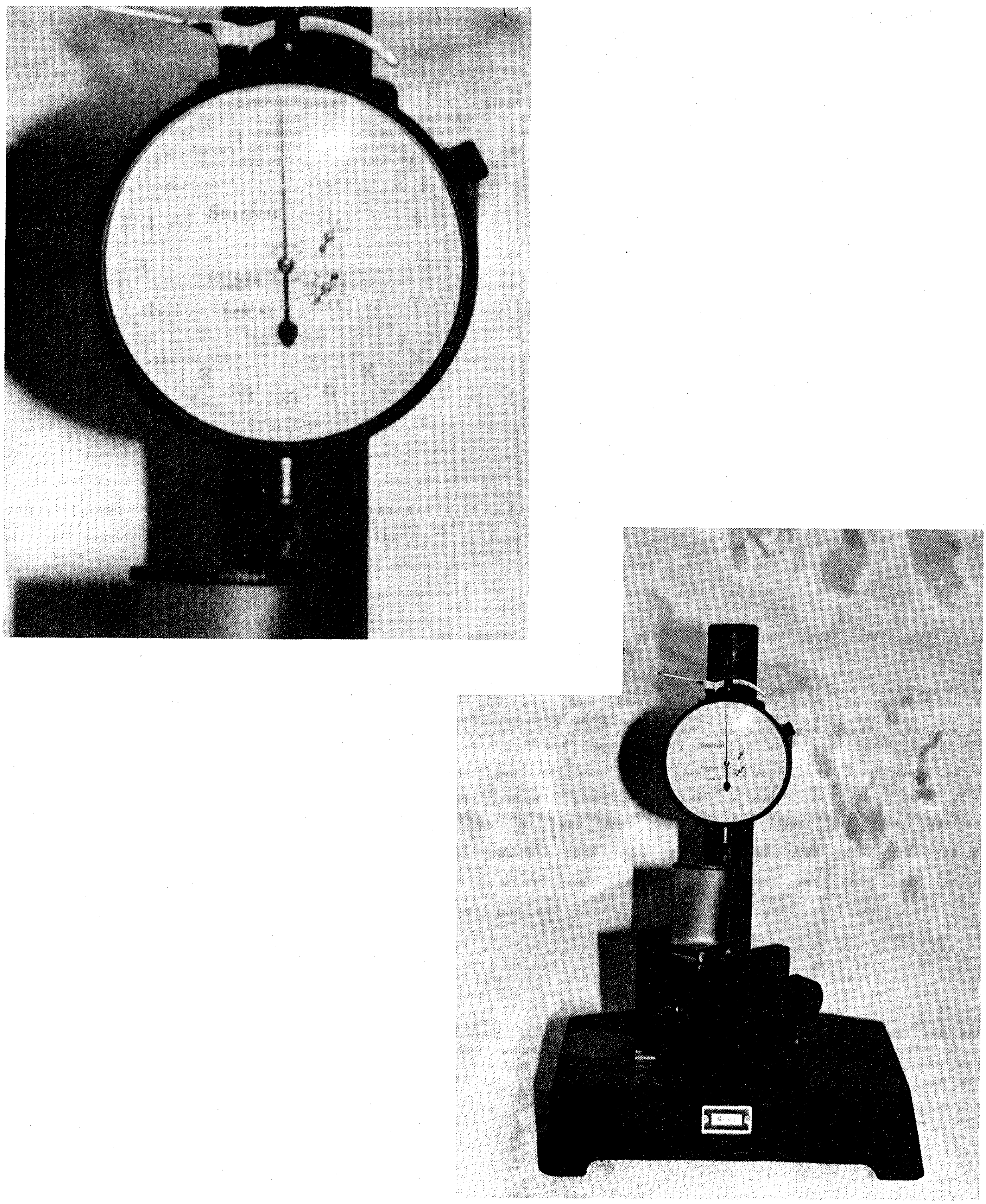
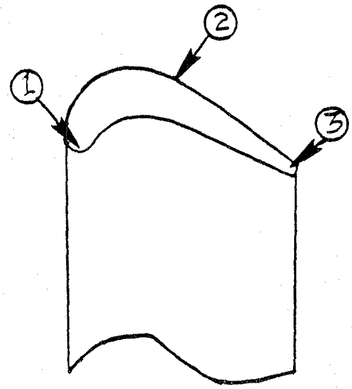


Figure 36. Fixture for Measuring ADB Joint Thickness.



ENGINE ____________

DATE ____________

S/N ____________

BEFORE BRAZE

1. ________

2. ________

3. ________

AFTER BRAZE

1. ________

2. ________

3. ________

BOND THICKNESS

1. ________

2. ________

3. ________

OPERATOR: ________________

Figure 37. Blade Bonding Record Sheet.

3.6 TASK VI - MANUFACTURING PROCESS PLAN

3.6.1 Procedure

The integrated manufacturing process sequence for producing monocrystal-tipped and abrasive-treated blades for MATE Project 3 is shown in Figure 38.

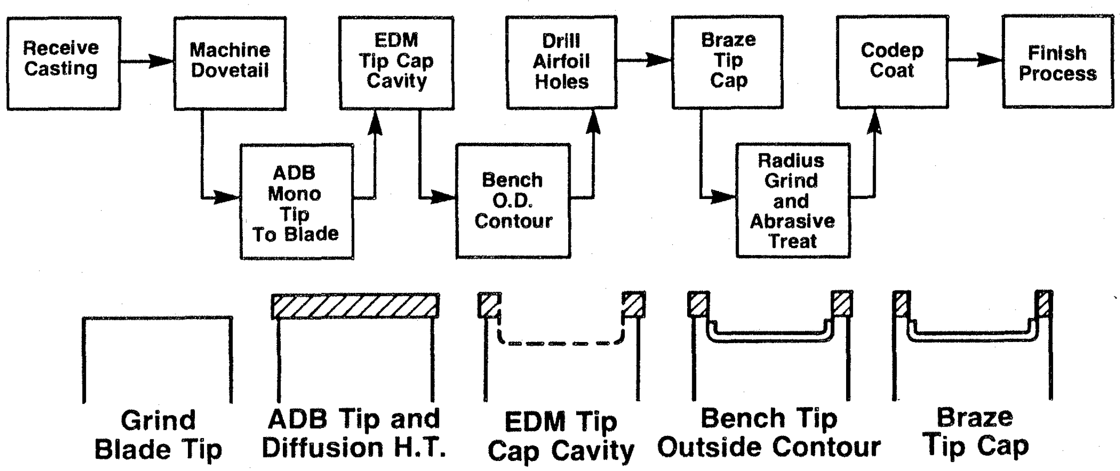


Figure 38. Manufacturing Process Sequence for Advanced Blade-Tip System.

As noted in this plan, the blades were removed from the standard manufacturing cycle on three occasions. Initial removal was after the dovetail-grind operation. At that time the blades were ground to length, the monocrystal tip was bonded to the blade, and the blade was returned to the shop for EDM of the tip-cap cavity. After the EDM operation, the blades were again removed from the normal blade-manufacturing cycle, and the excess tip on the outside wall was polished to within 25.4 μm (0.001 inch) of the finished outside-wall contour. (The tip overhang was removed at this stage of manufacture to prevent interference with the existing manufacturing tooling in subsequent hole-drilling operations.) Figures 39, 40, and 41 show the blade in various stages of the manufacturing process.

The blades were reintroduced into the normal blade-manufactruring cycle through tip-cap braze, laser hole drilling (at nose and tip), and inspection. The blades were again removed, radius-ground to rotor dimensions, abrasive treated, heat treated, and returned to the manufacturing cycle for the balance of the normal operations. All standard inspection criteria required for flight-engine hardware were performed on these blades. A finished-processed blade is shown in Figure 42.

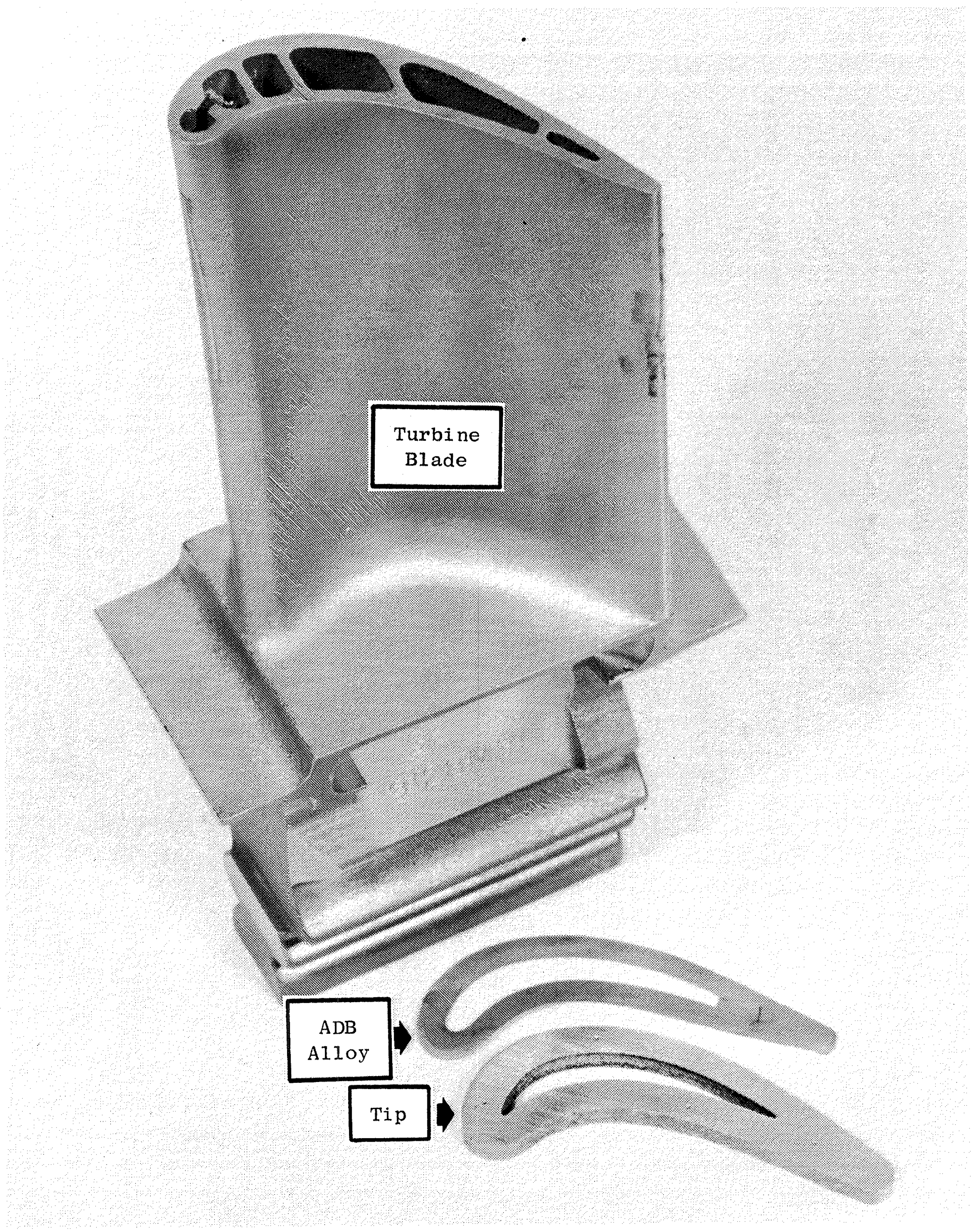


Figure 39. Monocrystal Tip, ADB Alloy, and Turbine Blade Prior to Assembly.

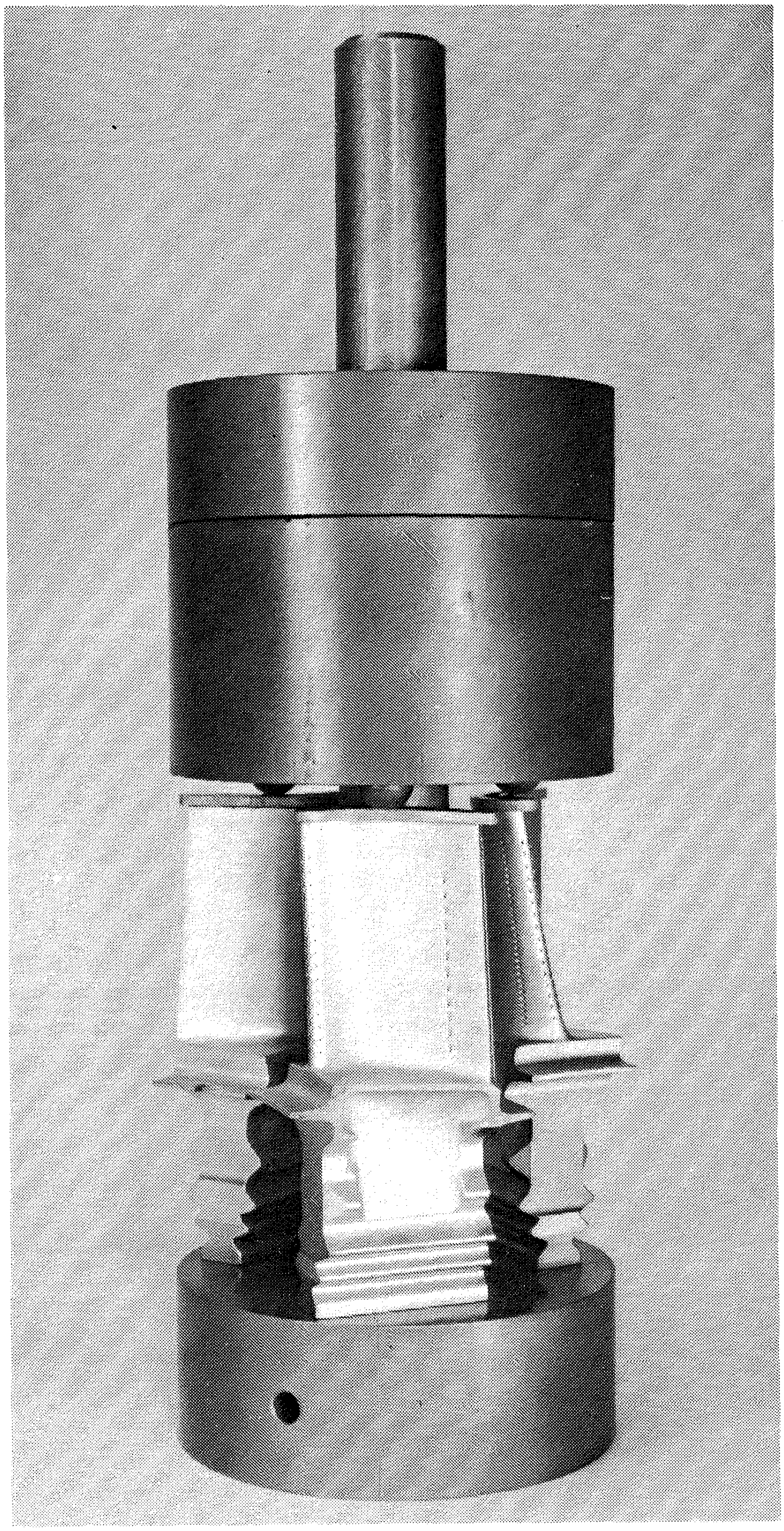


Figure 40. Blade/Tip Assembly in Bonding Fixture Proir to Furnace Bonding.

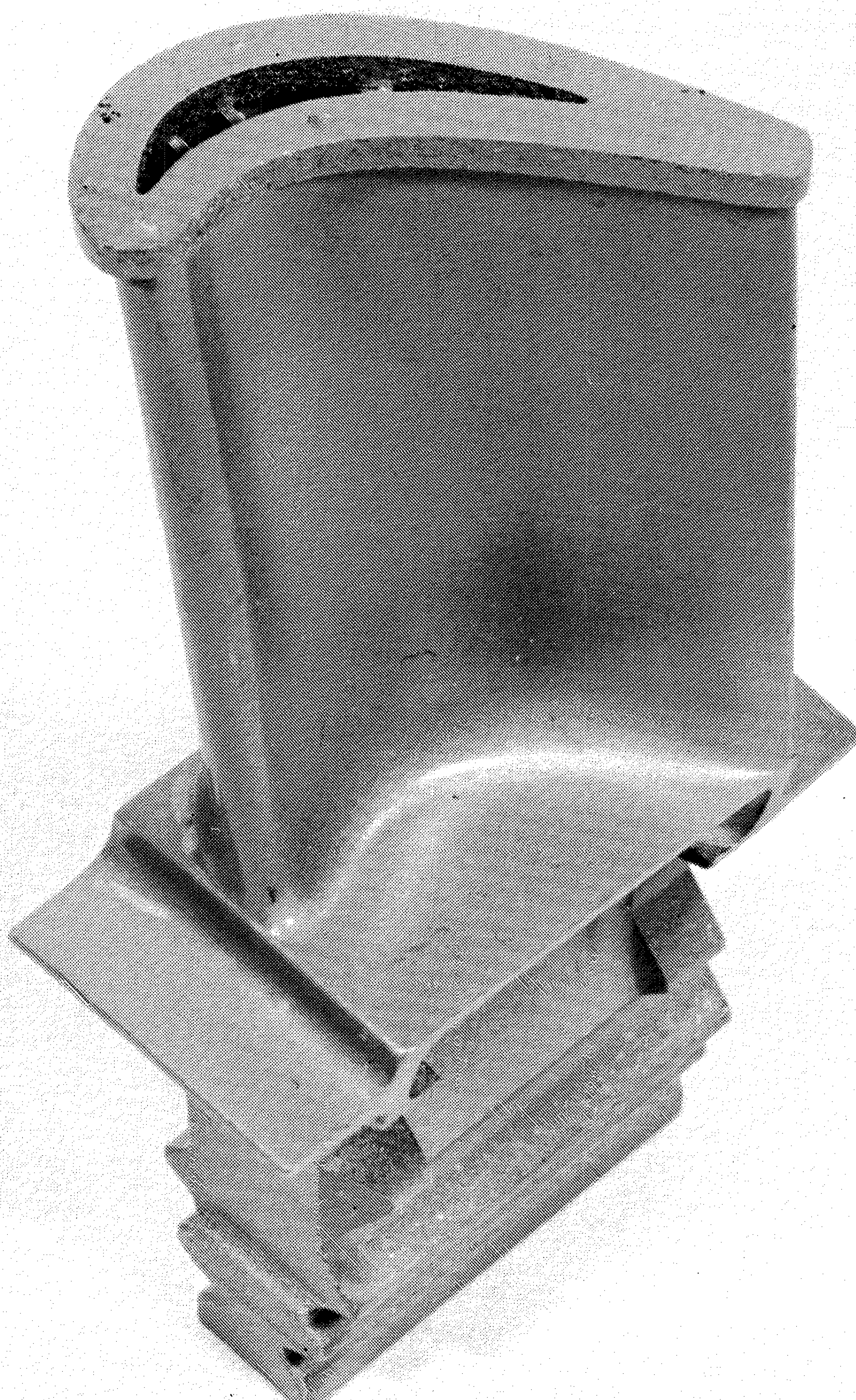


Figure 41. Blade/Tip Assembly after Bonding.

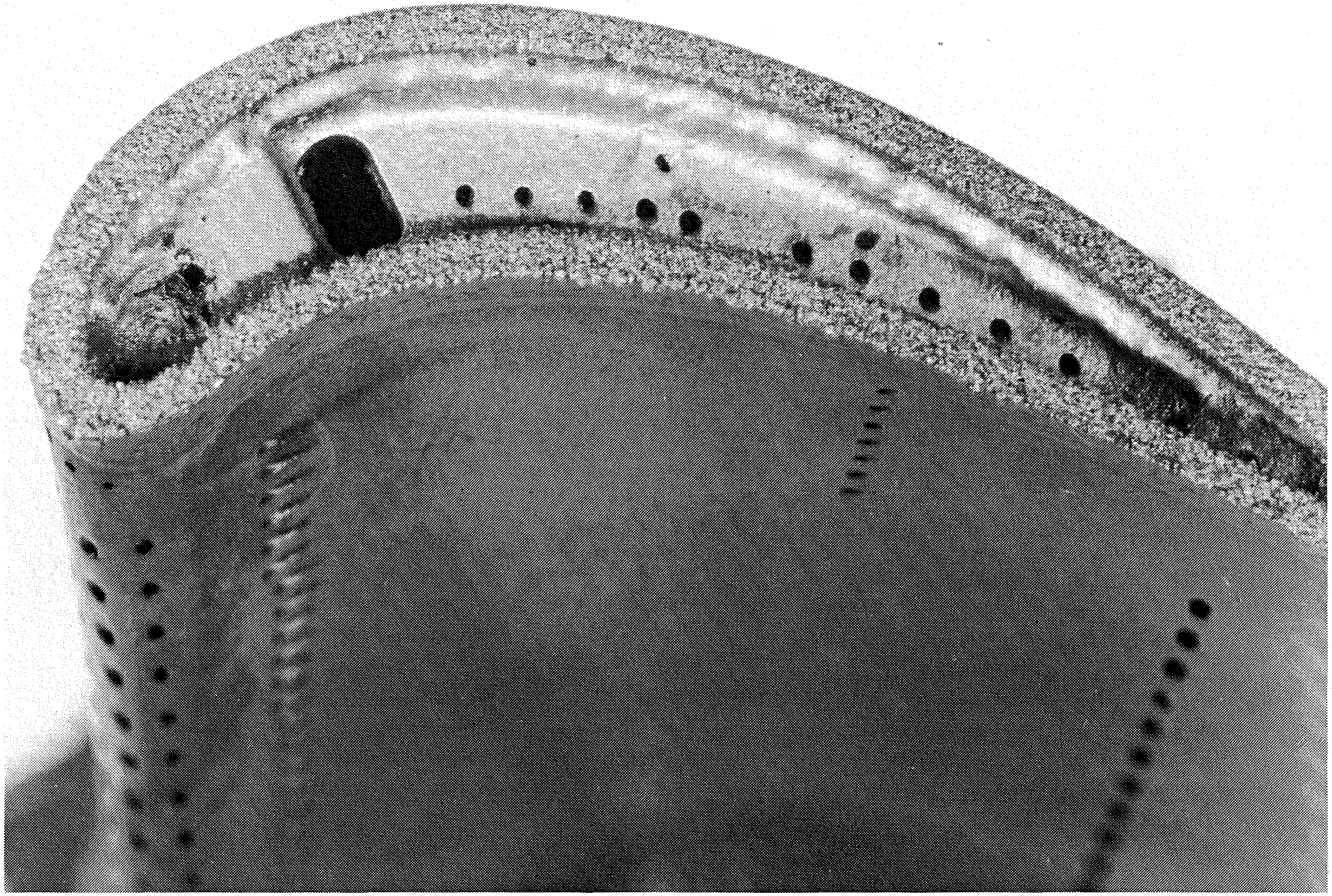


Figure 42. Fully Processed Turbine Blade with Advanced Tip System.

Appendix F contains a detailed description of each tip-related processing operation including dimensions, temperatures, processing limits, etc. All standard blade-manufacturing operations are listed on the routing cards in Appendix G.

3.6.1.1 Monocrystal Tip

Squealer tips were electrodischarge machined from monocrystal slices (Figure 43) with known crystollographic orientation to the contour indicated in Drawings 4013245-208 and 4013238-985G01 (Appendices H and I).

The ADB alloy D15, in the form of 76.2 μm (0.003 inch) boronized foil, was mechanically stamped to the tip configuration and cleaned in solvent prior to use.

3.6.1.2 Abrasive Treatment

The abrasive treatment was applied, by the AMPLEX Corporation, to the blade tips in the radius-ground condition immediately prior to Codep coating. The abrasive-tip treatment is a proprietary process of the AMPLEX Corporation.

3.6.2 Confirmation

Reliability and reproducibility of the blade-tip abrasive treatment was accomplished through component-test evaluation of completed hardware as described under Task IV. Testing of Genaseal, Bradelloy, and CoNiCrAlY shroud specimens was accomplished in Tasks III and IV.

3.6.3 Manufacturing Costs

The recommended advanced turbine blade tip-seal system includes both the environmental/abrasive tip and a compatible shroud material. The testing in this project defined the blade tip to be composed of an ADB monocrystal superalloy with an electroplate-encapsulated abrasive treatment. This shroud system was defined as either Genaseal (sintered NiCrAlY powder) or vacuum plasma sprayed CoNiCrAlY. Both were shown to be abradable with the abrasive-tip system. However, since the most current and advanced engine designs include VPS CoNiCrAlY shrouds, manufacturing cost estimates were based on that system.

The manufacturing process plan that was established in this project was designed to be closely compatible with the standard CF6-50 HPT blade manufacture procedures; therefore, none of the standard operations was modified. Also, some of the operations associated with this advanced tip system (such as rough tip grind and radius grind) were already integral parts of the standard blade manufacturing although not normally conducted at the same time as necessary for the tip application.

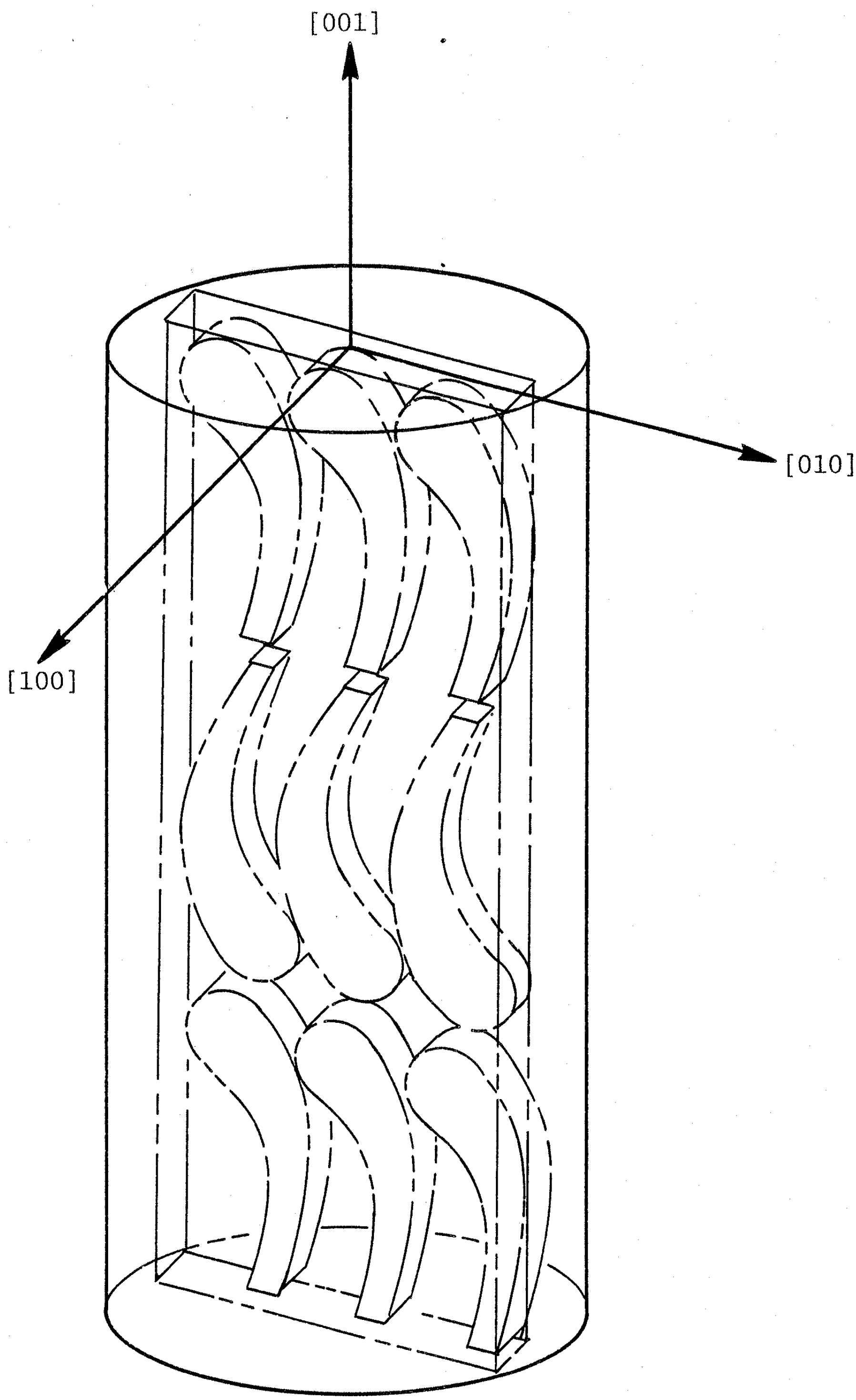


Figure 43. Method of Tip Removal from Monocrystal Bar Castings.

The only added operations to the blade processing were tip bonding and inspection, polishing at the outside contour of the tip, and the abrasive-tip application. Moreover, the tip bonding could conceivably be accomplished during solution heat treatment. The only added materials were the monocrystal tip and the ADB alloy foil preform.

Estimated manufacturing costs of this system were established based on the following assumptions:

1. The monocrystal material would be cast in airfoil shapes and sliced to the desired thickness.

2. The blade-tip design would either be like that of the CF6-50 or be a cast-in tip-cap design.

3. The blade tips would be fixture radius-ground prior to abrasive-tip treatment.

4. The abrasive treatment would be applied through an outside vendor.

5. The shroud material would be VPS CoNiCrAlY.

6. The blade alloy would be conventionally cast René 80.

Based on these assumptions, it is estimated that the bonded tip would increase the blade manufacturing cost by about 11%; the abrasive treatment would add about 3% for a total estimated blade cost increase of around 14%. However, the effect on the entire tip/seal system, including the cost of the shrouds, is only about 10% or 1.1 times that of the current system. The goal of this project was to achieve a system cost of not more than 1.2 times that of the current system.

3.7 TASK VII - SEAL SYSTEM MANUFACTURE AND COMPONENT TEST

3.7.1 Manufacture

A total of 180 CF6-50 Stage 1 HPT blade castings, of which 120 were of the standard configuration and 60 were an advanced C_2E_2 design, were procured from the airfoil manufacturing shop. As discussed under Task I, the tip design was such that all standard manufacturing operations could be performed with minimum modification. The tip-bonding and abrasive-application operations, however, required that blades be temporarily removed from the manufacturing line. Task VI and Appendix F describe the details of the manufacturing process plan required to fabricate the blades. A total of 101 fully manufactured, engine-quality blades (Figure 44) were produced in this effort. A 73% yield of engine-quality blades was realized for the standard MATE 3 blades; this was somewhat higher than expected. No blades were rejected as the direct result of the presence of the monocrystal tip. The yield of the C_2E_2 blade with

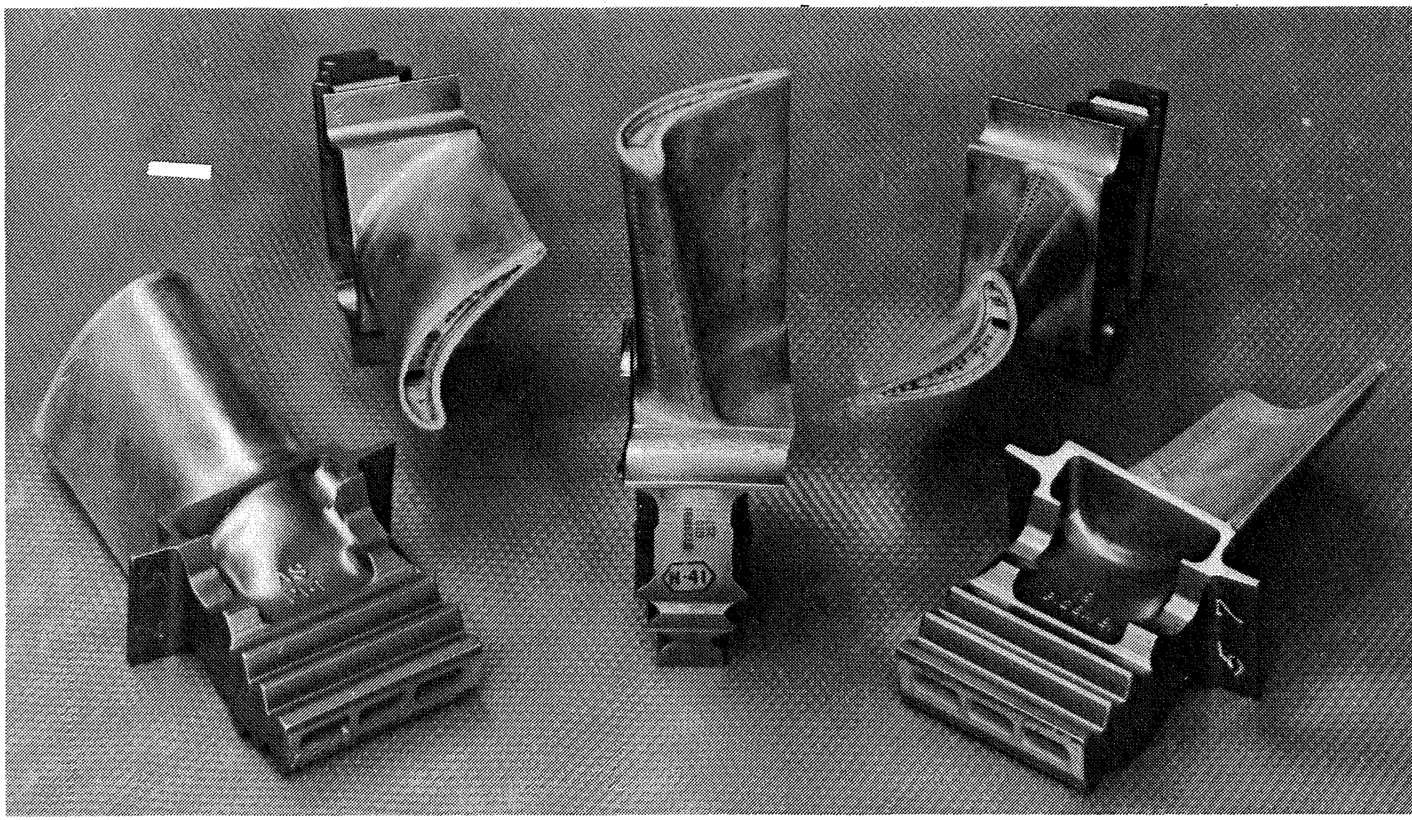


Figure 42. Fully Processed CF6-50 Stage 1 HPT Blades with the Advanced Tip-Seal System.
44.

the advanced tip system, however, was only 37% because usually high rejections occurred as the result of a nonstandard EDM tip-cavity operation. (This advanced C_2E_2 blade is not yet in full production and, as such, select operations are still being done in the development laboratory and are more prone to error). Excluding the EDM rejections, the yield of the C_2E_2 blades would have been at least 70%. All blades were fully processed regardless of status; most were used for component tests in Task IV, metallographic examinations, and display samples.

Two complete engine sets of both Bradelloy and Genaseal shrouds were obtained and were made available for engine testing.

3.7.2 Verification

The selected system proved to be compatible with normal airfoil shop operations. As noted on the manufacturing routing (DO) cards discussed in Task VI, the blades were removed and reinserted in the normal blade-manufacturing flow with a minimum of interruption. Only two blades of the 171 bonded had tips which failed the ADB joint quality criteria. The yield of engine-quality blades verified that the tip treatment had no influence on normal airfoil shop operations.

High-speed, high-temperature rub tests and ballistic impact testing conducted in Task IV verified the reliability of the advanced tip system.

3.7.3 Engine-Test Components

From the manufactured hardware for MATE 3, 20 monocrystal-tipped abrasive-treated blades were selected for 1000 "C" cycle endurance testing. These blades are shown in Figure 45 installed in the rotor prior to engine assembly. Bradelloy and CoNiCrAlY shrouds were also made available for the endurance test. Eighty monocrystal-tipped, abrasive-treated blades were selected for performance engine testing.

3.8 TASK VIII - ENGINE TESTING

A total of 101 fully manufactured CF6-50 Stage 1 HPT blades with the advanced tip system were produced in this effort. Twenty blades were selected for 1000 "C" cycle endurance testing and 80 blades for performance testing. The details of the engine tests are classified as Category 2 FEDD data and will be reported in the MATE 3, Volume II report.

3.9 TASK IX - POSTTEST ANALYSIS

The results of the posttest analyses of the endurance and performance engine tests of the advanced tip-seal system are classified as Category 2 FEDD data. The analyses are to be reported in the MATE 3, Volume II report.

Figure 43. Turbine Blades, with the Advanced Tip System, Assembled into the Rotor.
45.

4.0 CONCLUSIONS

Mechanical and physical properties of the tip alloy and the bond joint were conducted at conditions that closely simulate those during actual engine operation.

The abrasive tip treatment was evaluated through elevated-temperature, high-speed wear testing into both current and advanced engine shroud materials. Both aluminum oxide and cubic boron nitride (Borazon) particles in varying sizes were wear tested into Bradelloy, Genaseal, and VPS CoNiCrAlY to define a suitable tip/shroud system. Component testing (that is, thermal shock, ballistic impact, oxidation, and hot corrosion) of fully manufactured blades was also conducted. Two engine tests, one endurance and one performance, were run to demonstrate the payoff of the advanced tip-seal system.

The results of the physical- and mechanical-property testing of the tip material and ADB joints, the high-speed/high-temperature abrasive wear testing, and component testing were considered fully adequate to release hardware for engine-test evaluation. The results of the engine testing will be reported in the MATE 3 Volume II report.

Based on the results generated in this project, the following conclusions were reached:

1. All standard mechanical properties that were generated on both the tip material and the tip-to-blade bond joint met or exceeded engine requirements.

2. The environmental resistance of the tip alloy met the project goals (2X René 80).

3. The blade-tip design and manufacturing sequence that was established facilitated manufacture and assured process reproducibility.

4. The bonding process (that is, activated diffusion bonding) proved to be extremely reliable with $<1\%$ rejection rate.

5. Al_2O_3 abrasive particles attached via electroplated Ni and Cr were considered to be the best all-around abrasive tip system.

6. The Al_2O_3 abrasive tip treatment was capable of abrading both Genaseal and VPS CoNiCrAlY.

7. The Al_2O_3 abrasive tip treatment does not significantly abrade Bradelloy.

8. Borazon type 500 abraded new Bradelloy and was marginally successful in abrading oxidized Bradelloy.

9. Slight changes in particle size only slightly affect abrasive-system abradability.

10. Fast incursion rates, that is, 50.8 - 101.6 μm/sec (0.002 - 0.004 inch/sec), produce better rub characteristics than slow incursion rates, <25.4 μm/sec (0.001 inch/sec).

5.0 RECOMMENDATIONS

The NASA MATE 3 Project was structured toward the demonstration (engine test) of an advanced tip-seal system and was designed to be a precursor for a manufacturing technology scale-up program. As such, the blades that were manufactured for component testing and engine testing were made from standard, production castings and were bonded and machined using temporary fixturing and tooling. The monocrystal Normalloy tips were machined from 3.2 cm (1-1/4 inch) diameter bars rather than sliced from airfoil-shaped castings. The abrasive tip treatment was applied at an outside vendor that was facilitated to run only small "batches" of blades rather than high-volume quantities; nevertheless, the blades were manufactured with a minimum of problems and were delivered to engine assembly on time.

Assuming the planned engine tests provide sufficient data such that desirable life and efficiency payoffs can be realized, the next logical direction for this technology is a process scale-up program. However, to effectively transition this technology from laboratory status to full-scale manufacture, several improvements to the process would be required. The following recommendations should be considered when scaling-up this technology:

1. The blade casting should be designed to facilitate ease of manufacture, reproducibility, and reliability (such as, cast-in tip cap and excess airfoil stock at the tip).

2. The blade must be designed such that, in the event of joint failure, the tip cap and, consequently, blade cooling would remain unaffected (again, the cast-in tip cap is the ideal configuration).

3. A reliable, inexpensive, nondestructive-evaluation technique for bond-joint quality should be established.

4. Low-cost techniques for the monocrystal-tip manufacture should be developed.

5. Low-cost/high-volume techniques for fixturing the parts in the ADB process should be developed.

6. A longer life abrasive matrix should be developed in the event that a nonrub condition exists.

7. Recently developed "superabrasives" should be investigated.

8. The abrasive tip system should, if possible, be used only with oxidation-resistant shroud materials.

9. Blade radii should be fixture-ground (versus rotor-ground) to a set dimension. Fixture grinding eliminates the logistics problems and assures consistent part-to-part radius dimensions.

A Navy/Air Force-sponsored follow-on Manufacturing Technology Program has recently been awarded and is addressing most of the factors discussed above.

APPENDIX A - TIP-GRIND INSTRUCTIONS

MANUFACTURING ENGINEERING INSTRUCTIONS

E.I. No. : 681
Part No. : 9128M91
Part Name: CF6/50 Stg 1 Blades
Total Qty: 56
Customer : Norm Fairbanks X4511
Order No.: -

W.O. #: 20105
Estimate Hrs. : -
Engineering Req'd Date: 11/1/79
Production Commit Date: - 11-14-79
Funding: External

Description: Grind Tip Length

Where in Processing Sequence:

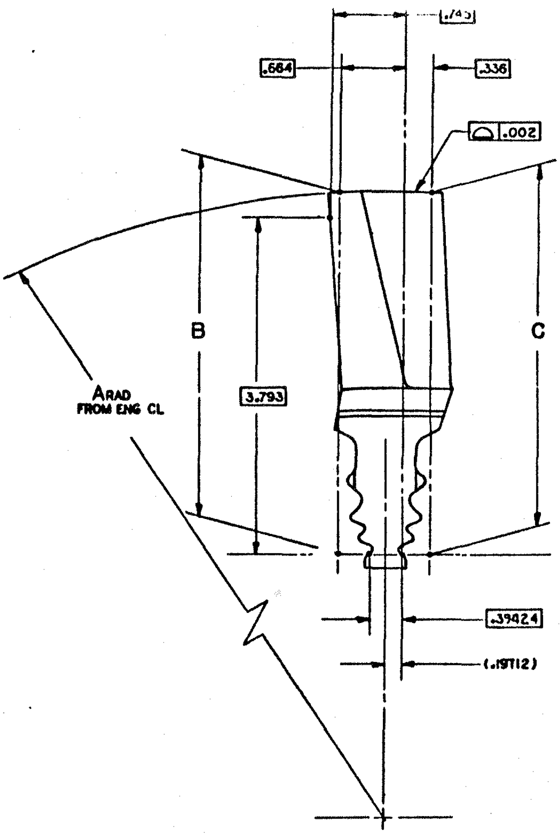
ITEM	INSTRUCTIONS	PROD. SCHED.	OPER	DATE
1	Grind Tip Length	Comp.	L Marcum 11/21/79	
	Dimension is 3.849 ± .005; flatness to be within .0005".			
	Use Oper. 097 except set dial indicator to zero with set master. The dimension for these blades will then read -.077 ± .005.			
	The last .010" of stock must not be removed at more than .0005" per complete pass.			

Prep. By: L.A. Marcum Function: M.E. Date: 10/24/79

"APPROVALS"

Manufacturing: [illegible] Date: 10/24/79
Engineering: [illegible] Date: [illegible]
Quality Control: [illegible] Date: 10/25/79
Production Control: [illegible] Date: [illegible]

APPENDIX B - DIMENSIONS FOR FINAL GRINDING



PART IDENTIFICATION NUMBEP	A BASIC (C8)	B BASIC (C7)	C BASIC (C6)
4013241-653P01	16.585	4.021	4.019
P02	16.590	4.026	4.024

DWG TYPE WORKING LAYOUT

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

ALL SURFACES 63/

MATL

FOR GE USE ONLY

SIMILAR TO —

L/O —

OR GL

CONTRACT

SIGNATURES	YR MO DA
RICK CAUDILL	79-2-7
C.Y. OVERBECK	79-2-12
JIM HADDER	79-2-13
D. CARTRIGHT	79-2-20
—	—
RAY WISBEY	79-2-20

GENERAL ELECTRIC
AIRCRAFT ENGINE GROUP CINCINNATI, OHIO U.S.A.

BLADE — STAGE 1

SIZE D | FSCM NO 07482 | DWG NO 4013241-653

SCALE 2/1 | WT | SHEET

WALBAR

Walbar, Inc.
Peabody Industrial Center
Peabody, Massachusetts 01960
(617) 532-2700

Boston
Phoenix
Toronto
West Palm Beach

CERTIFICATE OF COMPLIANCE

CONFORMANCE OF PARTS TO THE DRAWING AND PERFORMANCE OF SPECIAL PROCESSES TO APPLICABLE SPECIFICATIONS.

"This is to certify that 77 pieces of BLADES shipped to you (date) 2-23-81 on your order 457-17A10104 were manufactured to the best of our knowledge and belief, to the complete requirements of Drawing No. 4013241-653 P02 Change Letter ________ Change No. ________. It is also certified that all special processes, as defined in Government Specification MIL-Q-9858 which were performed by us and/or our subcontractors were accomplished on approved equipment and by approved personnel, in accordance with the applicable customer Specification. Evidence of such approval is on file in our plant and is kept up-to-date."

Material records by serial number or other positive means covering these parts are on file subject to examination and indicates conformance with applicable specification requirements.

SIGNED [signature]
Chief Inspector

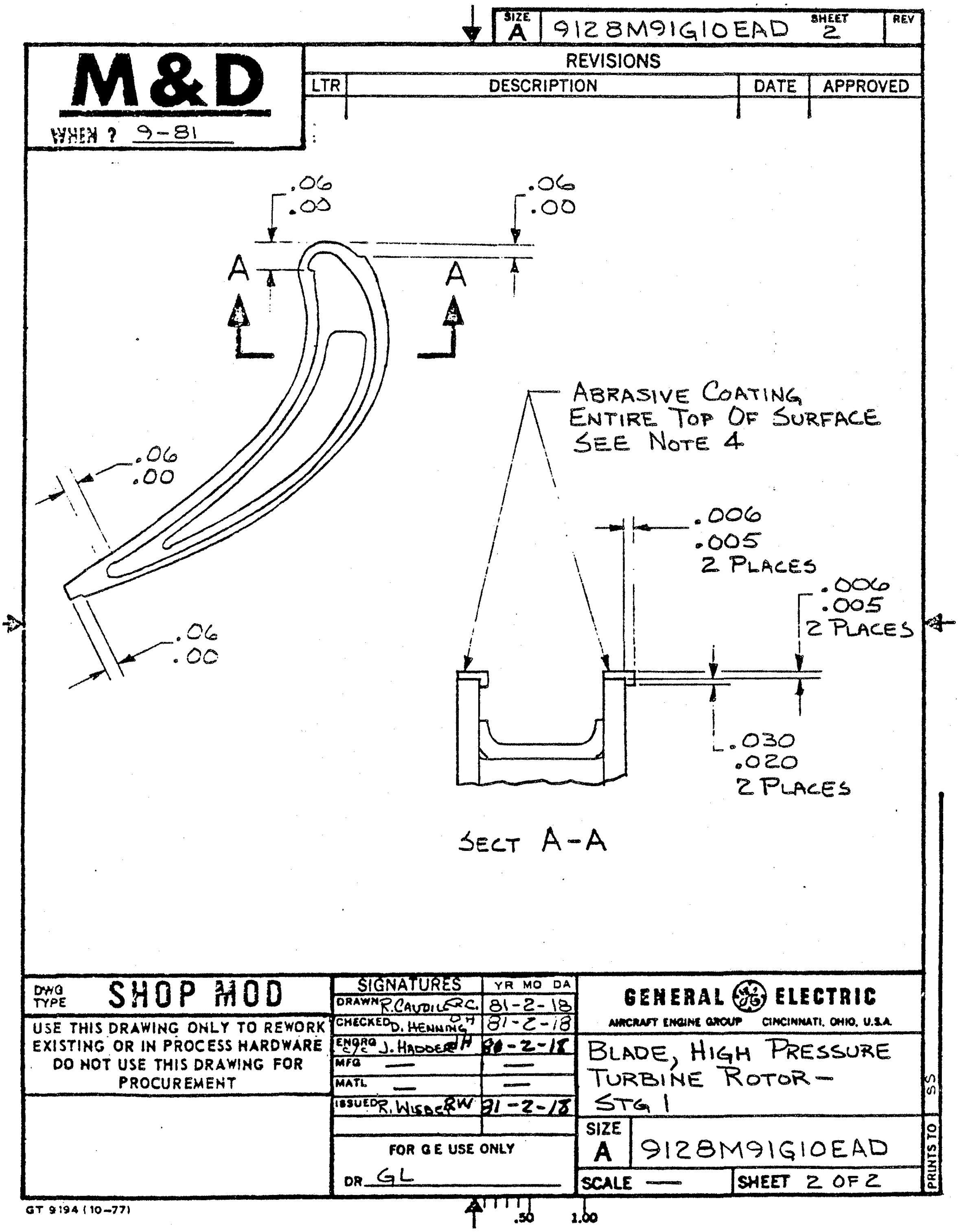
P/S 16516

PROCESS PER RFMK 246108
GRIND BLADES TO LENGHTS
SPECIFIED ON DWG. 4013241-653-P02

PARTS HAND CARRIED BY
G.E. REP

WAL-79-1 PRECISION MACHINING FOR MODERN INDUSTRY

APPENDIX D - SHOP MODIFICATION FOR ABRASIVE-TIP APPLICATION



APPENDIX E - CERTIFICATE OF COMPLIANCE FOR ABRASIVE-TIP TREATMENT

AMPLEX CORP (Abrasive Coating Division)

Work done for: G.E. (Aircraft Engine Group)

WORK & INSPECTION SHEET FOR HIGH PRESSURE TURBINE BLADES

Date Started 2-24-81 Date Finished 3-13-81

Lot# 37 Type of Blade HOLE 3

Stage —— Other 200-452-17A10105

PROCESS

WARNING: No changes in this process, or alteration of any document is permitted, unless written permission has been obtained from the G.E. (A.E.G.), and the Plant Manager and the Director of R&D of the Amplex Corp.

Performed by (Initials)

1) Abrasive treatment (per instructions on T38X) - Date 3/13/81 By N.P.W.

2) Surface treatment (per instructions on STHPTB-78) - Date 3/13/81 By N.P.W.

3) Abrasive Tacked (per instructions on AIT-78) - Date 3/13/81 By N.P.W.

4) Abrasive Anchored (per instructions on AIA-78) - Date 3/13/81 By N.P.W.

5) Chromium Flash (per instructions on AlCrF-78) - Date 3-13-81 By RS

6) Heat Treatment (350°F/½ hour) - Date 3-13-81 By RS
(per instructions on Heat Treatment of Nickel, Abrasive and Chromium coated surfaces-78)

7) H_2O (at~5PSI) - Date 3-13-81 By RS
(must be run through blades I.D.s, to assure all holes are open, plus subsequent Acetone Rinse).

INSPECTION OF THE MATRIX

1) Mechanical Inspection - Date 31381 By RK
(measurements)

2) Hole Inspection - Date 31381 By RK.
(Holes must be free of obstructions)

3) Visual Inspection - Date 3-13-81 By RS
(appearance)

4) Microscopic Inspection - Date 3-13-81 By RS
(uniformity)

5) Packed - Date 3-13-81 By RS

Ship to the attention of NORMAN FAIRBANKS

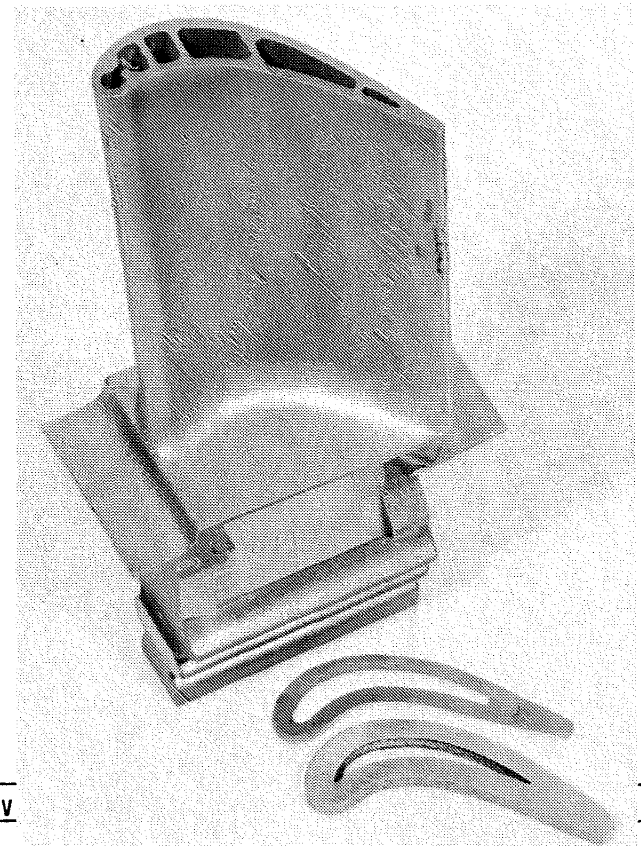
Bldg.# — Mail Drop# —

G E (Aircraft Group) - Evendale, OH 45215

DWG. NO. 4013245-208

PART NAME ______ GROUP ______

OPER. NO SP-1B OPER. Prepare Tip Squealers for Bonding MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST	SKETCH
1. Identify tip on unbond surface at T.E.		
2. Place tips, surface to be bonded up, on tungsten or Molybdnum flat plate, 1 layer deep, and load into vacuum furnace *		
3. Evacuate furnace to 1 + 10^{-4} torr - 30 μ/hr. ~~heat~~ leak rate, and heat to 2200°F for 1 hr., cool to room temperature		
4. Vapor hone surfaces to be bonded using the following conditions. 80# in^2 air pressure and 1250 grit novacite media. Clean parts after vapor honing in flowing water before the media dries on surfaces.		
5. Use within 10 days after cleaning.		
* Note: If tips are sliced from airfoil shaped mono casting, casting can be heat treated prior to tip removal, negating opr 2 & 3		REV

Foreman's Approval ______ Section Leader ______ Methods Planner ______

Prepared by: ______ O.C.E. ______

DWG. NO. ______

PART NAME ______ GROUP ______

OPER. NO SP-1B OPER. Prepare Blades for Bonding MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST	SKETCH
1. Be sure ground tip surfaces are free from grinding burrs.		
2. Immerse in Acetone and agitate to remove grinding grit.		
3. Immerse in Acetone and ultrasonically clean to complete grit removal. Position vertically		
4. Place in vacuum furnace, ~~air cool~~ EVACUATE to 1 X 10^{-4} torr, heat to 2200°F (R'80) Hold 2 hours, cool to room temperature.		
5. Vapor hone bond surface, using the following conditions FC # in^2 air pressure, and 1250 grit Novacite media. Flush with water before media can dry. When completely flushed, dry in filtered air stream.		
6. Must be used within 10 days after cleaning.		

REV.	DATE	REV.	DATE	REV.	DATE

Foreman's Approval ______ Section Leader ______ Methods Planner ______

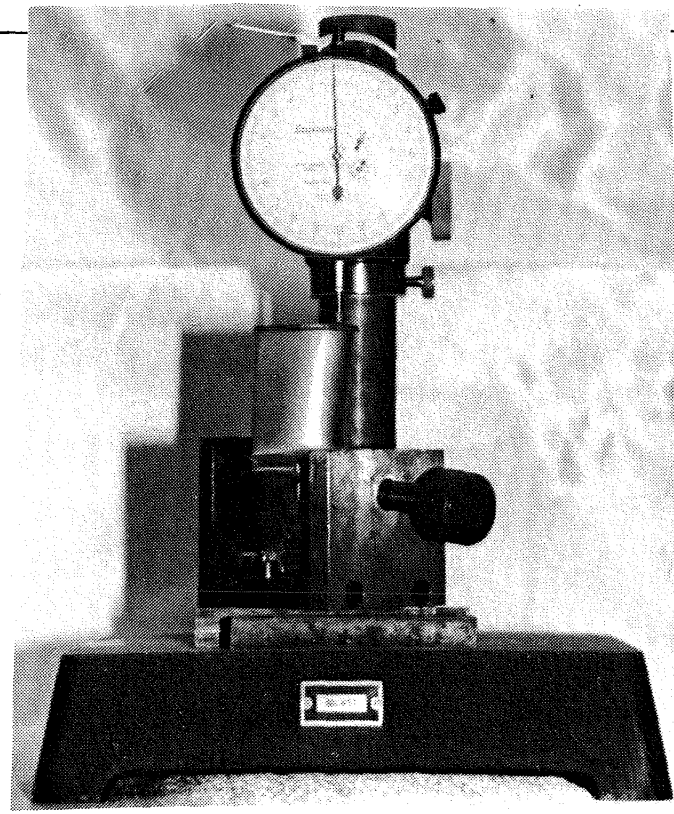
Prepared by: ______ O.C.E. ______

DWG. NO. ______

PART NAME ______ GROUP ______

OPER. NO SP-1B OPER. Measure Blade and Tip Prior to Bonding MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST
1. Obtain measuring fixture and take three point readings with "standard" blade in fixture	
2. Adjust if needed until each reading agrees with "standard" readings.	
3. Place blade in fixture, taking care to assure proper seating. Place tip on blade and center	
4. Record all three readings on sheet in the before bonding column	
5. Record blade number and tip number on sheet	
6. Put blade and tip at bench spot welder until enough have been accumulated ~~from~~ FOR a furnace run	
7. Take 3 point readings with "standard" blade after each 10 blades. If readings vary more than .0002" from first readings, reset and remeasure all blades and tips.	



REV.	DATE	REV.	DATE	REV.	DATE

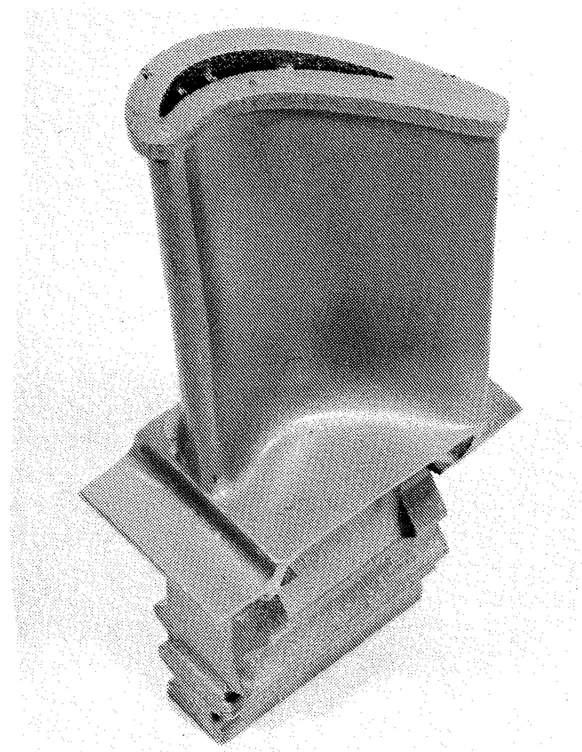
Foreman's Approval ______ Section Leader ______ Methods Planner ______

Prepared by: ______ O.C.E. ______

DWG. NO. ______

PART NAME ______ GROUP ______

OPER. NO SP-1C OPER. Assemble Blade Braze Alloy Sheet and Tip for Bonding MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST	SKETCH
1. Acetone clean the surfaces of the blade and tip which are to be bonded.		
2. Acetone clean both sides of the brazing alloy preform. (D15 boronized foil .003" thickness)		
3. Center preform on blade and "lightly" tack weld to the blade. Keep fingers off bond surface		
4. Center tip on blade and tack with sufficient current to hold the tip in place. Take care not to tack at points where fixture will measure		
5. Place in bonding fixture, center 1/8" tungsten spacer on tip. Locate the 3 fixtures in the proper position to receive partial ball on fixture weight. Add additional weights to assure a minimum of 15 psi on tips.		

REV.	DATE	REV.	DATE	REV.	DATE

Foreman's Approval ______ Section Leader ______ Methods Planner ______

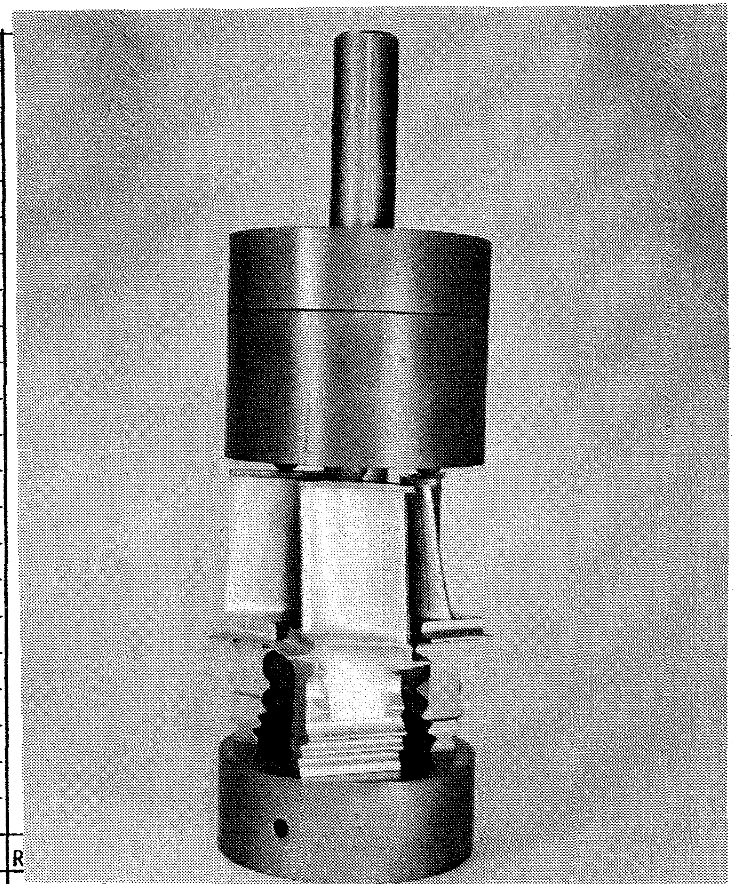
Prepared by: ______ O.C.E. ______

DWG. NO. ______

PART NAME ______ GROUP ______

OPER. NO SP 1-C OPER. Furnace Bond Tips to Blades MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST
1. Load fixtures into a vacuum furnace and evacuate to 1 X 10^{-4} Torr. After outgasing and prior to initiation of braze cycle. Leak rate 30 µ/hr. max. Vacuum must never exceed $1\text{-}10^{-3}$ ~~total~~ TORR during the cycle.	
2. Heat to 2190°F ± 25° and hold for 30 minutes. Cool to 2000°F hold 2 hrs. Heat to 2100°F hold 2 hrs. Then heat to 2200°F hold 10 mins. Cool to 2000°F in 6-10 minutes. ANY Cool below 2000°F.	
3. Remove blades from fixtures.	



R

Foreman's Approval ______ Section Leader ______ Methods Planner ______

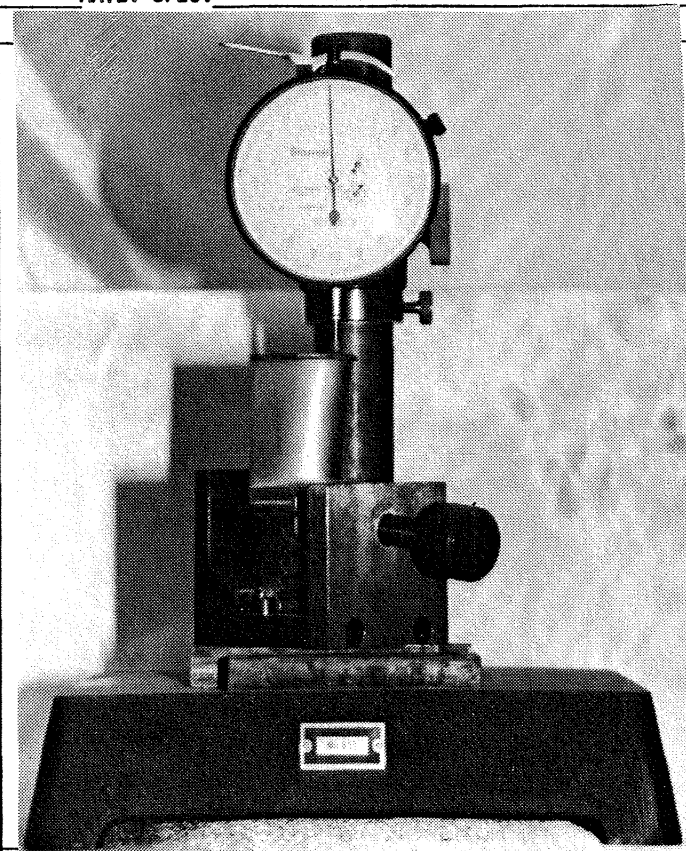
Prepared by: ______ O.C.E. ______

DWG. NO. ____

PART NAME ____ GROUP ____

OPER. NO SP-1-D OPER. Measure Blades after Tip Bonding MATL. SPEC. ____

OPERATION SEQUENCE	TOOL LIST
1. Obtain measuring fixture and take three point readings with "standard" blade in fixture	
2. Adjust if needed until each reading agrees with "standard" readings	
3. Place blade in fixture, taking care to assure proper seating	
4. Record all three readings on sheet which has the before bonding measurements for this blade	
5. No readings must exceed + .0025" from original readings for that point	
6. Remove blade from fixture	
7. Take 3 point readings with "standard" blade after each 10 blades. If readings vary more than .0002" from first readings reset and remeasure all blades	



REV.	DATE	REV.	DATE	REV.	DATE

Foreman's Approval ____ Section Leader ____ Methods Planner ____

Prepared by: ____ O.C.E. ____

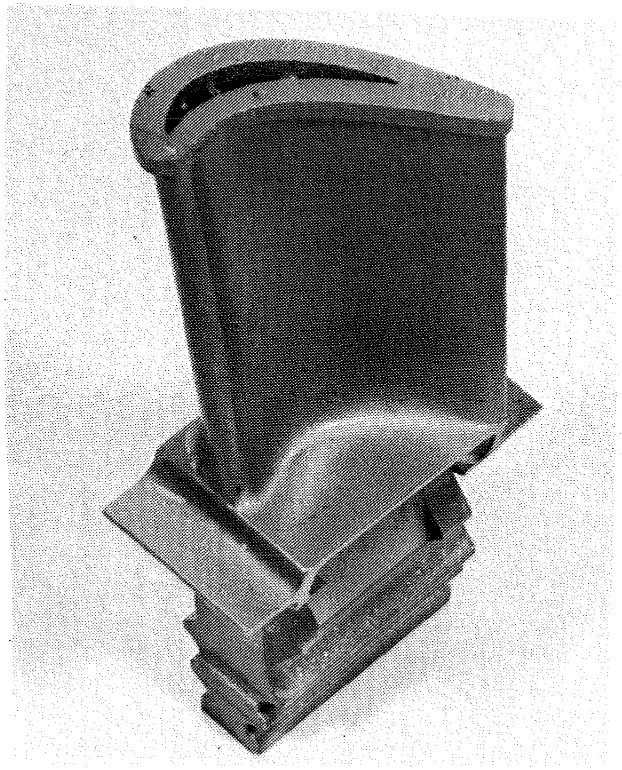
DWG. NO. ______

PART NAME ______ GROUP ______

OPER. NO SP-1-E OPER. 30X Microscopic Inspect Tips MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST
1. Use stereo macroscope with capability of 30X magnification	
2. Look at entire bond line between blade and tip on the outside of the blade. No voids permitted. Look at inside, for fillets at cross bars of the blade	

SKETCH



REV.	DATE	REV.	DATE	REV.	DATE

Foreman's Approval ______ Section Leader ______ Methods Planner ______

Prepared by: ______ O.C.E. ______

DWG. NO. ______

PART NAME ______ GROUP ______

OPER. NO SP-1-E OPER. Clear Paperwork MATL. SPEC. ______

OPERATION SEQUENCE	TOOL LIST	SKETCH
1. Remove DO card and put badge number, initials and date in appropriate boxes for bonding and 30X inspection		
2. Make copies of the inspection measuring sheets, send 1 copy with DO card.		
3. Put paperwork and blade into plastic travel envelope and return blades to airfoil operations.		

REV.	DATE	REV.	DATE	REV.	DATE

Foreman's Approval ______ Section Leader ______ Methods Planner ______

Prepared by: ______ O.C.E. ______

EAD

EAD

S/N Msc

VOUCHER: ESORL 79-013 Part No. 9128M91G10 STG. 1 Mate "3"

S/N Msc

VOUCHER: ESORL 79-013

Qty. / Sheet 2 of 2 Planning: Same as 9128M91G10/Except for SP-#'s

Acct. 2004 Class "N" Casting Vendor: Misco 9128M90P13

OPER.#	DESCRIPTION	OPER./INSP. DATE
SP-1	Grd Bld to Length Dim. Bld/Tip ADB mono tip Bld Dim. Inspect 30X Vis. Inspect	LAB MTL
0140-C	EDM ip Cavity REJ ☐	Sigo
3150-0	Degrease	
2165-0	Insp. Functional	
2170-0	Insp. Blade	
0175-0 X	E.A.G. L.E. ACC ☐ REJ ☐	Sigo 1946
0180-0 X	Drill Fan Holes ACC ☐ REJ ☐	Sigo 1946
0190-0 X	Drill T/E Holes ACC ☐ REJ ☐	Sigo 1946
0191-0 X	Dr C/C Bleed Holes ACC ☐ REJ ☐	Sigo 1946
0192-0	Dr 1-2 C/O Holes ACC ☐ REJ ☐	Sigo 1946
3193-0	X-Ray	2822
2194-0	Inspect X-Ray	2822
0200-0 •	Dr C/C Diffusers ACC ☐ REJ ☐	Sigo 1946
0205-0 •	Dr C/C Gills ACC ☐ REJ ☐	Sigo 1946
0215-0 •	Dr Nose Holes ACC ☐ REJ ☐	Sigo 1946
3230-0	X-Ray	2822
2240-0	Inspect X-Ray	2822
2260-0	Clear Paperwork	2822
3270-0	Acid Clean	Sigo 2060
3280-0	Nickel Plate	Sigo 2060
0315-0	Insert Plug	2066
0320-0	Stop Off Cavities	2066
2330-0	Inspect Stop Off	2823
0340-0	Seat Tip Cap	2066
3350-0	Shim Tip Cap	2066
0370-0	Alloy & Stop Off	Sigo 2066
3390-0	Braze & Diffuse	Sigo 2066
Codes +,X,•	See Back	

OPER.#	DESCRIPTION	OPER./INSP. DATE
2400-0	Visual Inspect	2823
0430-1 -2	Laser Drill ACC ☐ REJ ☐	Sigo 1946
3433-0	X-Ray	2822
2435-0	Inspect X-Ray	2822
SP-2	Blend tip to Bld Rotor Grd Tip Apply Abra to Tip Diffusion H.T. Visual Inspect	LAB MTL
2452-0	Visual Inspect	
3455-0	Prep for F.P.I.	2827
2460-0	F.P.I.	2827
3470-0	Degrease	
3500-0	Ultrasonic Degrease	2066
3505-0	Seal all Holes	2066
3520-0	Load Codep Box	2066
3530-0	Codep Coat Retort #	Sigo 2066
3540-0	Unload Furnace	2066
3550-0	Unload Boxes	2066
3555-0	Water Clean	2066
2560-0	Visual Inspect	2823
3570-0	Chem Clean (RPC-14)	Sigo 2063
3575-0	Ductilize & Age	Sigo 2066
2585-0	Clear Retort	2823
0590-0	Mask for Peen	1933
0600-0	Peen & Unmask	1933
3630-0	Pol-Weigh-Mark Grams:	
2643-0	Waterflow	
2646-0	Airflow WA = .00 WB = .0 PD Min WT = .0	Code
3646-0	Mark Code	
2650-0	Final Inspect	
3660-0	Bag & Box	

G03 EAA MATE '3'

VOUCHER: ESORL 79-014 ⟷ VOUCHER: ESORL 79-014

G03 EAA MATE '3'

S/N MSC PART NO.: 9311M73G03 EAA S/N MSC

STG. 1 CF6-50 C2/E2

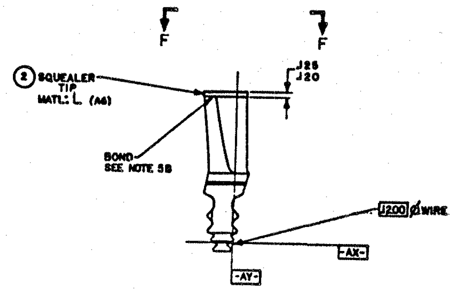
Qty. 1 SHEET 1 OF 1 PLANNING: SAME AS 9128M91 G10/EXCEPT FOR SP-#s

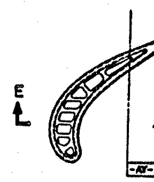
ACCT. #2004 CLASS "N" CASTING VENDOR: MISCO 9186M34P01

OPER.#	DESCRIPTION	OPER./INSP. DATE
6005-0	Rhodine Leach	CT#
2007-0	Issue	
3010-0	Load Matrix	
2020-0	Inspect Matrix	
0040-0	Grind Tip REJ ☐	
0050-0	Grind T/E Shank REJ ☐	Sigo
0060-0	Grind C/C D/T REJ ☐	Sigo
3080-0	Melt Out Matrix	
0090-0	~~Grind C/V D/T~~ REJ ☐	Sigo
0100-1 -2	Grind L/E Shank REJ ☐	Sigo
0121-0	Deburr & Radius D/T	
0122-0	Polish C/V Airfoil.	
SP-1	Transfer S/N	
SP-2	GRIND ROOT	
3125-0	Vibra Tumble	
SP-3	Grd Bld to Length Dim. Bld/Tip ADB mono tip Bld Dim. Inspect 30X Vis. Inspect	
0140-0	EDM Tip Cavity REJ ☐	Sigo
3150-0	Degrease	
2165-0	Insp. Functional	
2170-0	Insp. Blade	
0175-0 X	E.A.G. T/E ACC ☐ REJ ☐	Sigo 1946
0180-0 X	Drill Fan Holes ACC ☐ REJ ☐	Sigo 1946
SP-4	Drill T/E Holes '49' ACC ☐ REJ ☐	Sigo 1946
SP-5	Dr 1-2 C/O Holes ACC ☐ REJ ☐	Sigo 1946
3193-0	X-Ray	2522
2194-0	Inspect X-Ray	2822
SP-6	EDM C/V Diffusers Acc ☐ Rej. ☐	Sigo Lab
SP-7	EDM C/C Gills Acc. ☐ Rej. ☐	Sigo Lab
SP-8	Laser Nose & Bleed Acc ☐ Rej. ☐	Sigo Lab

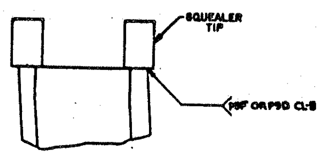
OPER.#	DESCRIPTION	OPER./INSP. DATE
3230-0	X-Ray	2822
2240-0	Inspect X-Ray	2822
SP-9	Clear Paperwork	2822
3270-0	Acid Clean	Sigo 2066
3280-0	Nickel Plate	Sigo 2066
0315-0	Insert Plug	2066
0320-0	Stop Off Cavities	2066
2330-0	Inspect Stop Off	2823
SP-10	Seat Tip Cap	2066
3350-0	Shim Tip Cap	2066
SP-11	TACK ROOT PLATE	
SP-12	Alloy & Stop Off	Sigo 2066
3390-0	Braze & Diffuse	Sigo 2066
2400-0	Visual Inspect	2823
SP-13	Laser Drill ACC ☐ REJ ☐	Sigo 1946
3433-0	X-Ray	2822
2435-0	Inspect X-Ray	2822
SP-14	E.D.M. T/E DUMP HOLE	
SP-15	DEGREASE	
SP-16	Blend tip to Bld Rotor Grd Tip Apply Abra to Tip Diffusion H.T. Visual Inspect	
SP-17	MACROETCH SHANK	
3455-0	Prep for F.P.I.	2827
2460-0	F.P.I.	2827
3470-0	Degrease	
3500-0	Ultrasonic Degrease	2066
3505-0	Seal all Holes	2066
3520-0	Load Codep Box	2066
3530-0	Codep Coat Retort #	Sigo 2066
3540-0	Unload Furnace	2066
3550-0	Unload Boxes	2066
3555-0	Water Clean	2066
2560-0	Visual Inspect	2823

APPENDIX H - MONOCRYSTAL-TIP CONTOUR DRAWING

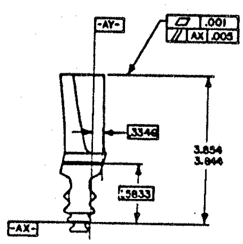




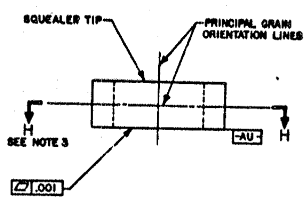
VIEW F-F



SECT E-E



VIEW J
SEE NOTE 2



ASSEMBLY IDENTIFICATION NUMBER	L
4013238-985G01	Co 33, Ni 33, Cr 23, Ta 3, Al 4, W 3, Si .75, & C .5 (NORMALLOY)

(1)

10 P9D BRAZE PROCESS DOES NOT REQUIRE OPERATOR QUALIFICATION

9 NON TRADITIONAL MACHINING ALLOWED TO PRODUCE SQUEALER TIP SHAPE PRIOR TO BONDING PROVIDED RECAST LAYER AND IGA DO NOT EXCEED .005. MICROCRACKING MUST BE CONFINED TO THE RECAST LAYER

8 BONDING OF THE SQUEALER TIP PER NOTE 4 TO OCCUR PRIOR TO EDM OF TIP CAVITY OF THE ORIGINAL DRAWING

7 WHEN REPAIR NEEDED, ENTIRE SQUEALER TIP PLUS .005 MATERIAL BELOW THE JOINT MUST BE REMOVED

6 BOTH ORIGINAL BONDING AND REPAIRS PER NOTE 7 ARE TO BE CONSIDERED AS REBRAZE OF TIP CAP. THE TOTAL NUMBER OF REBRAZES NOT TO EXCEED THE ALLOWABLE LIMIT OF ORIGINAL DRAWING

5 AFTER BONDING, INSPECT JOINT AND TIP ALIGNMENT
- A) BOND MUST BE CONTINUOUS AROUND ALL EXPOSED SURFACES, NO VOIDS, PIN HOLES OR POROSITY ALLOWED
- B) JOINT THICKNESS MUST NOT EXCEED .0025
- C) CAVITY OF ITEM 3 MUST BE TOTALLY LOCATED WITHIN THE CAVITIES OF BLADE TIP SUCH THAT SUBSEQUENT MACHINING OPERATIONS WILL RESULT IN ACCEPTABLE BLADE TIP THICKNESS AND BRAZE GAP REQUIREMENTS

4 BOND TIP ONTO BLADE USING .003 INCH [B50TF184 CL-A] (D15 FOIL ALLOY)
- A) BONDING TO BE DONE IN A VACUUM OF 5×10^{-4} TORR OR LESS AT 2190°F + 10°F -25°F FOR 35 MINUTES MAX. COOL TO 2000°F IN LESS THAN 3 MINUTES - COOL TO 1200°F IN LESS THAN 60 MINUTES
- B) TIP MAY BE TACK WELDED TO BLADE AND FOIL PRIOR TO BONDING. USE MINIMUM WELD SETTING TO ACCOMPLISH TACK

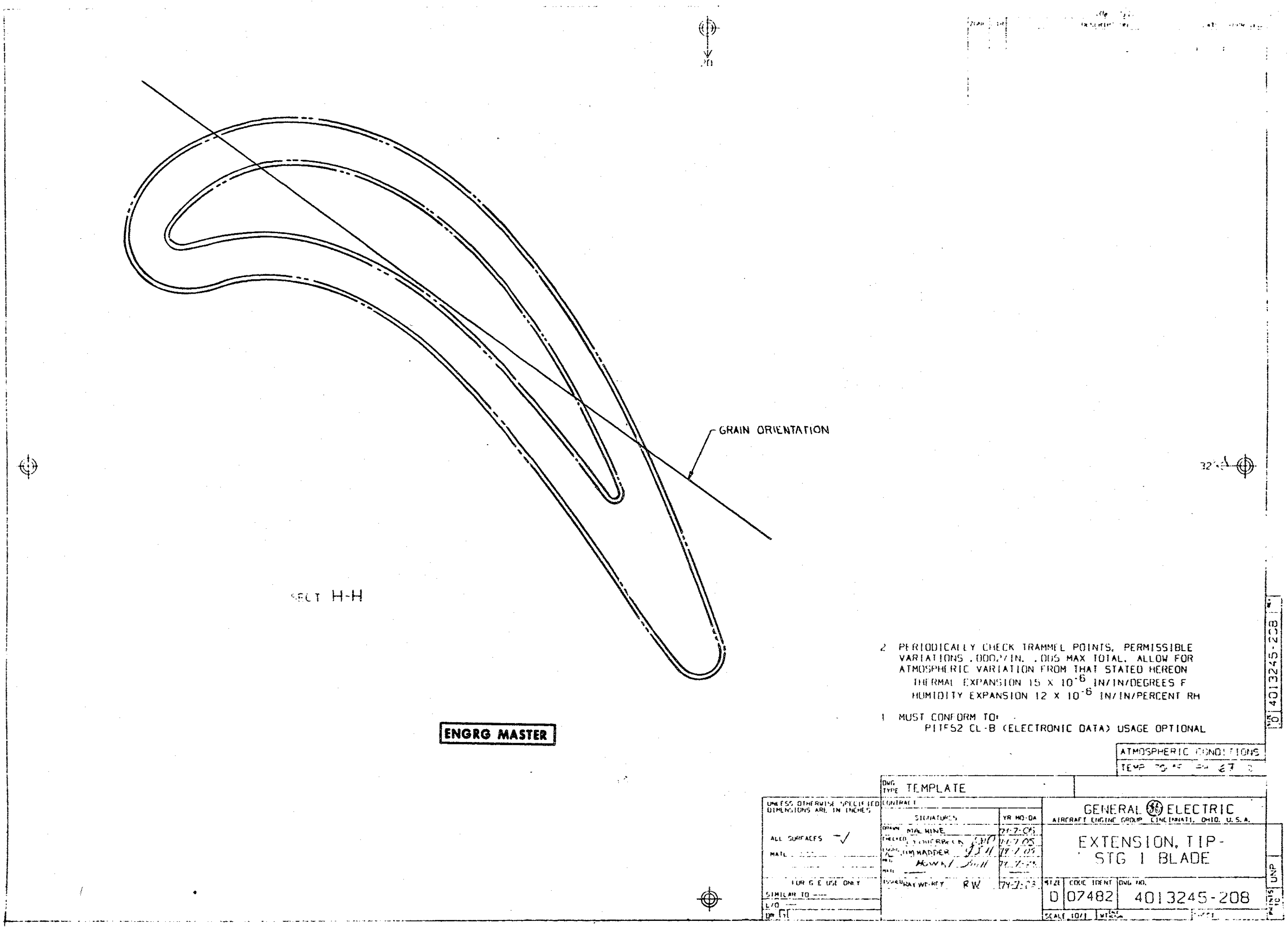
3 INSIDE AND OUTSIDE CONTOURS OF ITEM 3 (SQUEALER TIP) ARE DEFINED BY ENGINEERING MASTER [4013245-800] BOTH INSIDE AND OUTSIDE CONTOURS MUST CONFORM SIMULTANEOUSLY

2 PRIOR TO BONDING SQUEALER TIP TO BLADE, GRIND BLADE TO DIMENSION SHOWN IN VIEW J NO ELECTROLYTIC ASSISTED GRIND PERMITTED

1 MUST CONFORM TO:
- P1TF3 CL-A (INTERPRETATION OF DWG)
- P9TF1 (BRAZING)

WORKING LAYOUT	GENERAL ELECTRIC AIRCRAFT ENGINE GROUP CINCINNATI OHIO USA
ALL SURFACES ✓	BLADE, HPT ROTOR-STAGE 1
4013244-628	E 07482 4013238-985

APPENDIX I - CRYSTALLOGRAPHIC ORIENTATION DRAWING



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