ADVANCED TURBINE BLADE TIP SEAL SYSTEM

J. W. Zelahy
General Electric Company

In axial-flow gas turbines, the turbine is designed to minimize the radial clearance between the blade tips and mating shroud segments. This helps to maximize aerodynamic efficiency. In spite of the designers' best intentions, the shroud assembly may go out-of-round, and/or the rotor and shroud may be slightly eccentric resulting in potential interference between the blade tips and the shrouds. Any interference which occurs generally removes material from the blade tips (Figure 1a) in preference to the stationary shroud, creating a larger annular clearance between the rotor and stator than if the blade tips had remained unaffected and the shroud material had been removed. Furthermore, the blade tip may be damaged, reducing useful blade life, and/or requiring expensive repair operations. At best, any rub on the bucket tip removes the environmental coating, thus making the blade vulnerable to both oxidation and hot corrosion (Figure 1b).

A NASA-sponsored (MATE Project 3) program is being conducted to establish and demonstrate the payoff of an advanced blade/shroud system designed to maintain close clearance 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 target goal of this project is to demonstrate the increased efficiency and increased blade life attainable by using the advanced blade tip seal system. Increased efficiency results from the improved clearance control when blade tips preferentially wear the shrouds. Increased blade life results from the superior single-crystal superalloy tip.

The project will establish tip design, joint location, characterize the single-crystal tip alloy, finalize the abrasive tip treatment, fabricate blades, component test and engine test. The project will also establish quality control plans and define the total manufacturing cycle required to fully process the blades.

The turbine blade tip is of a multicomponent construction consisting of an Activated Diffusion Bonded (ADB) oxidation/hot corrosion resistant single-crystal superalloy squealer capable of withstanding thermal cycling, combined with a thin layer of alumina (Al_2O_3) abrasive particles held in place by an oxidation/corrosion resistant matrix (Figure 2). The shroud materials investigated included the current CF6 shroud (Bradelloy) and two advanced shroud materials, Genaseal and Vacuum Plasma Deposited (VPD) CoNiCrAlY.

The project is structured toward the successful engine demonstration of an improved efficiency, long life turbine blade tip system. The technical effort is divided into nine principal tasks.

Initial blade tip design work established the joint design and location, optimum squealer thickness and single-crystal orientation (Figures 3 and 4). The design that was established allows the single-crystal tip-to-blade bonding to be accomplished very early in the manufacturing cycle (possibly at the casting vendor) thereby not appreciably altering the standard manufacturing sequence. The tip design eliminated inside contour mismatch, located the joint in a low stress region and had total manufacturing acceptance. Using property data of both the single-crystal tip material and the bond joint, an economic benefit analysis (payoff) was subsequently performed by CF6-50 engineering on the single-crystal/abrasive tip system. The analysis predicted a minimum 2X increase in blade life via the superior tip material and a 0.013" tip clearance improvement (0.43% Specific Fuel Consumption (SFC) reduction) as the result of the abrasive tip treatment.

Since the 2X blade life goal was totally dependent upon both the increased environmental resistance of the single-crystal blade tip and the strength of the activated diffusion bonding (ADB) tip attachment process, a comprehensive evaluation of the mecahnical and physical properties of both the Normalloy (single-crystal tip material) and the Normalloy-to-Rene'80 (blade material) was conducted. The evaluation included elevated temperature, tensile, rupture, oxidation, corrosion and simulated engine thermal shock (SETS) testing. The results of the testing (Figures 5-8) confirmed that the properties exceeded those required for safe engine operation and would be expected to achieve the goal of 2X tip life.

The SFC reduction attainable with the advanced tip system is the direct result of the capability of the abrasive-tipped turbine blade (Figure 9) to resist wear during rub interactions with the shroud material. Several factors including particle size, particle type, particle relief, incursion rate, tip speed, test temperature and to a large degree shroud material have been shown to affect the wear characteristics of the abrasive system. Variations in particle size and type, degree of particle relief and rub incursion rate were evaluated. Test temperature (2000F) and tip speed (1400 ft/sec) were held constant. Three shroud materials: Bradelloy, Genaseal, and VPD CoNiCrAlY were evaluated. The particle types included various grades of aluminum oxide (Al_2O_3) and Borazon (Cubic Boronitride). In all cases, the method of abrasive application was the electroplate encapsulation process.

All wear testing was conducted at the Solar Research Laboratory (division of International Harvester) in San Diego, CA. Solar's facility has the capability of 1400 ft/sec. tip speed, 2000F shroud temperature, and direct readout/record of all vital functions including chamber temperature, shroud temperature, rotor speed and incursion rate. Measurements of both the blade specimens and shroud specimens were made before and after wear testing to establish the total wear of each. In addition, thermocouples were placed at the surface and 0.050" into the shroud specimens to record surface temperature and shroud temperature rise (and rate) as the result of the incursion. After each test, the blade specimens were evaluated visually, dimensionally, microstructurally and in some cases, by SEM analysis to establish both the total amount of blade and shroud wear and the wear mechanism (i.e., machining, compaction, melting, etc.) of each (Figure 10). Throughout the program over 50 wear tests were conducted.

The results of the testing showed that in all cases the abrasive tips resisted wear when rubbed into the Genaseal (both new and preoxidized) and the VPD CoNiCrAlY (Figures 11 and 12). The new Bradelloy was shown to be moderately abradable. The oxidized Bradelloy, however, was extremely difficult to "cut" and in most cases, after a small incursion into oxidized Bradelloy, the abrasive tips were rapidly consumed (Figure 13). The results of all of the wear testing are summarized in Figure 14. With respect to particle type, with the exception of Borazon, all particles behaved similarly. The Borazon system, in virtually all instances, abraded the shroud materials to a greater degree; even the oxidized Bradelloy was abraded more effectively by the Borazon particles. In addition, neither increased size nor relief significantly affected the abrasive characteristics of any particular system. The only test variable shown to appreciably effect abrasiveness was incursion rate. Slow incursions, i.e., 0.001 inch per sec or less, were shown to generate higher shroud temperatures and resulted in greater tip wear than at the 0.002 and 0.004 inch/sec tests (typical incursion rates in engines have been estimated at 0.002 inches/second or greater).

The results of the above wear testing have tentatively indicated that:

1. A large allowable latitude in abrasive system variables exists, i.e., particle type, particle size, relief, and environmental coating can be varied considerably without decreasing the abrasive characteristics of the tip treatment.

2. An oxidation resistant shroud material (e.g. Genaseal or VPD CoNiCrAlY) should be used to achieve full benefit of the abrasive system.

3. Alundum 38X, 100 grit aluminum oxide/NiCr electroplate with a Codep aluminide coating is the best <u>all-around</u> tip system.

4. Slower incursion rates (i.e., $\leq$ 0.001 in./sec.) are more detrimental to the abrasive system than faster incursion rates (0.002 to 0.004 inch/sec).

The abrasive tip system designated for component and engine testing is defined below.

- particle type: 38X alundum (Al_2O_3)
- particle size: 0.005" - 0.007" diameter
- matrix: 0.006" Ni, 0.001" Cr Diffusion H.T. with aluminide coating
- relief: matrix plated "flush" with particles
- shroud: either Genaseal or VPD CoNiCrAlY

Using both simulated and actual hardware, the environmental resistance and abrasive capability of the environmental/abrasive tip/shroud system was verified. Wear testing was conducted on Solar wear specimens that were modified with single-crystal/abrasive tips (Figure 15). The wear testing of the simulated tip system specimens indicated the tip system was capable of withstanding the rigors of severe shroud rub with no deleterious affects on either the single-crystal tip material or the ADB joint. The single-crystal-to-Rene'80 joint sustained very severe rub loading, particularly in the case of one bare bladed rub where $\approx$ 0.050" of tip was removed and no joint degradation was evident. Although minimal success was achieved in rubs of abrasive tipped blades into Bradelloy, successful rubs were made into Genaseal and CoNiCrAlY shrouds without loss of abrasives.

The environmental testing (i.e., oxidation, corrosion), impact and thermal shock testing will be conducted on actual hardware (scrap "fall-out" from fabrication task). This testing is currently in progress.

An integrated quality control plan including control over the tip material, the attachment process, the abrasive treatment and all related blade processing operations is currently being prepared. Temporary specifications have been issued and will be revised and updated as needed. Drawings for the single-crystal tip have been issued defining crystallographic orientation and tip configuration. Tooling for inspection of joint thickness has shown dimensional accuracy of $\pm$ 0.0005" and has been used to inspect all fabricated blades to date.

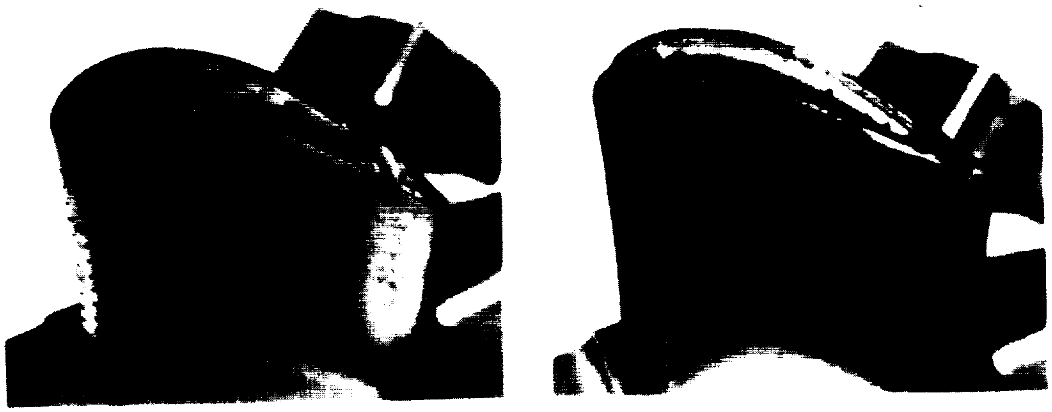
Each of the separate processing steps established in earlier tasks were formulated into an integrated processing sequence for the manufacture of turbine blades with the advanced tip system. The sequence of operations allowed the single-crystal tip bonding to be accomplished without any appreciable changes in normal blade processing (Figure 16). The blades were removed from the production airfoil operation immediately prior to tip cap cavity EDM operation and ground to a specified length. The single-crystal tips were bonded to the blades and the blades were re-introduced to the airfoil operation for the tip cap cavity EDM operation. The EDM operation provided a smooth tip squealer/blade internal wall surface and eliminated any need for internal tip/blade "blending" operations. This task is also still in progress and when completed will fully define the blade casting configuration, tip preparation and heat treatment, the single-crystal tip configuration, orientation and processing, the bonding process operations, fixturing and inspection, the abrasive tip treatment and all nonstandard operations associated with the blade manufacture. A total processing plan, including step-by-step sequence, will be provided.

A total of 171 blades were subsequently fabricated using the manufacturing sequence defined earlier. Tips were bonded in "dead weight" load fixtures in a cold-wall high vacuum furnace. The activated diffusion bonding (ADB) alloy was D15 (Rene-80-BASBD Chemistry) and was applied as 0.003" foil. Of the 171 parts that were bonded only 2 failed inspection (joint thickness measurement). Approximately 150 blades are fully manufactured (Figures 17-20) and are either undergoing or awaiting factory engine test evaluation (Figure 20). The remaining blades will undergo exhaustive destructive evaluation to further assess process reliability and reproducibility.

Two engine tests are planned to fully evaluate the payoff of the advanced tip system. The first engine test will evaluate the benefits of the single-crystal tip via "C-cycle" (simulated flight cycle) endurance testing (1000 cycles minimum). The second engine test will evaluate the abrasive capability of the system via performance testing under closely controlled clearance and engine operating conditions. The second test will be of short duration and is designed to "push" the abrasive tip system to the "limit" to fully establish maximum abrasive capability.

The results of the engine tests will be evaluated and analyzed to assess the effectiveness of the entire system to achieve the program goals.

Successful completion of the program can provide engine manufacturers a viable approach to increase blade life and reduce fuel consumption.



(a) TIP WEAR

(b) OXIDATION/CORROSION/
CRACKING

FIGURE 1. TYPES OF TIP DETERIORATION

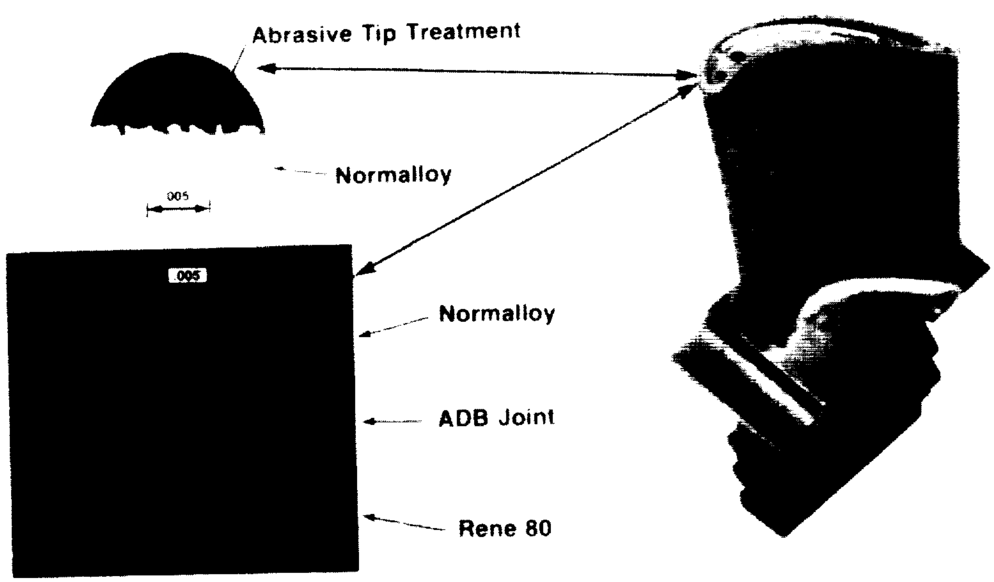
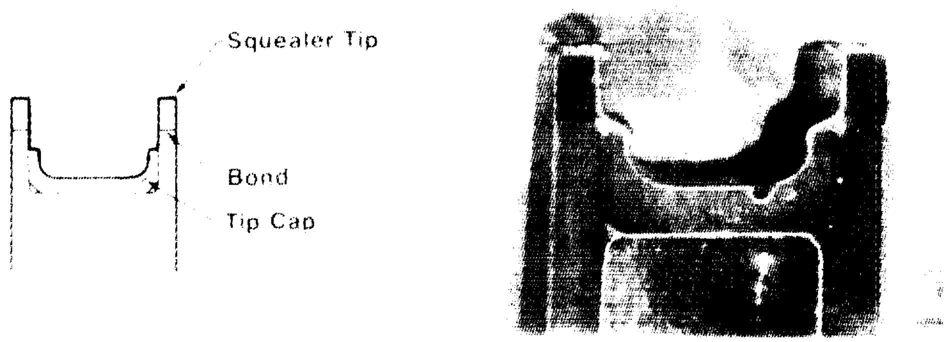


FIGURE 2. CF6-50 STAGE 1 HPT BLADE WITH ADVANCED BLADE TIP SYSTEM

Task I — Blade Tip Seal System Design

Joint Design Location



- Low Stress/High Reliability
- Ease of Manufacture
- Consistent With Current Blade Processing

FIGURE 3. JOINT DESIGN LOCATION

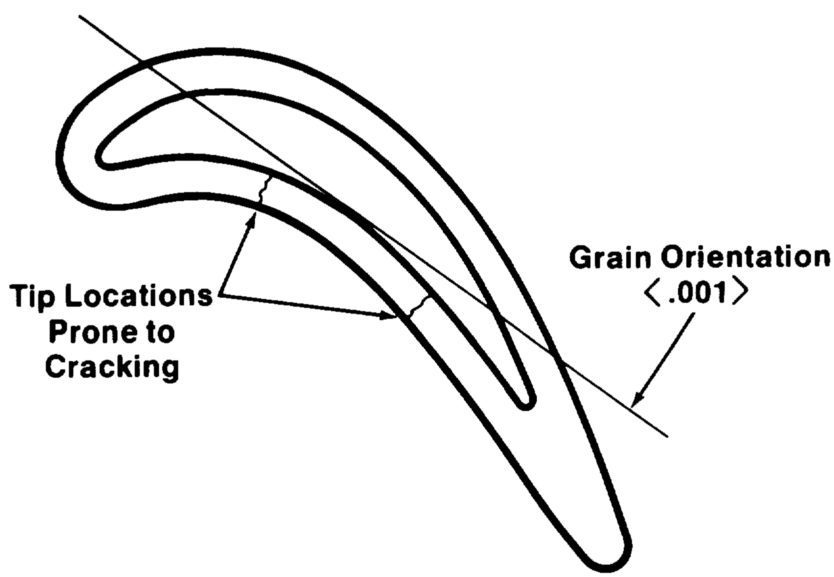


FIGURE 4. MONOCRYSTAL ORIENTATION

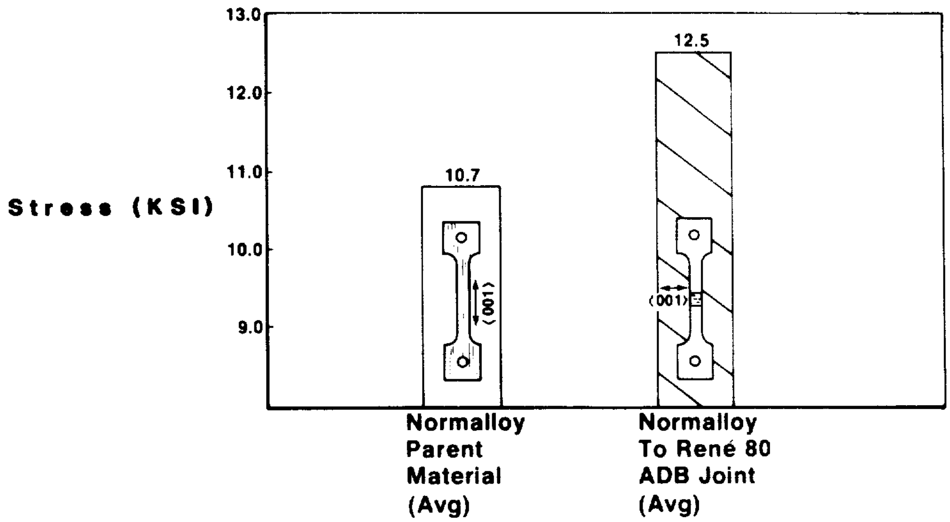


FIGURE 5. 2000F TENSILE PROPERTIES

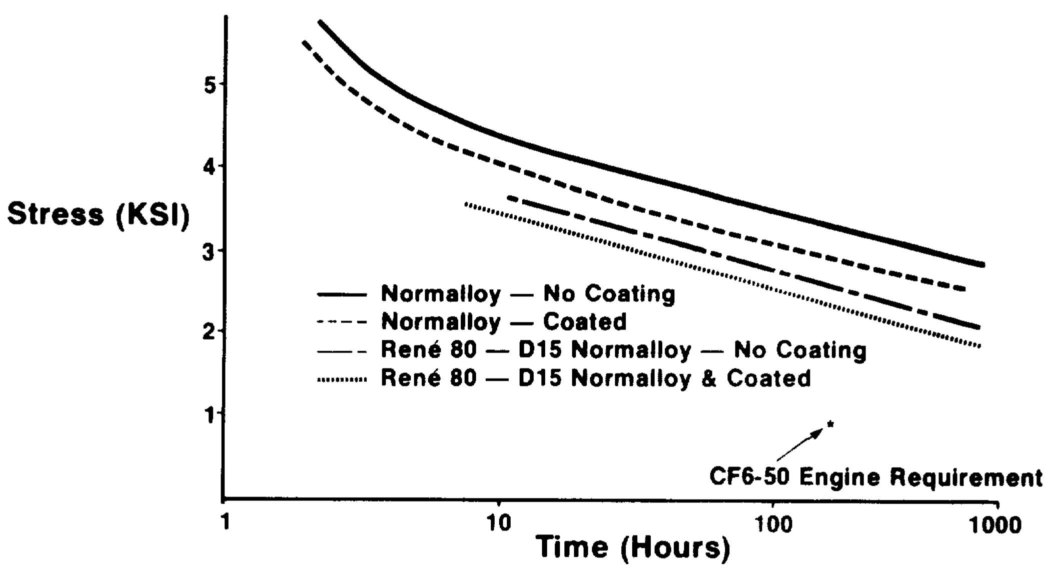


FIGURE 6. 2000F STRESS RUPTURE (AVERAGE)

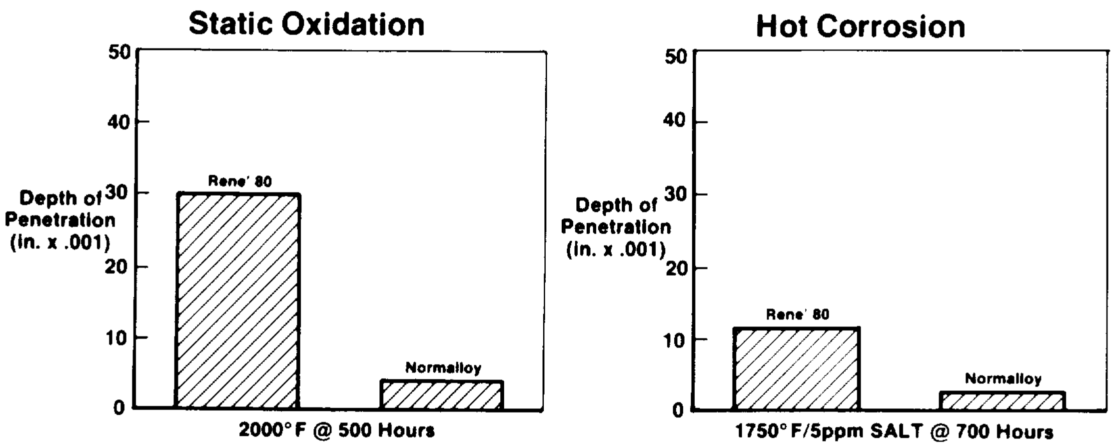


FIGURE 7. ELEVATED TEMPERATURE OXIDATION & CORROSION TESTING

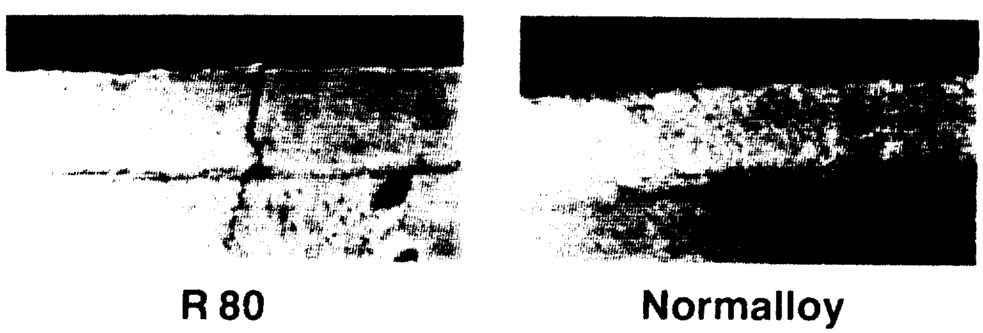


FIGURE 8. THERMAL FATIGUE RERISTANCE (2000 THERMAL CYCLES)

FIGURE 9. ABRASIVE TIPPED TURBINE BLADES

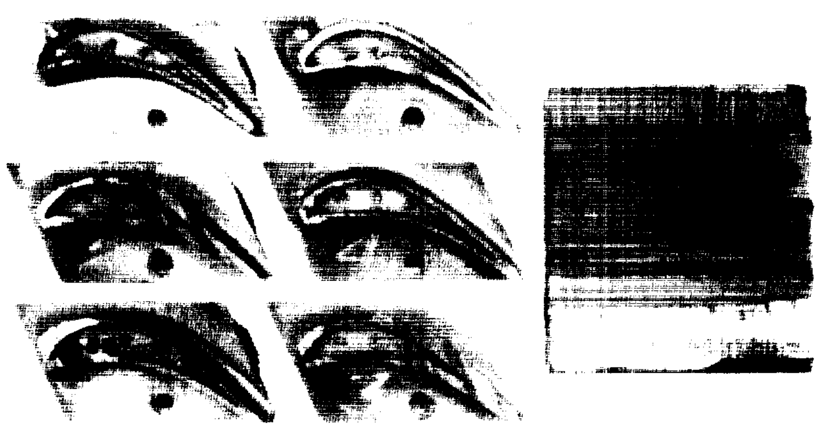


FIGURE 10. SOLAR WEAR TEST SPECIMENS - AFTER TEST

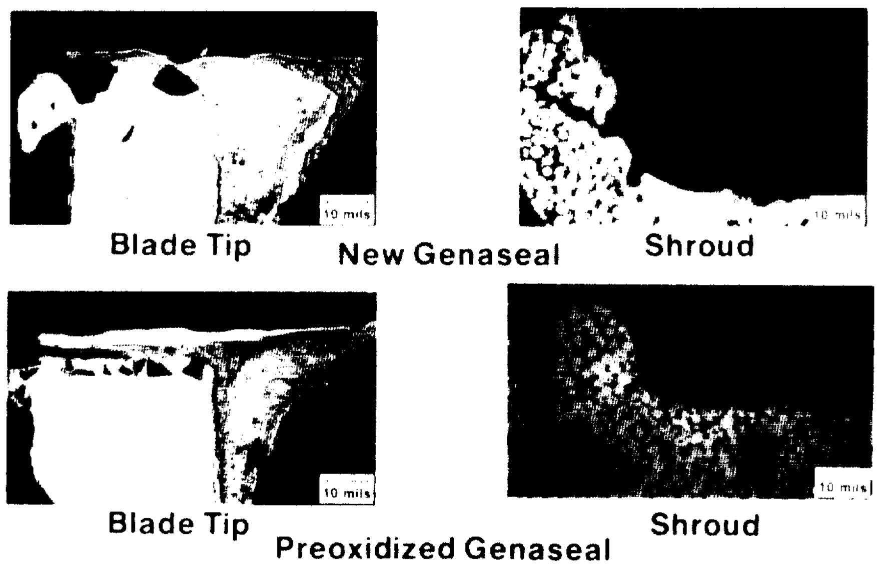


FIGURE 11. WEAR TESTING - ABRASIVE TIP INTO NEW & PREOXIDIZED GENASEAL

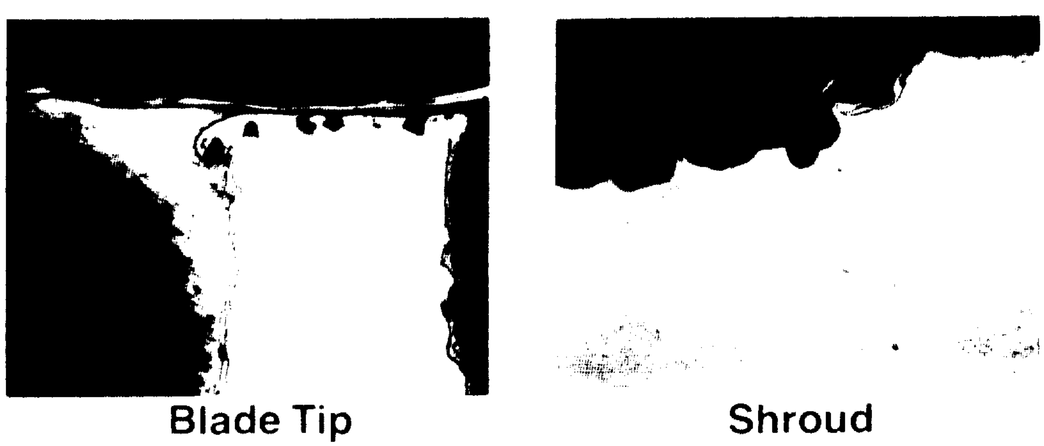


FIGURE 12. WEAR TESTING - ABRASIVE TIP INTO NEW VPD CoNiCrAlY

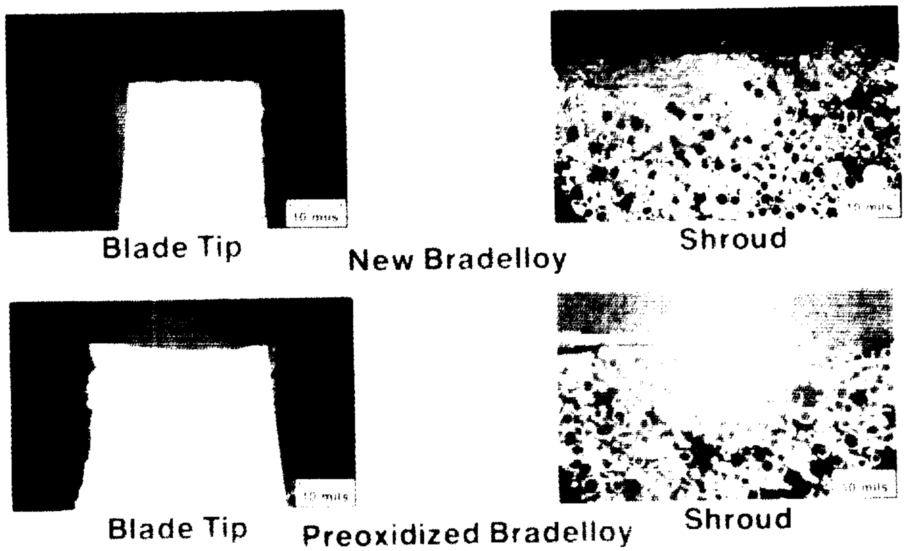


FIGURE 13. WEAR TESTING - ABRASIVE TIP INTO NEW & PREOXIDIZED BRADELLOY

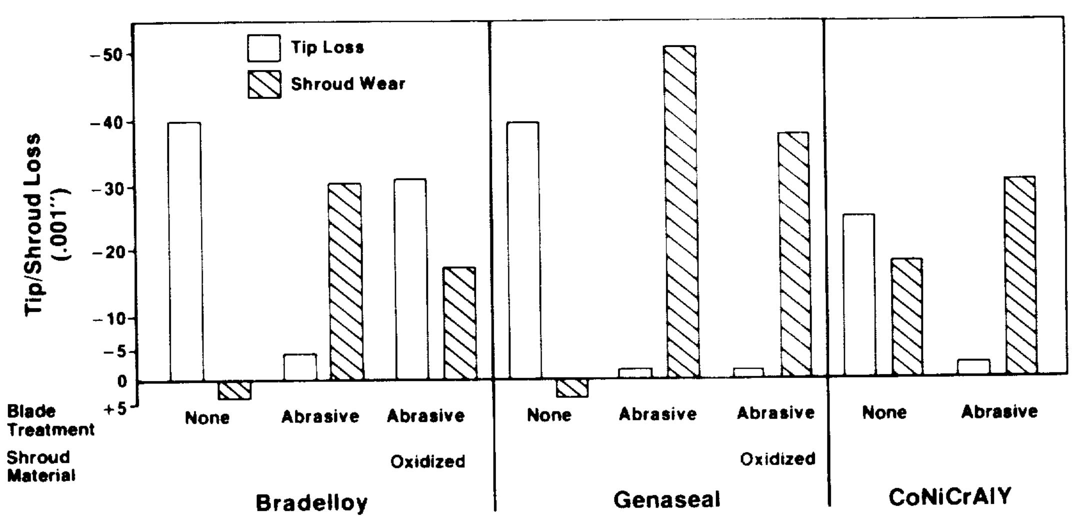


FIGURE 14. WEAR TEST RESULTS (2000F, 1400 ft/sec)

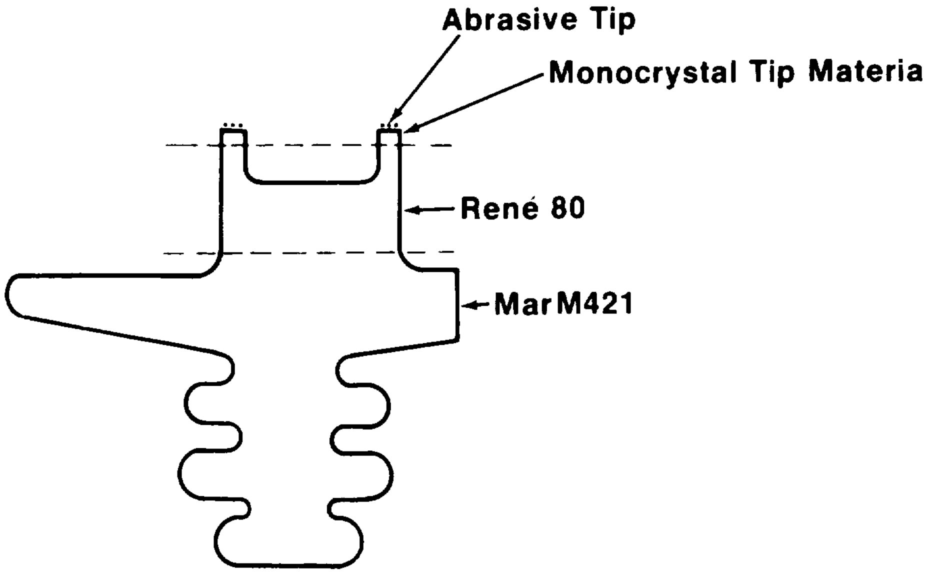
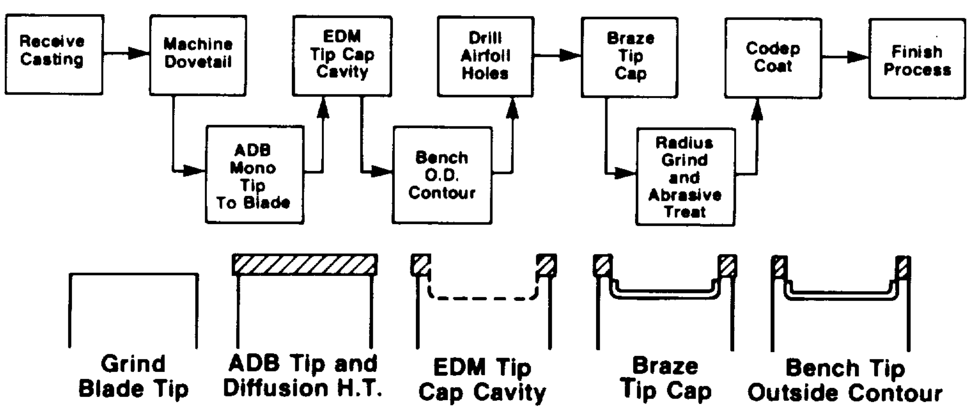


FIGURE 15. WEAR TEST SPECIMEN



Finishing Steps:

- Finish Process as Standard Blade
- Radius Grind Tip
- Apply Abrasive and Diffusion H.T.
- Coded Coat and Age

FIGURE 16. MANUFACTURING PROCESS PLANS

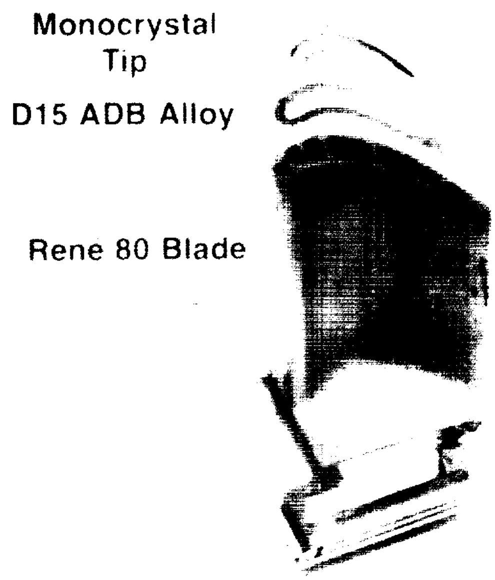


FIGURE 17. BLADE/TIP/ADB ALLOY ASSEMBLY

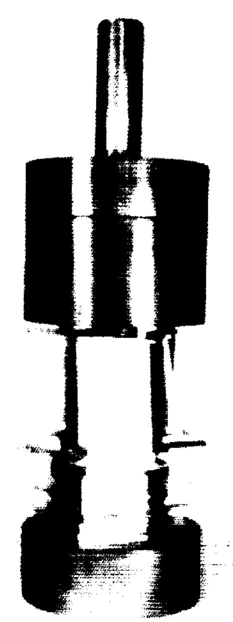


FIGURE 18. BLADE SUBCOMPONENTS & FIXTURE

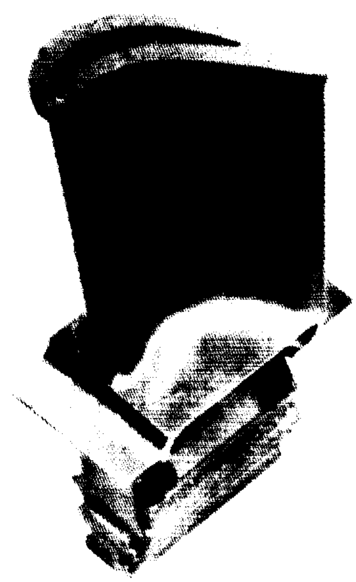


FIGURE 19. BLADE WITH MONOCRYSTAL TIP AFTER BONDING

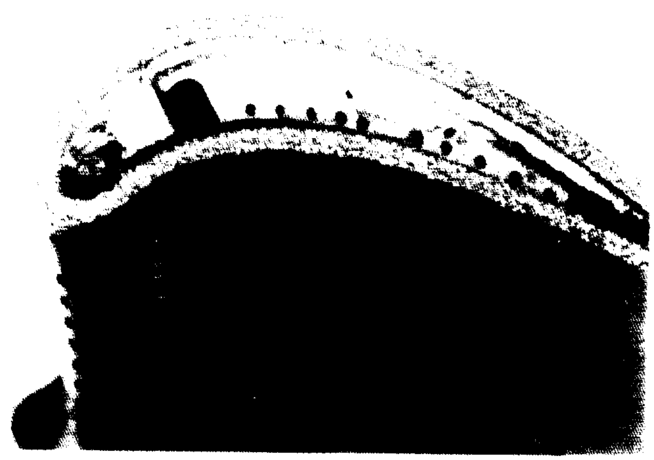


FIGURE 20. ABRASIVE TIP APPLIED & FULLY PROCESSED

FIGURE 21. STAGE 1 HPT BLADES WITH ADVANCED TIP SYSTEM ASSEMBLED IN TURBINE ROTOR PRIOR TO ENGINE TEST