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MANUFACTURING METHODS AND TECHNOLOGY
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MANUFACTURING PROCESS DEVELOPMENT FOR DUST AND RAIN EROSION RESISTANT COATED METALLIC CLADS FOR HELICOPTER ROTORS

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June 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Manufacturing processes for creating erosion resistant coatings on metallic rotor blade leading edges were optimized as a follow-on to a coating development program sponsored by AMMRC (Contract DAAG74-C-0054). Solide™ coated, titanium rotor nose caps were produced in sections up to 30 inches long. Commercially pure (A75) and alloyed (Ti-6Al-4V) titanium was used. Newly developed graphite coating mandrels made possible simultaneous coating and creep forming of titanium sheet material to accurate airfoil contours. Sand

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and rain erosion tests were performed along with tensile, impact, salt spray and adhesive bonding tests. Costs per part for production quantities were estimated.

Solide™ coated test specimens of titanium and SAE 430 stainless steel were provided to three major helicopter manufacturers for test and evaluation: Hughes, Sikorsky and Bell. Their conclusions were that Solide™ coatings are excellent in rain erosion resistance and low angle sand erosion resistance but do not meet minimum survival requirements when subjected to sand erosion by large particles (>100 μm) impinging at high angles (>45°).

degrees

[illegible]

micrometers

FOREWORD

This final summary report covers the work performed under Contract Number DAAG46-76-C-0033 from April 5, 1976 through June 30, 1980. It is published for technical information only and does not necessrily represent recommendations, conclusions or approval of the Department of the Army.

Contract DAAG46-76-C-0033, with Solar Turbines International, An Operating Group of International Harvester, San Diego, California is sponsored by the Army Materials and Mechanics Research Center, Watertown, Massachusetts and is administered under the technical direction of Mr. George Harris of AMMRC and Mr. Gerry Gorline of the Army Aviation Systems Command.

The program is being conducted at Solar Turbines International Research Laboratories with Mr. A. R. Stetson, Manager of Materials Technology, as Technical Director, and Mr. David P. Huey, Engineer, as the Principal Investigator.

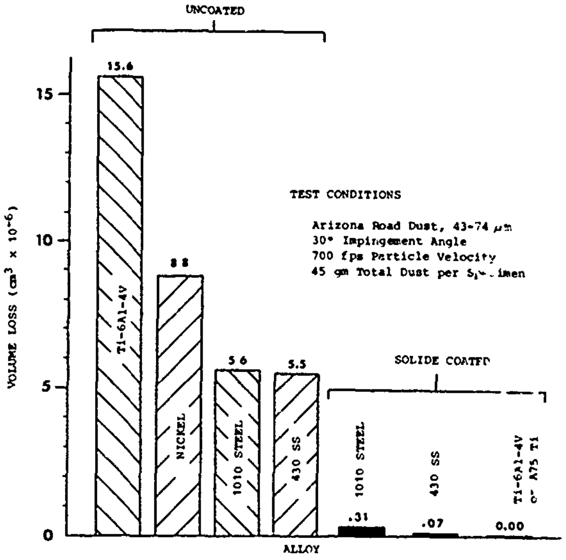
The authors wish to acknowledge the special assistance provided by Mr. George F. Schmitt of the Nonmetallic Materials Division of the Air Force Materials Laboratory, Wright-Patterson Air Force Base. Mr. Schmitt made available rig time and supervised some initial rain erosion tests performed in this program.

The Solar program reference number and report reference number is SR80-M-4511-37.

SUMMARY

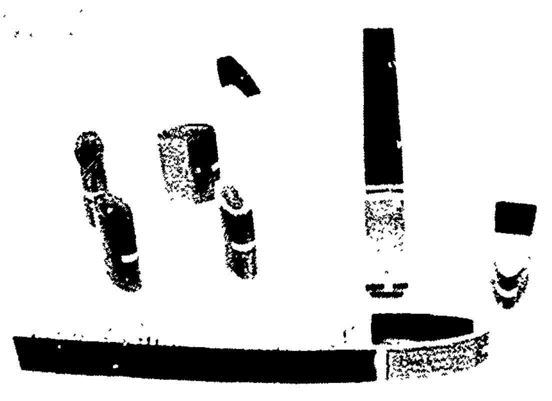
SOLIDE™ COATINGS: PROVEN EROSION RESISTANCE

Rain and dust erosion damage can severely decrease the useful life of helicopter rotor blades. Over sandy terrain blade airfoil configuration at the blade tips can be destroyed in minutes. Erosion-resistant leading edge caps are essential features of rotor blade design, especially for new composite blade materials. No currently used material (titanium, nickel, stainless steel, polyurethane tape) is entirely satisfactory.



SOLIDE™ COATED CLAD CONCEPT

In February 1974 the U.S. Army contracted with Solar to investigate the feasibility of using intermetallic boride coatings applied to metal substrates as clads for rotor leading edges. The developmental program optimized diffusion processes for applying Solide™ coatings to several substrate alloys. Preliminary tests on coated samples confirmed bonding capability, corrosion resistance, and coating integrity. Sand erosion tests at rotor tip speeds verified the excellent erosion resistance of Solide™ coated metals. The graph at the left displays the dramatic improvement in erosion prevention possible with very thin Solide™ coatings on several alloys commonly used in erosive environments. Solide™ coated titanium (comm. pure or alloyed) was identified as the superior choice for a rotor blade clad application. The coated clad concept demonstrated the potential for significant advancement in field service reliability for the Army's airmobile forces.

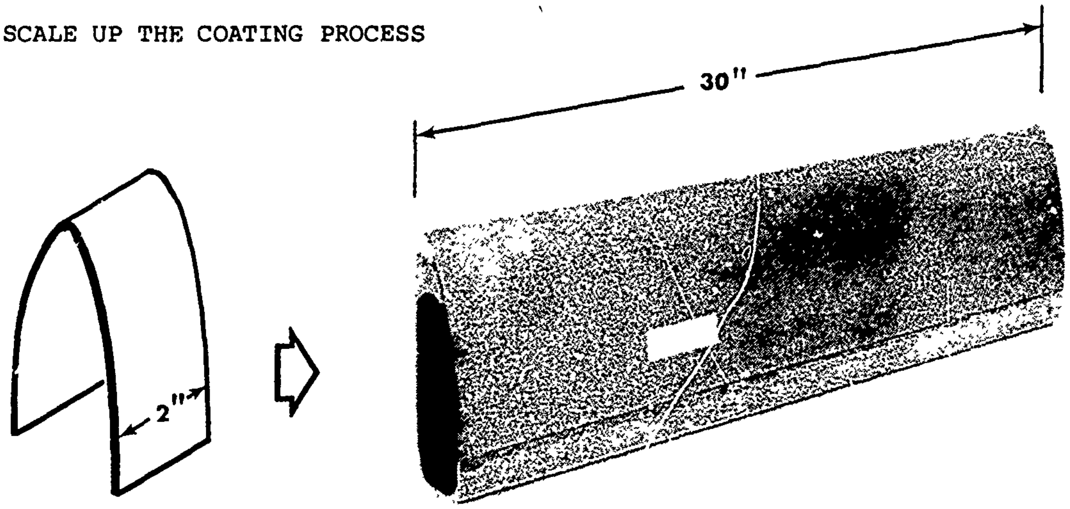


COATED CLADS ON ROTOR AIRFOILS

The final achievement of the predecessor program was to develop methods of producing Solide™ coated clads with accurately maintained airfoil shapes suitable for bonding to typical helicopter rotor blade leading edges. The samples shown at the left are titanium clad specimens coated and bonded to fiberglass dogbone airfoils and 2-inch wide sections of Bell UH-1H all-metal main rotors.

PROGRAM OBJECTIVES

1) SCALE UP THE COATING PROCESS



The current MM&T program had two primary goals. First, the Solide™ coating process had to be scaled up from 2-inch wide, 0.020-inch base material to 0.040-inch by 30 inches long, full scale samples with no loss in coating quality or airfoil configuration. Accomplishing this required:

- Production of all new tooling to restrain airfoil shapes during coating.
- Optimization of coating chemistry and application for full scale parts.
- Demonstration of process versatility by producing parts for metal and composite rotor designs.
- Testing coated specimens to determine mechanical properties, bondability and environmental durability.
- Sand and rain erosion tests to verify erosion resistance.
- Cost estimate for production quantities.

2) TESTING BY HELICOPTER MANUFACTURERS

To effect transfer of the new Solide™ coating technology to the Army's helicopter fleet, major Army helicopter manufacturers were provided with Solide™ coated titanium and stainless steel specimens for test and evaluation by their rotor design specialists. The companies participating were:

- Hughes Helicopters (AAH)
- Sikorsky Aircraft (UTTAS)
- Bell Helicopter Textron (UH-1, AH-1)

PROGRAM SCOPE

PHASE I - TOOLING DESIGN AND DEVELOPMENT

Design, test and improve tooling to enable coating titanium and stainless steel sheet metal shapes to achieve optimum coating quality and minimum physical distortion. Fabricate tooling to coat flat specimens for tensile, adhesive bonding and corrosion testing. Fabricate tooling to coat small airfoils for erosion testing and 30-inch long airfoils for UTTAS and UH-1H rotor blade sections.

PHASE II - COATING WORK

Use newly produced, special tooling to Solide™ coat flat test specimens, airfoil test specimens and 30-inch long demonstration full scale airfoil samples. Verify uniform, consistent and reproducible coating quality. Bond all required specimens and samples using state-of-the-art aerospace adhesive bonding technology.

PHASE III - TESTING AND EVALUATION

Perform a full range of tests on Solide™ coated specimens. Document sand and rain erosion resistance, tensile strength, strain-erosion compatibility, adhesive shear strength, ballistic impact survivability, salt spray exposure and subsequent adhesive properties.

PHASE IV - PROCUREMENT DATA PACKAGE

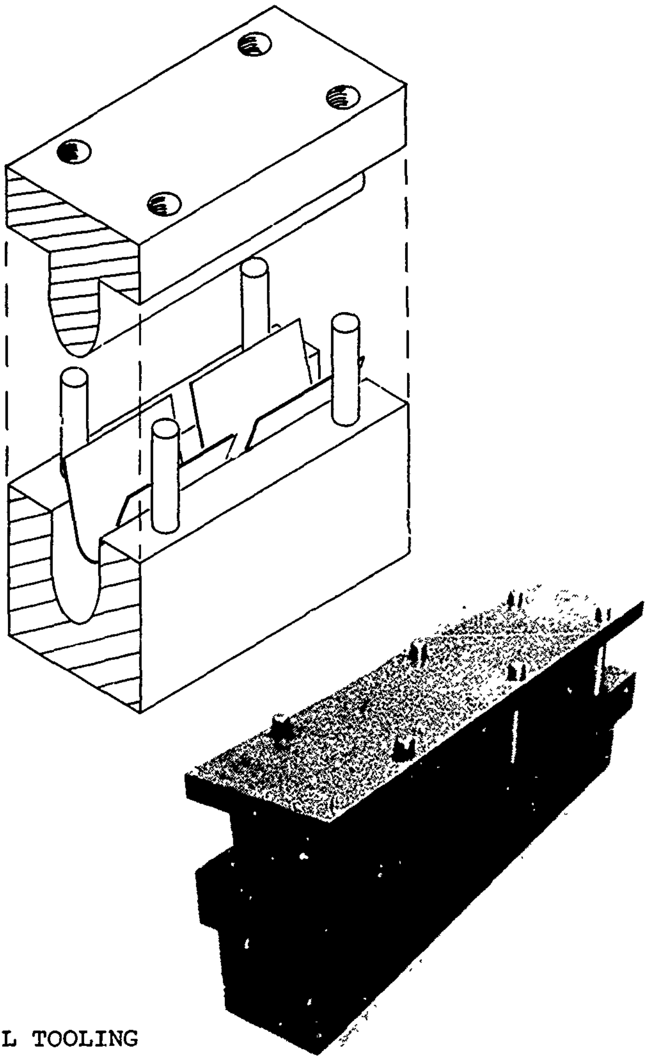
Prepare a Procurement Data Package for transferring the Solide™ coating technology from the laboratory scale to production, including specifications for: equipment requirements, material requirements, jig and fixture requirements, operational shop practices, physical test procedures, and non-destructive test procedures.

TESTING BY HELICOPTER MANUFACTURERS

Provide interested Army helicopter manufacturers with test specimens made to the specifications required for their rotor blade material evaluation test procedures. Assist rotor design and test specialists in evaluating the feasibility of using Solide™ coated clads for new design or retrofit rotor applications.

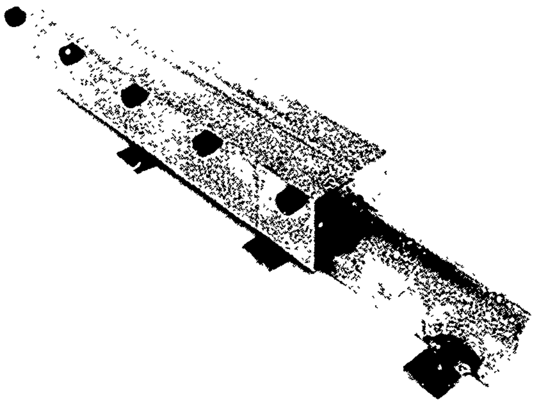
PHASE I - TOOLING DESIGN AND DEVELOPMENT

TITANIUM SUBSTRATES: GRAPHITE TOOLING



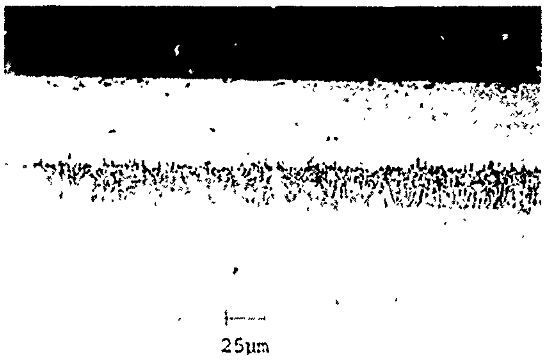
Maintaining formed sheet metal shapes while producing a Solide™ coating on small titanium specimens had been done in the past using refractory alloy (e.g., columbium) fixtures. This technique was too costly and not accurate enough for full scale airfoil sections. A new approach was required. Custom milled solid graphite male and female mandrels were the answer. Graphite mandrels provided full contact restraint to maintain highly accurate 3-D shapes for leading edge airfoils. In addition, the coating vapors were better confined than previously and resulted in enhanced coating quality and thickness for a standard coating cycle. Another important benefit of graphite tooling for titanium was discovered: forming to shape and coating could be done in a single operation, thus eliminating a costly production step. Flat, recessed graphite stacked tools were also made for coating dozens of small test specimens simultaneously.

SAE 430 STAINLESS SUBSTRATES: MILD STEEL TOOLING

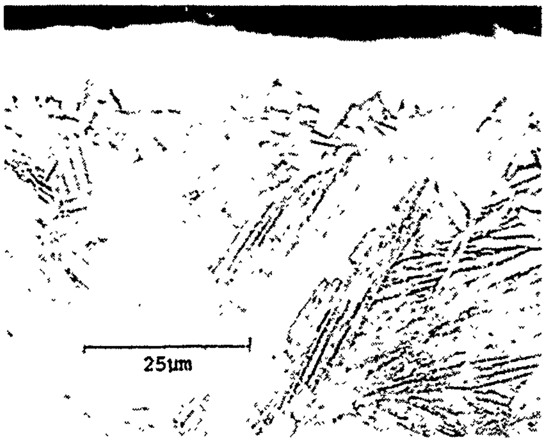


Solide™ coated SAE 430 stainless steel offers many of the erosion resistance advantages of coated titanium but at a lower cost. Graphite tooling is not compatible with the coating process for stainless steels, however. To solve the problem Solar developed custom machined, three part, full contact mild steel mandrels to satisfactorily coat stainless steel airfoil samples and maintain accurate profiles at a reasonable cost.

PHASE II - COATING WORK



430 Alloy

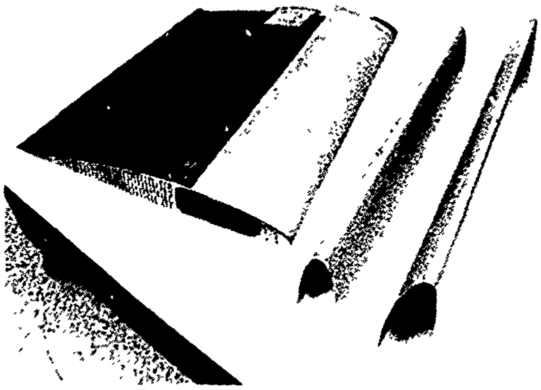


Ti-6Al-4V Alloy

Solar achieved all program goals in producing test specimens and full scale airfoil samples in the Phase II effort. Virtually distortion-free full size leading edge caps were coated at a consistently high level of coating quality. A major improvement in process refinement was accomplished by demonstrating the ability to coat and accurately creep-form titanium nose caps in one furnace operation requiring only minor preforming of the metal blanks.

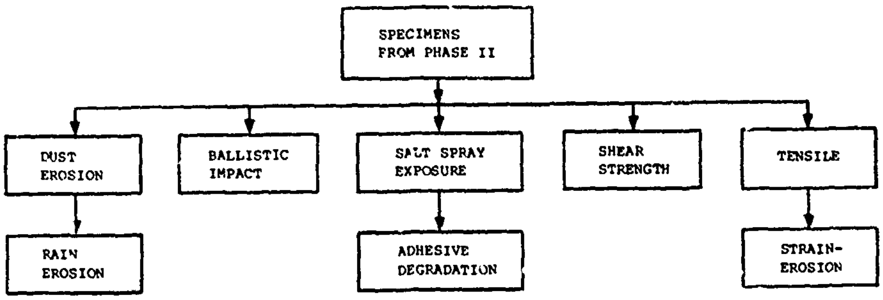
Microstructures of the two basic substrate alloys (left) confirmed that the coatings could be developed as required:

- monolithic and continuous
- virtually crack-free
- uniform over total metal surface area
- metallurgically bonded to substrate
- thickness controlled by time-temperature.



Full scale specimens made for sections of the Bell UH-1H main rotor blades and Boeing-Vertol's prototype UTTAS (left) passed all coating quality tests and were readily bonded to their respective blade sections using 3M brand 126-2 film epoxy adhesive.

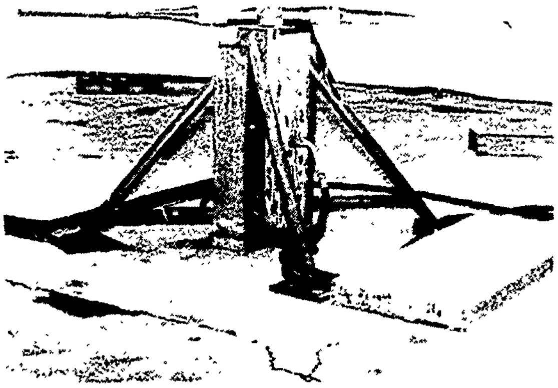
PHASE III - TESTING AND EVALUATION



A full range of critical tests were performed by Solar to confirm performance of the Solide™ coated scaled up samples. Bonding, tensile and corrosion properties were evaluated in the lab using coated, flat specimens. Sand erosion resistance on small airfoils was tested at 650 fps using Arizona Road Dust (43-74 microns). Erosion damage at either low or high angles was negligible. The same specimens subsequently subsonic rain erosion tested on small airfoils, yielded no damage.

EVALUATION BY HELICOPTER INDUSTRY

Solar worked closely with Hughes, Sikorsky and Bell to provide test specimens for evaluation by industry rotor blade specialists. Each of the erosion tests determined that Solide™ coatings were excellent in rain erosion but failed at high angles when exposed to large particles (>150 microns). Tests performed and results were:



Hughes

Whirl arm rain and sand erosion (left)
Rain erosion - No damage observed
Sand erosion - Coating removed at leading edge

Sikorsky

Bonding, fatigue and static specimen sand erosion
Bonding - Acceptable
Fatigue - Acceptable
Static erosion - Excellent for particles below 100 microns
Coating removed with large particles at high angles.

Bell

Whirl arm rain and sand erosion
Rain erosion - Not definitive
Sand erosion - Coating removed at leading edge

PROGRAM CONCLUSIONS

- SOLIDE™ COATINGS CAN BE SUCCESSFULLY APPLIED TO HELICOPTER ROTOR LEADING EDGE STRIPS.
- SOLIDE™ COATED CLADS ARE ADAPTABLE TO ROTOR DESIGN LIMITATIONS.
- SOLIDE™ COATED TITANIUM IS RECOMMENDED OVER SOLIDE™ COATED SAE 430 STAINLESS STEEL.
- SOLIDE™ COATED AIRFOILS HAVE DEMONSTRATED EXCEPTIONAL RESISTANCE TO RAIN EROSION.
- WITH COARSE SAND (>150 MICRONS) SOLIDE™ CLADS DO NOT MEET CURRENT HELICOPTER INDUSTRY REQUIREMENTS FOR SAND EROSION RESISTANCE ON ROTOR BLADE LEADING EDGES AT HIGH IMPINGEMENT ANGLES (>45°).
- SOLIDE™ COATED AIRFOILS DISPLAY UNPARALLELED SAND AND RAIN EROSION RESISTANCE AT LOW IMPINGEMENT ANGLES (<30°).

USES OF SOLIDE COATINGS

PAST AND PRESENT

- Surface hardening of 17-4PH diffuser vanes for Solar's Titan engine
- Standard surface treatment for one of Solar's gas compressor radial impellers
- Trial wearing noses for induced-draft fan blades used at coal-fired power plants.

POTENTIAL FUTURE

- Low angle sand erosion protection for Sikorsky Blackhawk main rotor tip caps
- Surface hardening treatment for titanium compressor rotor in Solar's Titan engine
- Hard surface to reduce frictional bearing wear in corrosive geothermal brine environment.

ESTIMATED COSTS FOR PRODUCTION QUANTITIES

COST PER PART FOR 41 INCH LONG SOLIDE™ COATED PARTS TO SUPPLY NEEDS OF TOTAL BELL UH-1H AND SIKORSKY BLACKHAWK FLEETS (UP TO 773 PARTS PER MONTH).

	1980	1986
Titanium:	$82.15	$105.39
SAE 430:	$45.25	$ 59.92

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1

INTRODUCTION

In December 1975, Solar completed a program for AMMRC/AVSCOM (Contract DAAG46-74-C-0054) in which a Solar boriding process was investigatd in the development of erosion resistant claddings for helicopter rotor blades (Ref. 1). In that program the most favorable combination of clad alloy and boriding process was determined. Processes were also developed for adhesive bonding the clads (nose caps) to leading edges of helicopter rotor blade sections. The results of the program were very encouraging. Solar's Solide™ boriding process applied to a Ti-6Al-4V substrate alloy produced a coated metallic nose cap which experienced extremely low levels of erosion in rain and dust tests. Figure 1 displays data derived from erosion tests in the previous program which demonstrate the potential improvement in erosion resistance possible with Solide™ coated clads. In a series of tests of other critical properties the excellent performance characteristics of these clads were also demonstrated. Borided titanium alloys were selected as those having the best overall properties. Other alloys were tested for use as boriding substrates as well. Solar currently uses the process to improve erosion resistance of 17-4PH alloy diffusion vanes in one of our small radial engines and on SAE 410 alloy gas compressor radial impellers. Among stainless steel alloys, SAE 430 was identified in the initial research program as being highly suitable for Solide™ coating.

The purpose of this program was to scale up the Solide™ coating process developed on 2-inch by 5-inch airfoil shape specimens to sizes that would demonstrate that the coated clad approach would be feasible for application to helicopter rotor blades. Full size clads were not fabricated due to the size of equipment required but clads up to 30 inches in length with a variety of leading edge radii and airfoil configurations were produced and tested.

This original goal was expanded during the course of the program to include a cooperative effort with some prime contractors in the helicopter industry. The major helicopter manufacturers were made aware of the potential of Solide™ coated clads and given the opportunity to test specimens made to their specifications under conditions which they established as screening criteria for candidate rotor blade leading edge materials.

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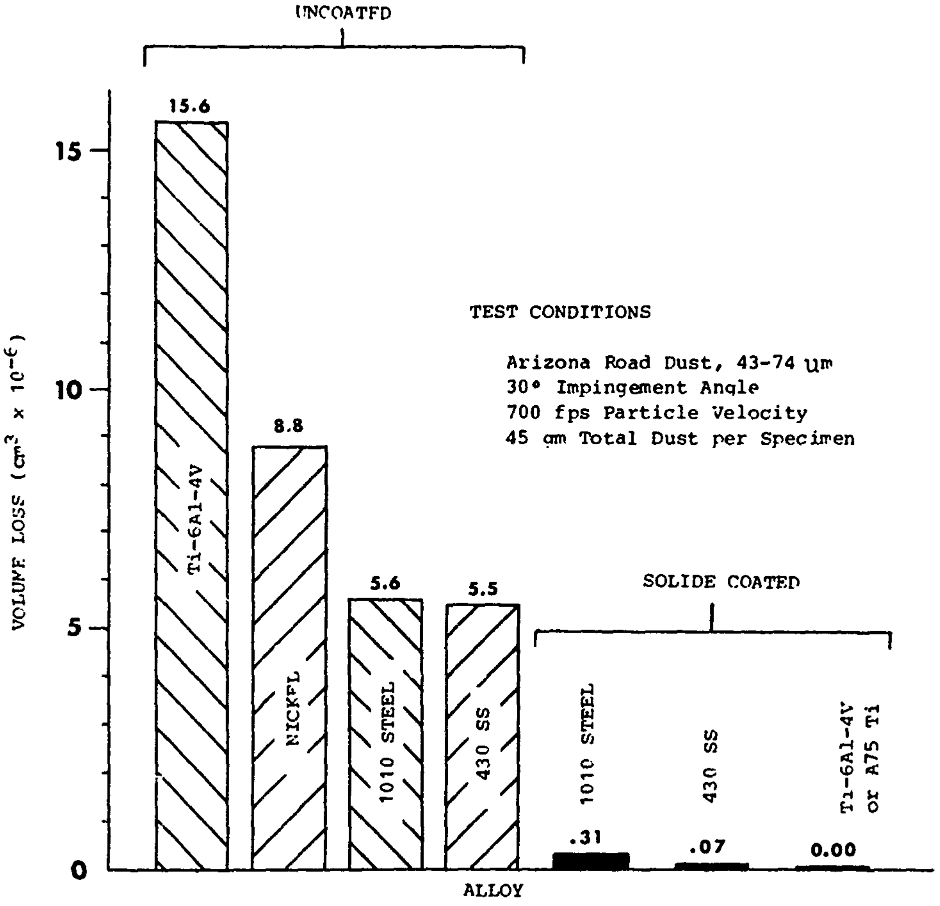


Figure 1. Erosion Test Results of Common Rotor Leading Edge Materials

The program was divided into two parts, each being subdivided into four phases. The first part included the coating process development and scale-up activities and was broken down as follows:

Phase I - Tooling Development

Phase II - Coating and Bonding

Phase III - Testing by Solar

Phase IV - Procurement Data Package

The second part of the program was devoted to providing appropriate test specimens to the four helicopter manufacturers:

Boeing-Vertol Company (funded under separate contract with them)

Hughes Helicopters, Division of Summa Corporation

Sikorsky Aircraft, Division of United Technologies

Bell Helicopter Textron

2

EXPERIMENTAL EFFORT

2.1 PROCESS SCALE-UP

The direction of the experimental efforts in this follow-on program was set by the accomplishments of the previous program (Contract DAAG46-74-C-0054). The abstract from the final report of that program is included here:

> The objective of this program is to optimize the Solar boriding process to obtain a well supported boride on a metallic substrate (clad) and to evaluate the erosion resistance and other critical properties of a clad substrate. Processes were also developed for adhesive bonding the cladding to the leading edges of helicopter rotor blades.
>
> The test results demonstrated that dense boride coatings on steel and titanium alloys can reduce the dust erosion rate, compared to uncoated metal, by 30 to several hundred fold. Overall the borided titanium alloy clad appeared most favorable of the four clad alloys evaluated (SAE 1010, SAE 410, SAE 430 and Ti-6Al-4V). The extreme hardness of TiB_2 (approximately 3250 KHN) afforded essentially complete erosion protection with a coating thickness of only 0.0005 inch. Resistance to rain erosion, impact, and saline water corrosion also favored the titanium alloy. Of the steels, the ferritic stainless steel, SAE 430, was best in performance in erosion, impact and saline water corrosion. Performance of boride coated 430 and Ti-6Al-4V alloys in rain erosion tests was excellent. No evidence of erosion of the boride was apparent after testing at 500 mph in a 1-inch/hour rainfall for 1 hour duration.
>
> The use of a boride coated metallic cladding to reduce rain and dust erosion to extremely low levels has been demonstrated. Forming of SAE 430 and Ti-6Al-4V alloys before boriding, maintaining dimensions during boriding, and the subsequent adhesive bonding of the borided shapes to sections of metallic and glass-epoxy rotor blades has also been shown to be feasible.

Sample specimens which were the end result of that developmental program are displayed in Figure 2. One of the primary accomplishments was development of a technique which enabled sheet metal nose caps pre-formed to airfoil shapes to be Solide™ coated without significant bowing, flaring or sagging of the parent material during the coating process. The technique developed used refractory alloy supports, as illustrated in Figure 3, and was employed to produce specimens up to 2 inches in width.

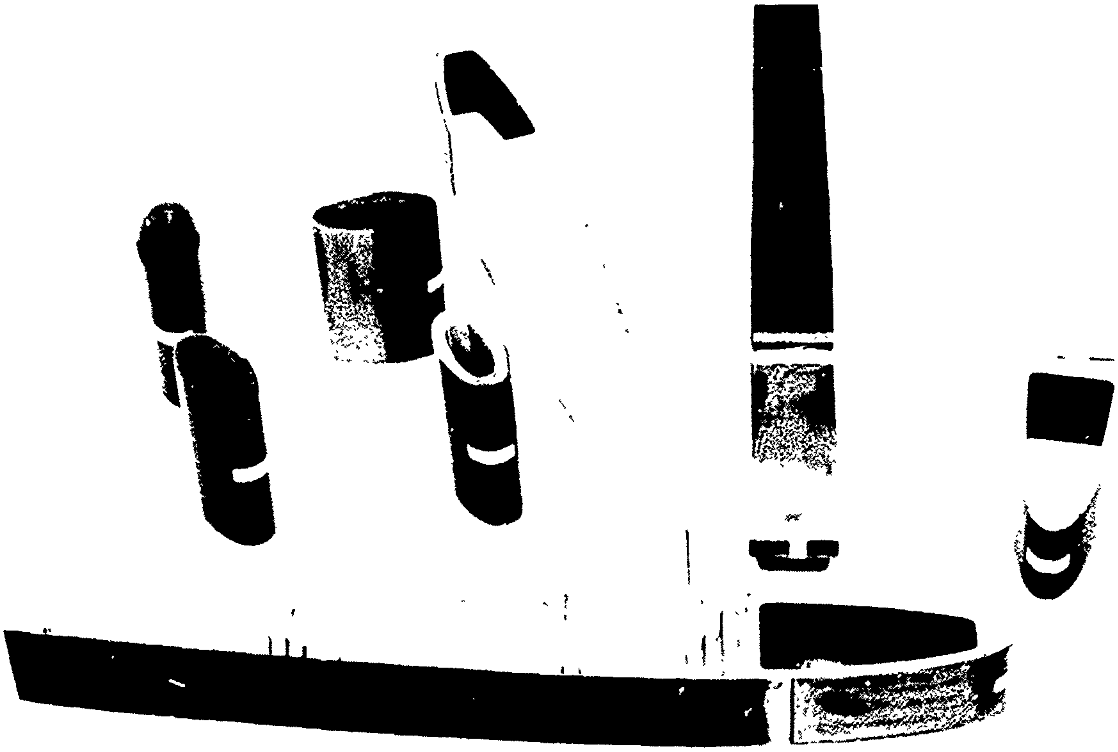


Figure 2. Clads Bonded to Bell UH-1H Rotor Blade Sections and to Glass-Epoxy Simulated Blade Sections

The goal of this follow-on program was a more thorough manufacturing development to achieve a proven technique which would enable production of sheet metal nose caps with high quality Solide™ coatings made to a degree of accuracy sufficient to allow bonding to conventional helicopter rotor blade sections in lengths up to 30 inches.

The identification of the boride process and selection of clad alloys for this program were a result of the information acquired in the previous program. The blade configurations chosen were based on availability of surplus blade types and applicability to current military requirements.

After an evaluation of blade specimens which were readily available and consideration of the current trends in design of helicopter rotor blades, the following two combinations of blade type and nose cap material were selected:

1. Bell Helicopter's UH-1H all-metal blades to be combined with nose caps of 0.040 inch A75 titanium coated with the Solide™ boride process,

2. Boeing Vertol's prototype UTTAS glass epoxy blades combined with 0.040-inch nose caps of Ti-6Al-4V alloy coated with the Solide™ boride process.

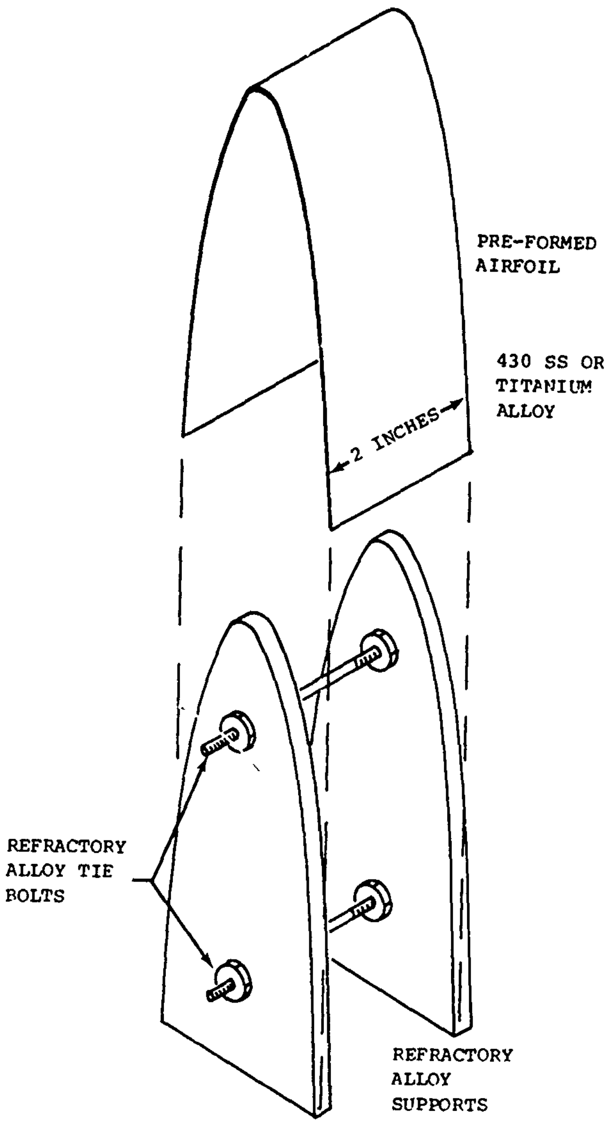


Figure 3. Refractory Alloy Support Tools

In both cases the nose caps would be bonded to their respective blade sections with "Scotch-weld" structural adhesive film AF-126 manufactured by the 3M Company. This is the adhesive in use by Boeing Vertol for rotor blade bonding and has been used by Bell Helicopter for the UH-1H blades.

The nose caps for the UTTAS blade sections were Ti-6Al-4V alloy which was identical to those in use on Boeing's developmental UTTAS blades. For that reason the blanks used for coating for this program were those formed by Boeing. Some of the required specimens were cryogenically removed from sections of used blades. Others were provided to Solar new from stock at Boeing Vertol. Figure 4 shows a typical UTTAS nose cap after removal from

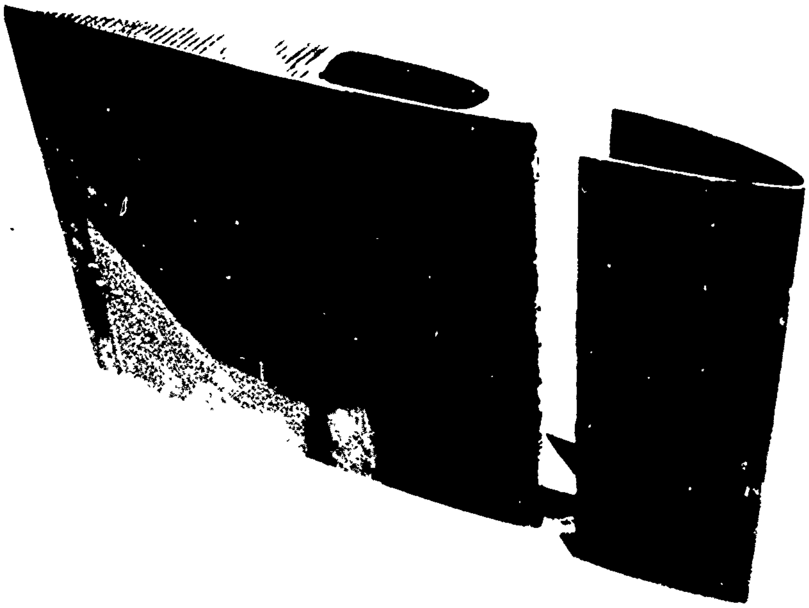


Figure 4. Ti-6Al-4V Alloy Erosion Cap Removed from Boeing UTTAS Blade Section

its rotor blade section. The existing nose caps for the Bell UH-1H rotor sections were Type 304 stainless and were not useful for this program. New nose caps of A75 titanium had to be formed prior to coating.

2.1.1 Phase I - Tooling Design and Development

Titanium sheet does not retain enough strength at the boriding temperature, 2100-2150°F, to resist physical deformation unless adequately supported. Special refractory metal tooling was developed in the previous program to support the short specimens. A different approach was sought for this program to show the feasibility of boriding longer specimens.

One idea was to use a sheet of refractory metal (e.g., columbium alloy) formed to the rotor leading edge contour. At the boriding temperature, this material would ideally retain its dimensional integrity. To test the validity of the concept, two experiments were performed with columbium alloy sheet material. In each case a piece of 0.060-inch material was formed to a typical leading edge shape and then run through the coating cycle alone to determine if warpage or distortion would occur. In both experiments the columbium test pieces warped severely due to stresses resulting from the boride formation. It was thus apparent that columbium alloy sheet could not be used as mandrel supports for the titanium alloy during coating.

Another experiment was performed using support pieces of solid CS grade graphite machined to half-cylinder shapes. Both a male and female form were made to enclose a piece of Ti-6Al-4V alloy 0.045 inch thick. Figures 5 and 6 show the grahite forms and the titanium test piece after boriding. In Figure 6 the pieces are shown partially assembled in the position in which the boriding was done. The titanium was cold-formed on a break press to an approximate fit on the male form. The female form was then placed over the metal to enclose it completely.

Figure 5. Graphite Boriding Support Forms. From Left: Female Form, Titanium Test Piece, Male Form

The initial results were very good. The test piece came out of the boriding process with a perfect fit to the male graphite form. The coating appeared to be excellent both on the inside and outside surfaces. Metallographic examination of the specimen showed the coating to be continuous and about 0.5 mil thick. No change in the coating character or appearance from previous techniques was noted.

The proximity of the graphite during boriding suggested the possibility of contamination of the titanium by carbon or oxygen. This could cause degradation of the substrate mechanical properties. As can be seen in Figure 7, the microphotograph of the boride coating, no carbides are in evidence. A microhardness survey was done on the substrate and compared to samples of titanium alloy which were borided in the previous program. Some differences were noted, but none that could be related directly to the use of the graphite tools. A chemical analysis revealed no significant increase in carbon content of the coated Ti-6Al-4V alloy specimens over samples of as-received, uncoated titanium alloy. An oxygen analysis was also run on the test piece with the following results. Uncoated Ti-6Al-4V samples contained 0.096 percent oxygen

Figure 6. Graphite Forge Assembled With Titanium Test Piece

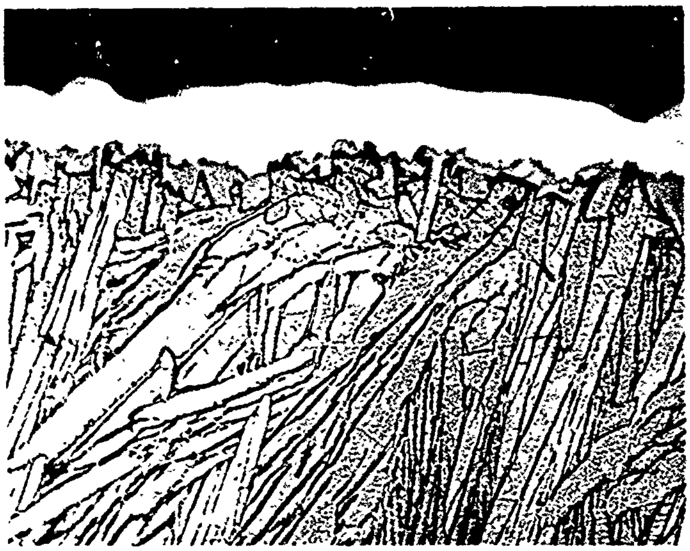


Figure 7.

Microstructure of Test Piece Borided on Graphite Forms

Magnification: 1000X

Time: 4 hours at 2150°F

Material: Ti-6Al-4V

Etchant: Kroll's

while the borided samples were found to contain 0.106 percent oxygen. This represents an increase of about 10 percent, which was deemed acceptable. Care was taken during actual boriding runs to prevent possible contamination by thoroughly outgassing the graphite and using only high purity argon for the inert atmosphere. Later, grade ATJ graphite was used which is of higher purity, denser and easier to outgas than CS grade.

It was noted in the experiment that the titanium test piece actually improved its dimensional accuracy during the boriding process. This phenomenon was credited to creeping of the titanium at the boriding temperature until the fit between the graphite and the titanium was excellent. This suggested that it might be possible to hot form and boride the alloy in the same step. An experiment testing this theory on a small half-cylinder test piece was performed combining boriding and forming of Ti-6Al-4V sheet in a single operation using graphite mandrels. The combined boriding/forming experiment was accomplished by using the graphite mandrels from the previous experiment and a pre-bent piece of 0.050-inch Ti-6Al-4V alloy.

Figure 8 shows the arrangement of the mandrels and test piece as they were assembled in the boriding retort. Notice in the figure that a piece of Inconel 600 strapping was used to maintain the alignment of the setup during handling of the retort. Figures 9 and 10 show the results. As was expected, the titanium was weak enough at the boriding temperature to allow it to creep form to the shape of the mandrels. The boride coating developed was equal in quality to previous coatings. This simultaneous boriding and forming experiment was repeated to verify the results. Every indication from these experiments was that combined boriding and forming on graphite mandrels would be a viable approach to the problem of producing finished UH-1H clads. The UTTAS nose caps on hand were already formed so that they need only be borided on a graphite mandrel to hold their dimensions.

Several significant advantages are achieved by hot forming/boriding. The expensive and time consuming steps of cold forming and stress relieving the titanium prior to boriding are eliminated almost completely. (Slight preforming of the titanium blanks is required.) Another plus to the method is that the expensive columbium alloy retort liner previously used was no longer required.

With these facts in mind, the graphite tooling required was designed. Figure 11 is a sketch showing the graphite tooling for the UH-1H specimens and how it was assembled for a boriding/forming run. Since the UTTAS configuration nose caps were already accurately formed the combination coating/forming operation was not required for them. However, experimentation with graphite tooling demonstrated that accurately made male and female mandrels employing nearly full contact with the titanium were required to assure acceptably low levels of distortion caused by coating stresses in the finished product. Thus, mandrels for the UTTAS shapes were also produced similar to those illustrated in Figure 11, but without the alignment pins.

Figure 8. Graphite Mandrel and Test Piece Arrangement for Combined Boriding/Forming

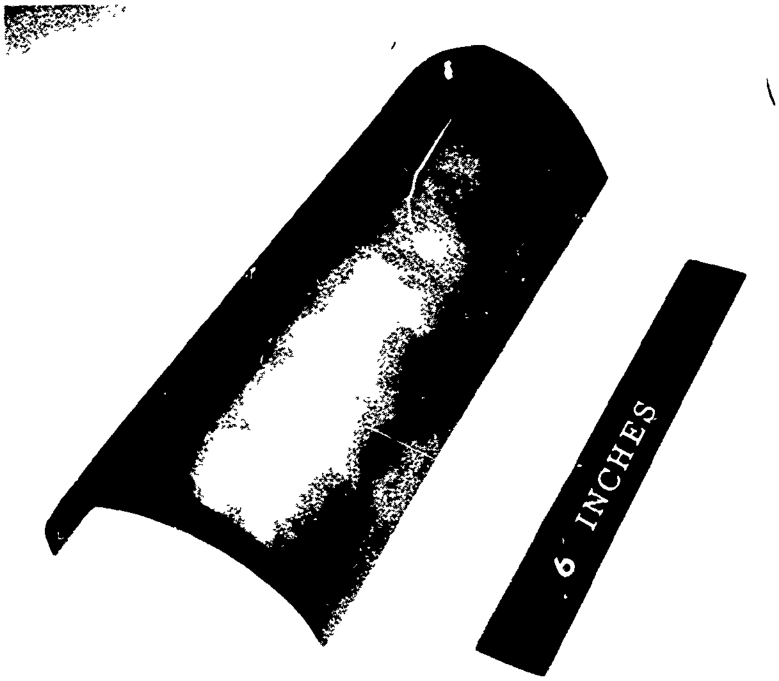


Figure 9. Ti-6Al-4V Test Piece After Boriding/Forming

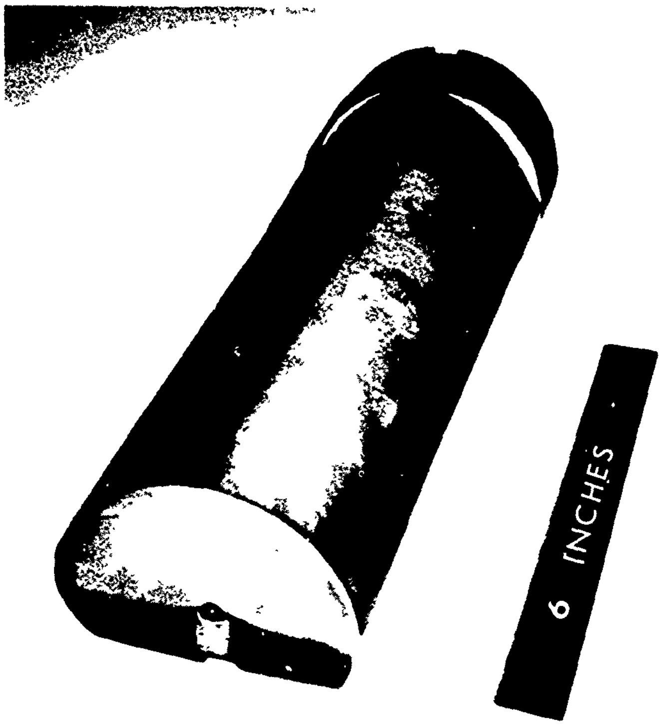


Figure 10. Test Piece and Male Mandrel Showing Good Fit

In addition to the full scale demonstration nose caps to be coated, a variety of test specimens were to be coated as well. These included miniature airfoil specimens for rain and dust erosion testing which were combination formed in pairs as illustrated in Figure 12, and flat specimens for bonding tests, fatigue tests, etc. which were coated between flat slabs of graphite recessed 0.040 inch and stacked in a retort. Figure 13 illustrates the technique. In this way, all titanium parts in the program could be coated under nearly identical conditions. The completed graphite mandrels are shown in Figures 14 through 19.

Certain other incidental tooling was required to enable production of the samples and test specimens for the full scope of the program. A variety of firing retorts were made to suit the parts being coated. A typical retort is shown in Figure 20. All were designed with the capability to purge the air from the weld-sealed, assembled retort and to maintain an argon atmosphere during firing.

Other small jigs and tools were required to produce the bonded test specimens. Figure 21 shows the existing fixtures which were used for bonding the flat airfoil fatigue, salt spray, and shear strength specimens. Figure 22 shows the fixture which was used for bonding the rain and dust erosion specimens.

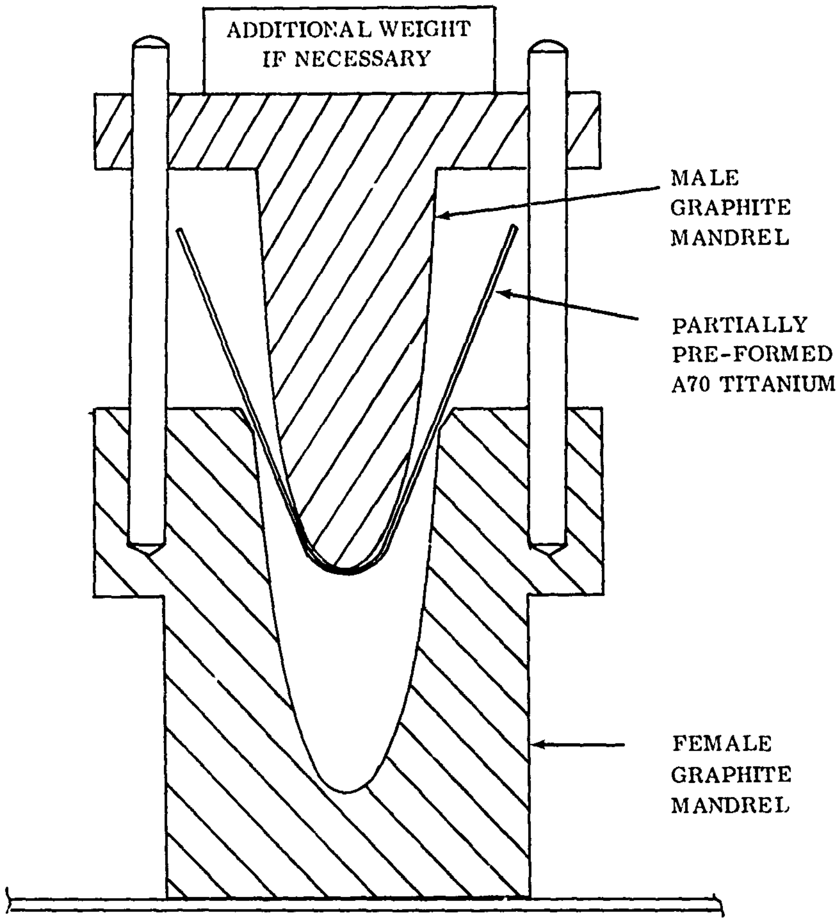


Figure 11. Graphite Tooling Arrangement for Boriding/Creep Forming of UH-1H Nose Caps

2.1.2 Phase II - Coating Work

The key to the erosion resistant behavior of the Solar Solide™ coating, and thus the interest in developing a process for applying it to metallic substrates, is that it offers an extremely hard surface to a part while the overall composite retains the other properties of fabricability, light weight, and toughness common to metal parts. Past experience has indicated that the two satisfactory substrate materials are SAE 430 ferritic stainless steel and titanium, either alloyed or commercially pure.

Microstructures of the two borided alloys are illustrated in Figure 23. The principal phase in Solide™ coated SAE 430 is FeB at the outer surface and Fe_2B at the inner surface. The complex structure at the substrate-coating interface has not been specifically identified. Coating hardness is approximately 1800 KHN (100 gm load).

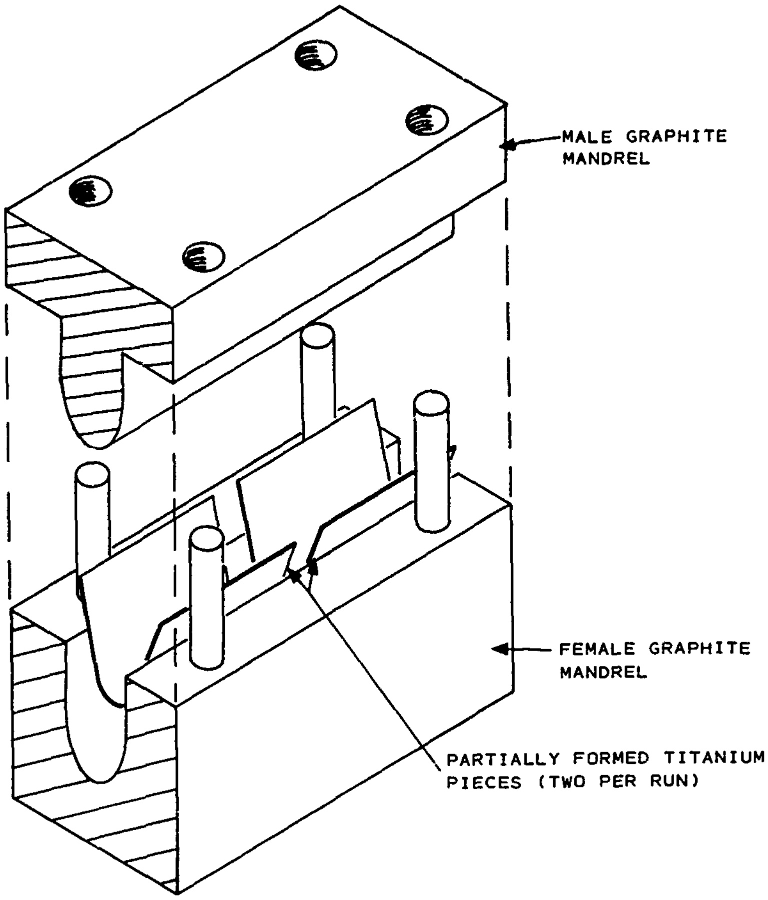


Figure 12. Graphite Tooling for Forming and Boriding Rain and Dust Erosion Test Specimens

The Solide™ coating on Ti-6Al-4V alloy is extremely dense, hard, and crack-free. The identified major coating constituent is TiB_2 with a hardness of approximately 3250 KHN, 100 gm load, on the outside with TiB at the interface. Pure titanium, A75Ti, which offers advantages in lower cost and ease of fabrication into airfoils, has coated properties similar to those of Ti-6Al-4V.

To develop the boride coating a slurry containing a source of boron and other chemicals is applied to the part. The slurry is then air dried before firing. Results achieved are similar to pack cementation techniques (Ref. 2) but offer advantages of lower cost, greater versatility, faster process time plus the unique ability to maintain accurately formed sheet metal shapes. With the Solide™ slurry process the boron finds its way to the reaction sites by a combination of vapor phase transport, intermediate compound chemical reactions and finally solid state diffusion into the parent metal matrix. In the case of alloyed base metals (e.g. Ti-6Al-4V) the elements such as aluminum are diffused from the coating back into the bulk which maintains the chemical consistency of the coating itself when applied to different titanium alloys (Ref. 2).

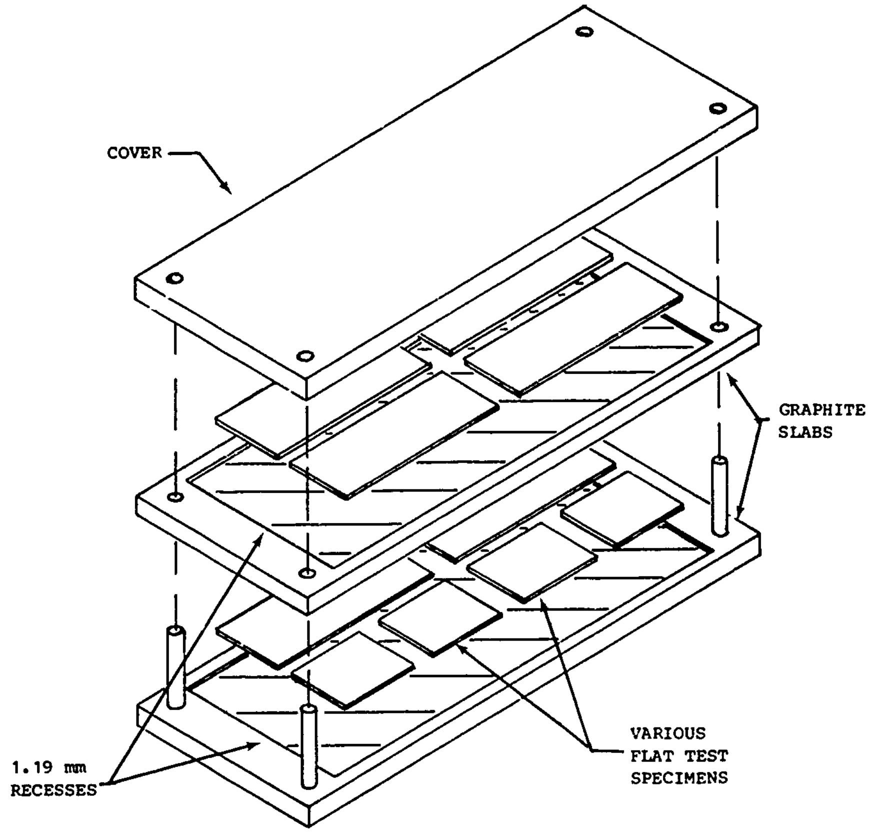


Figure 13. Graphite Boriding Tooling for Flat Specimens

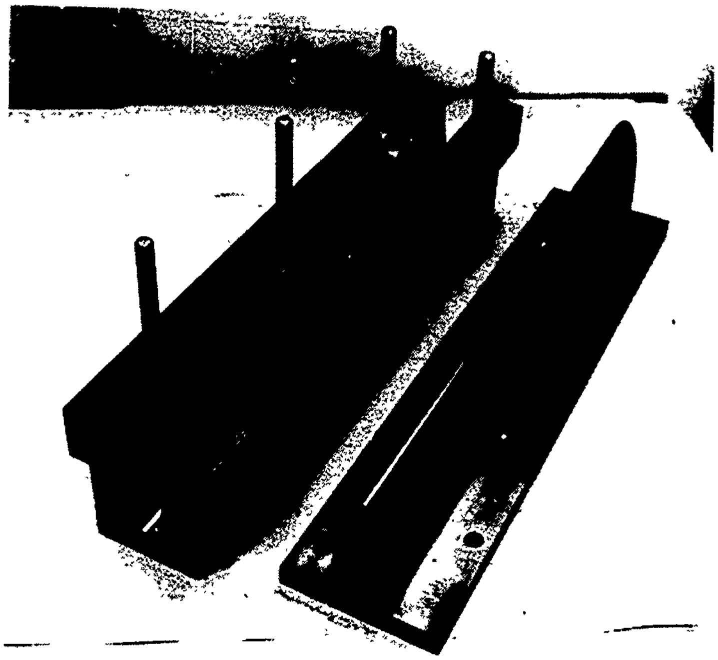


Figure 14. Male (Right) and Female (Left) Graphite Mandrels for Boriding/Creep Forming UH-1H Nose Caps

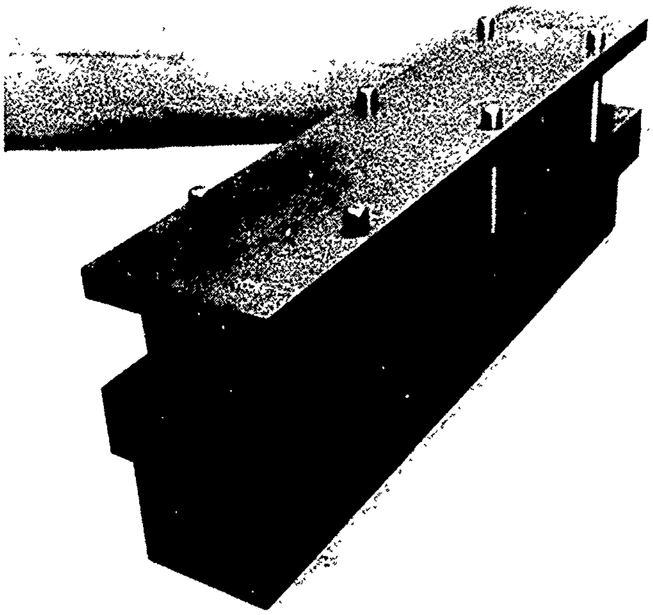


Figure 15. UH-1H Mandrels Assembled in Position Ready for Use

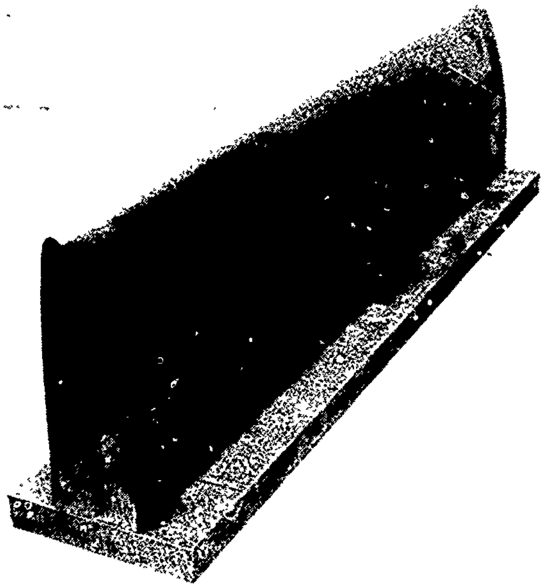


Figure 16. Male Graphite Mandrel for UTTAS Nose Caps

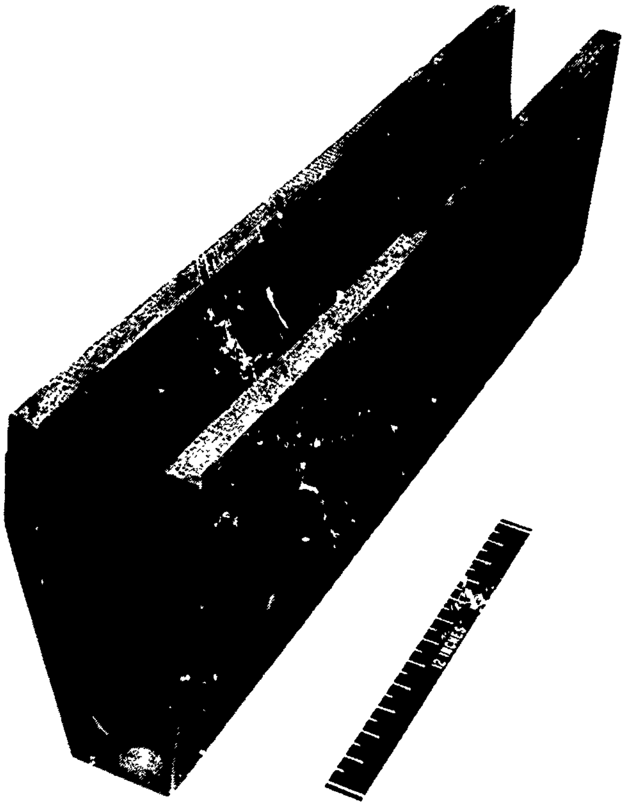


Figure 17. Female Graphite Mandrel - UTTAS Configuration

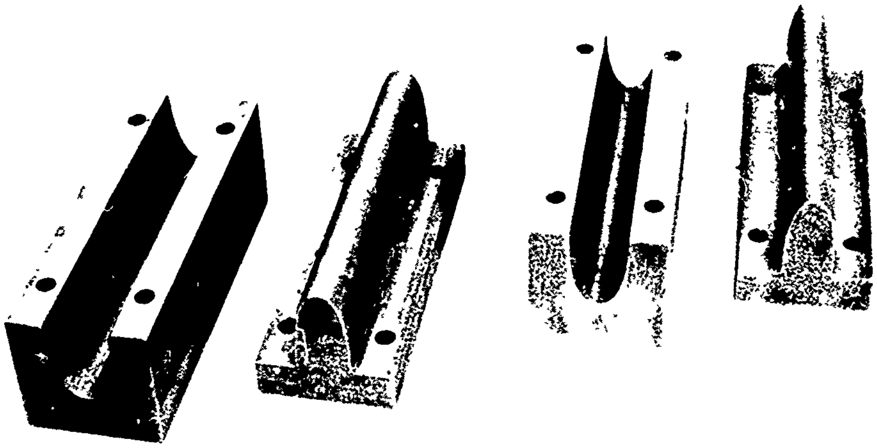


Figure 18. Male and Female Graphite Mandrel Sets for Producing Rain and Dust Erosion Specimens

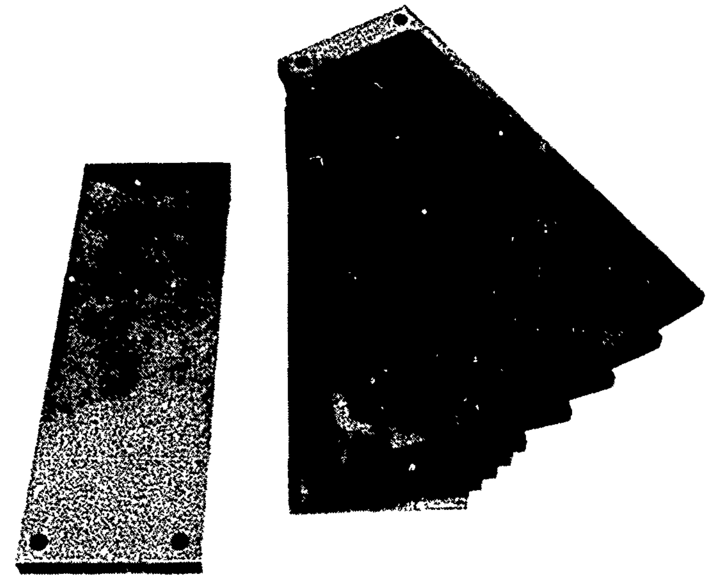


Figure 19. Graphite Mandrels for Flat Specimens

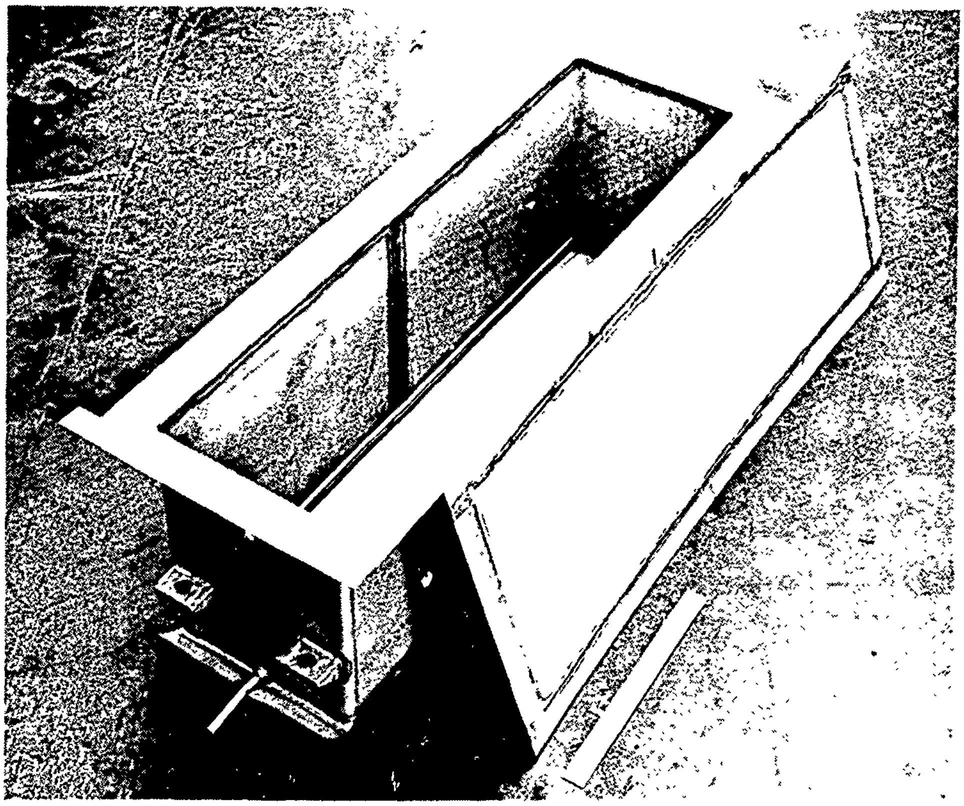


Figure 20. Boriding Retort. Material: Inconel 600; 12-Inch Rule Indicates Scale

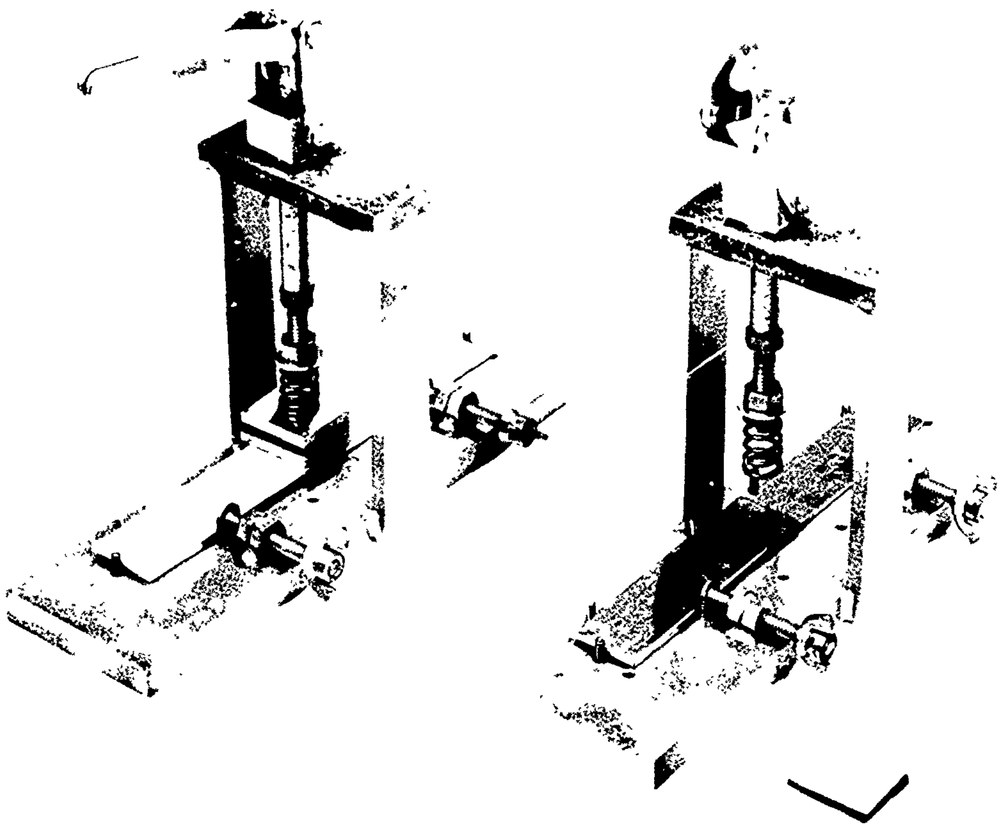


Figure 21. Fixtures Used for Adhesive Bonding Tensile Shear Specimens

Coating Processes

The process parameters selected for the coatings in this program are listed below.

Alloy	Process Temperature (°F)	Process Time (hrs)	Coating Thickness (mil)
SAE 430	1700	4	2.00 ± 0.21
Ti-6Al-4V	2100	4	0.50 ± 0.04
A75Ti	2100	4	0.50 ± 0.04

Several variations of conventional coating techniques were investigated in the early stages of the program. Use of a male mandrel for supporting large airfoil shapes without a female mandrel was attempted. Two problems were encountered with the use of this approach: (1) during the process the clad

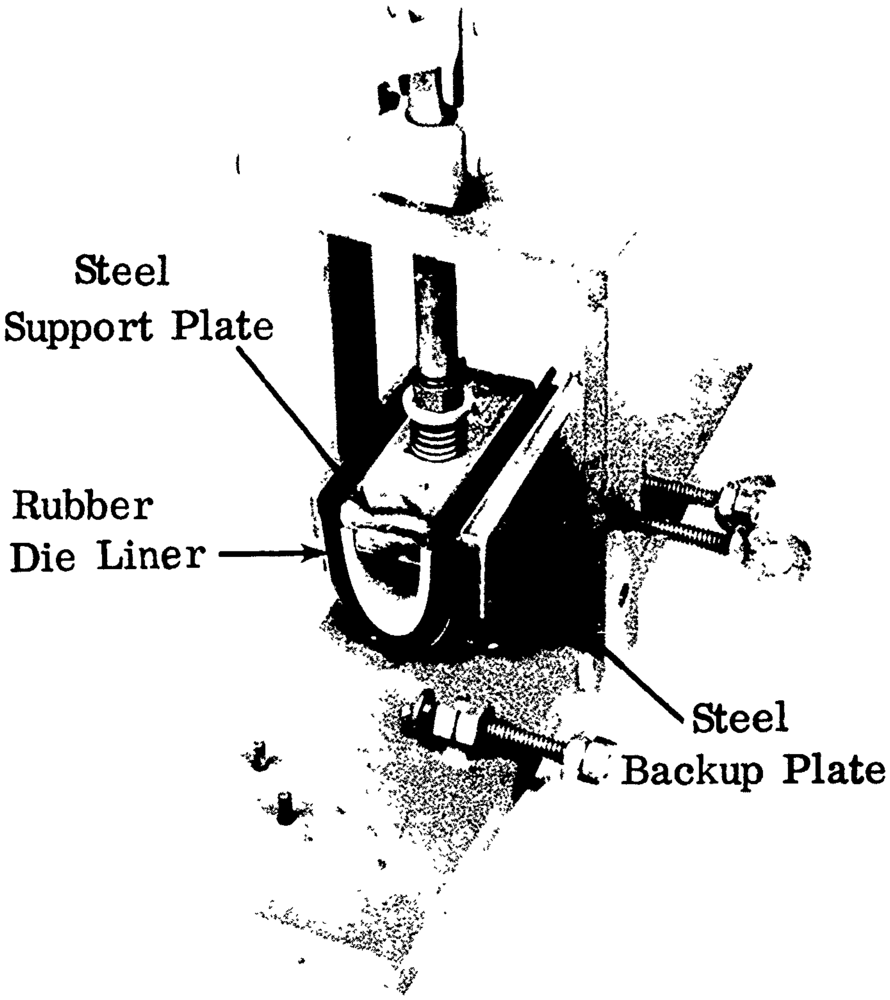
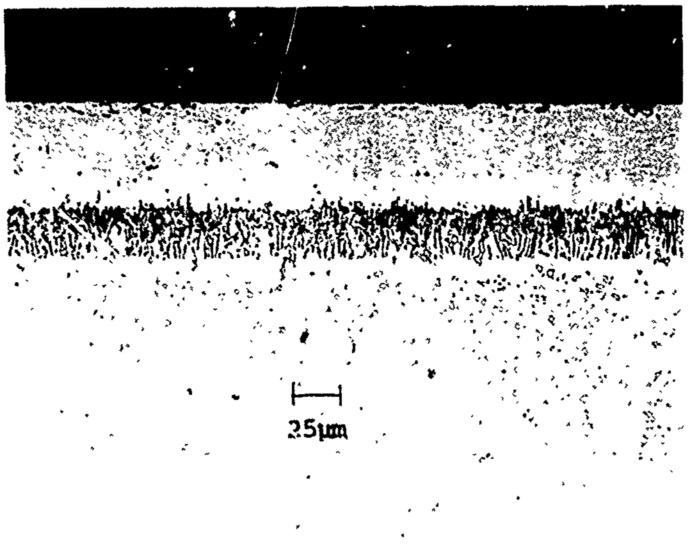


Figure 22. Fixture Used for Adhesive Bonding Borided Clads to AFML Substrates for Rain Erosion Tests

separated from the mandrel providing inadequate conformation to the rotor blade for adequate adhesive bonding and (2) a slightly different coating thickness side-to-side was obtained. Use of a full contact female mandrel proved essential to remedy these problems.

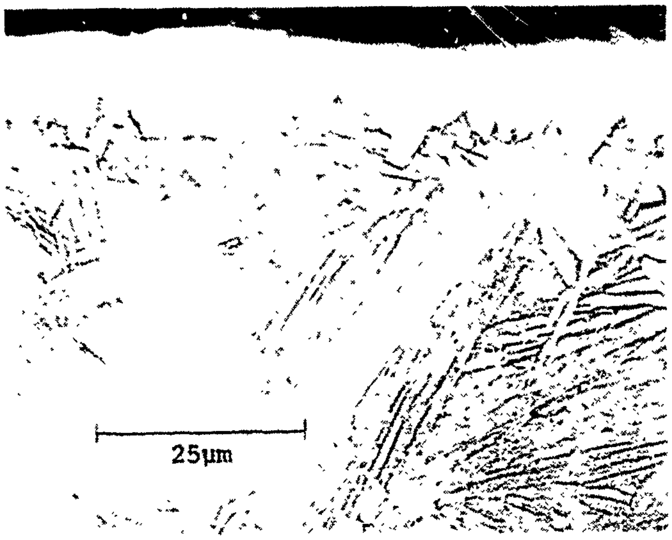
A different variation in technique involved coating in a vacuum furnace rather than in a retort with an inert gas atmosphere. Coating quality of the parts tested was equivalent to retort-fired parts and graphite mandrels were again required. Vacuum furnaces large enough to handle rotor blade nose caps were not available for this development program, so the technique was not pursued.



430 Alloy

Coating Hardness: 1800 KHN (100 gm load)

Magnification: 250x



Ti-6Al-4V Alloy

Coating Hardness: 3250 KHN (100 gm load)

Etchant: Vilella's

Magnification: 1000X

Figure 23. Microstructures of Solar Solide™ Coating on 430 Stainless Steel and Ti-6Al-4V Alloys

Initial attempts at coating using the newly designed custom graphite mandrels and the standard retort - inert gas technique revealed several phenomena which were critical to optimum process control. Coating cosmetic appearance, maintenance of dimensional accuracy and lengthwise growth were all addressed as potential problems during this phase of process development. It was discovered that cosmetic blemishes would occur on the coating when the mandrels scraped the bisque in locations of point contact. Also, it was necessary that the graphite completely enclose the prepared part. When openings were left where a large surface of the unfired part had a direct line-of-sight to a retort wall, the resulting coating was blotched or darkened. This was assumed due to vapors escaping to the surroundings. In all experiments, thicker, more continuous coatings were achieved when vapor confinement by graphite was maintained. Figure 24 shows side shields which were added to the UH-1H mandrels for this purpose.

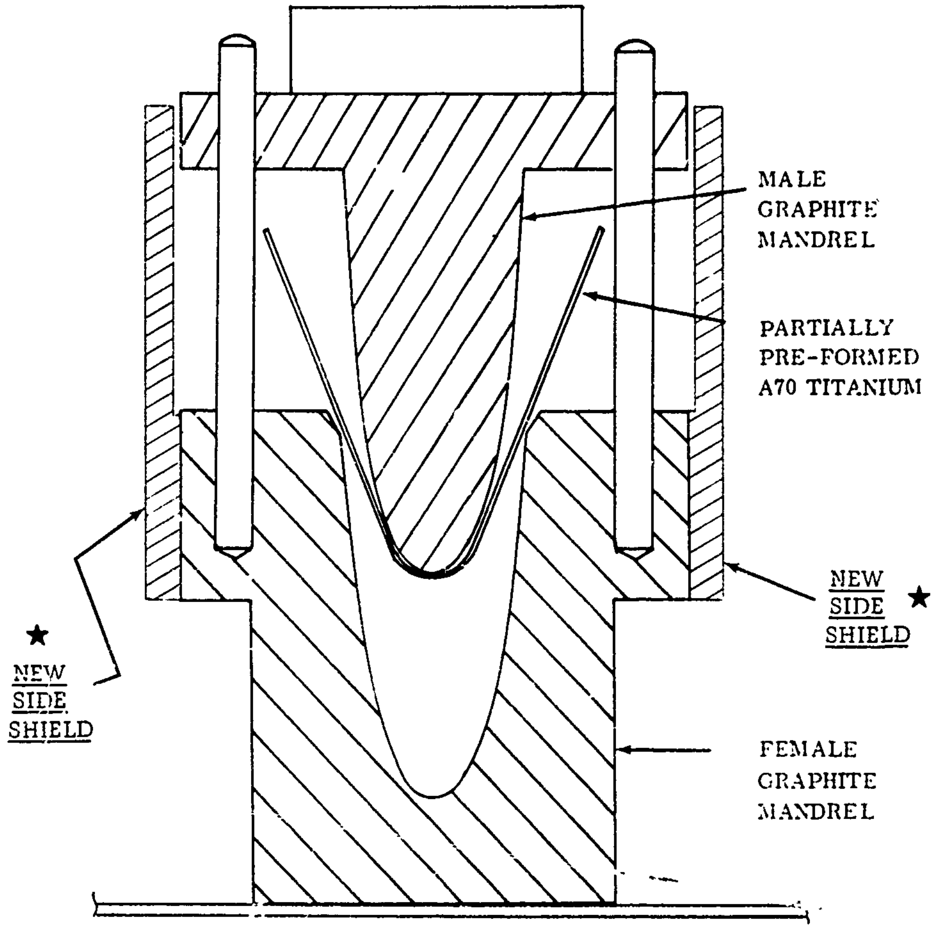


Figure 24. UH-1H Graphite Mandrel Set Showing New Side Shields

Additional coating quality improvement was obtained by pre-forming the titanium blanks closer to their final shapes prior to coating. This allowed for more complete assembly of the parts with the graphite mandrel sets. Optimum clearance between the male and female mandrels was found to be: substrate metal thickness +0.015-0.020 inch. Less clearance prevented complete creep-forming of the parts while greater clearances allowed the parts to undergo ripple or washboard distortion within the mandrels.

When the proper mandrel clearance was employed the volumetric expansion of the surface of the substrate material resulted in controlled lengthwise growth of parts (0.5-1.5%) without affecting the profile. The mismatched expansion between the coating and substrate results in a residual compressive stress in the coating upon cooldown. For titanium samples the residual compressive stress was calculated to be 3500-5000 psi typically.

Coating of Samples and Test Specimens

The samples and specimens called for in the contract for this program are illustrated in Figure 25. The first to be coated were the subscale airfoil coated and bonded specimens for rain and dust erosion testing. They were coated in pairs using the new graphite mandrel sets and were the initial specimens utilizing the new coating/creep forming technique. First to be attempted were the 0.040 inch thick A75 titanium test pieces which were to be bonded to standard aluminum airfoil substrates. The first pair processed was not completely formed, apparently because the male (top) mandrel was not heavy enough to cause the desired creep forming. For the next pair attempted (Nos. 3 and 4) a tantalum weight (1.88 lb) was added on top of the male mandrel producing a forming pressure of 0.24 psi. In spite of this, specimens Nos. 3 and 4 (as shown in Figure 26) were not formed successfully. Although the forming pressure was sufficient to initiate creeping, the specimens never formed completely because the clearance (0.045 in.) between the male and female mandrels was too small. The result was that both specimens acquired an excellent coating over the 75 to 80 percent of their surfaces which were properly formed and encased within the graphite mandrels. However,the tips which were clear of the mandrels and not shielded from the walls of the Inconel retort acquired a poor quality, discolored coating, as can be seen in Figure 26. To alleviate this problem, two changes were made in the process for the next pair of specimens. The clearance between the mandrels was opened to 0.055 inch and a graphite box was used to enclose the sides of the mandrel to shield the specimens from the retort walls. The next pair of specimens achieved very good quality coatings and were formed completely to the desired airfoil shape. The same technique was successfully used to produce eight good rain and dust erosion specimens of this type. Figure 27 shows the eight specimens and a sample of the standard aluminum substrate to which they were later bonded. The average coating weight gain per specimen was 2.13 mg/ per sq.cm of surface area on both inside and outside surfaces.

Using identical techniques, a set of eight rain and dust erosion specimens of nearly identical configuration were coated and creep formed in Ti-6Al-4V alloy. They acquired an average coating weighing 1.76 mg/sq.cm. They were made for eventual bonding to glass-epoxy substrates. Figure 28 shows the dimensions of the two airfoil blanks required for testing in the rain erosion facility at Wright-Patterson Air Force Base.

With the new flat graphite mandrels the entire group of flat test specimens was borided with excellent results. The 70 specimens are displayed in Figure 29. All are 0.040 inch flat material. Half were Ti-6Al-4V alloy and half are A75Ti. Included in the group are specimens for tensile testing, airfoil fatigue (strain compatibility), adhesive shear strength and salt spray tests.

The results of coating so many specimens at once under identical conditions provided a wealth of comparative data about the basic coating process with titanium. Several phenomena related to the coating were observed and recorded.

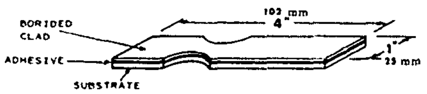
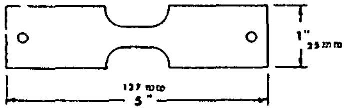
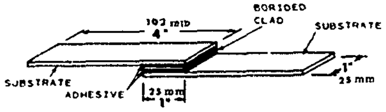
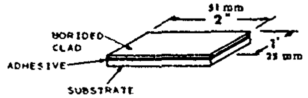
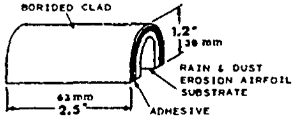
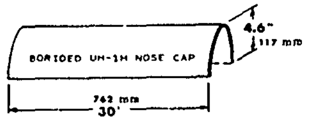
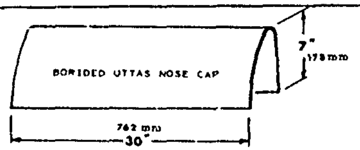
	Tests	Materials	Quantity	Test Conditions
	STRAIN COMPATIBILITY • Air foil fatigue test	Clad: 1.02 mm A75Ti Substrate: 2.03 mm 2024 Alum.	10	Vibrated to failure at resonant frequence
		Clad: 1.02 mm Ti-6Al-4V Substrate: 2.36 mm G-10 fiberglass	10	
	TENSILE TEST	Borided 1.02 mm A75Ti	9	Room temperature tensile tests • As received - no coating • After 1150°C H.T. - no coating • As coated • Coated and heat treated
		Borided 1.02 mm Ti-6Al-4V	9	
		Uncoated 1.02 mm A75Ti	9	
		Uncoated 1.02 mm Ti-6Al-4V	9	
	SHEAR STRENGTH TEST	Clad: 1.02 mm A75Ti Substrate: 2.03 mm 2024 Alum.	6	Sheared to failure • Baselines without clad insert • Standard with clad insert
		Clad 1.02 mm Ti-6Al-4V Substrate: 2.36 mm G-10 fiberglass	6	
		Substrate: 2.03 mm 2024 Alum. — Without Clad Insert	6	
		Substrate: 2.36 mm G-10 fiberglass	6	
	SALT SPRAY TEST	Clad: 1.02 mm A75Ti Substrate: 2.03 mm 2024 Alum.	10	Salt spray for 250 hours followed by tensile adhesion test
		Clad: 1.02 mm A75Ti Substrate 2.36 mm G-10 fiberglass	10	
	EROSION RESISTANCE • Dust erosion test • Rain erosion test BALLISTIC IMPACT	Clad: 1.02 mm A75Ti Substrate. 3.17 mm 2024 Alum standard	8	Dust erosion rig test Rain erosion rig test - (by AFML) BB ballistic impact
		Clad: 1.02 mm Ti-6Al-4V Substrate: 2.36 mm glass epoxy standard	8	
	BONDING	Clad: 1.02 mm A75Ti Substrate: 762 mm section of UH-1H blade	6	
	BONDING	Clad: 1.02 mm Ti-6Al-4V Substrate: 762 mm section of UTTAS blade	-	

Figure 25. Specimen Testing Details

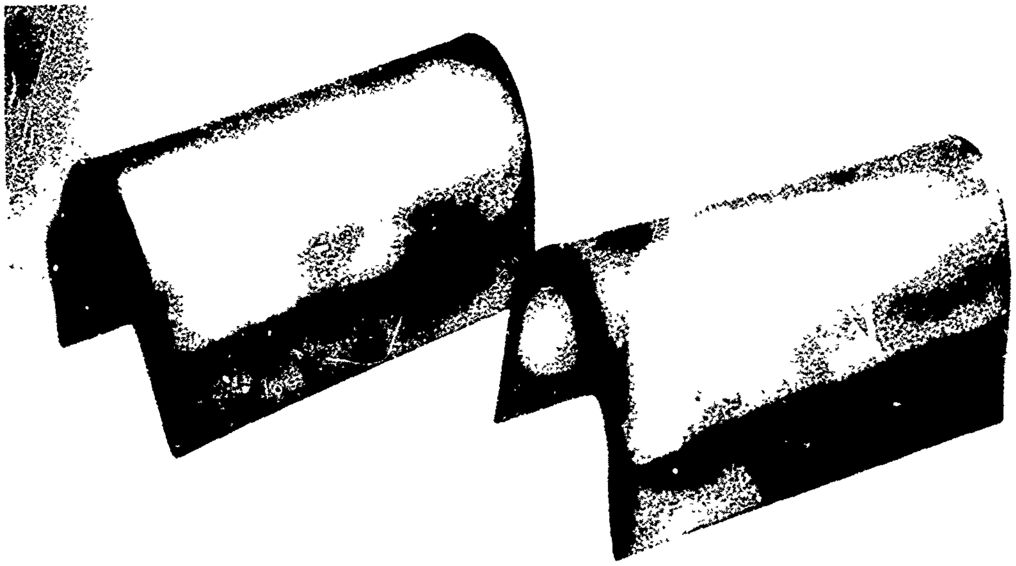
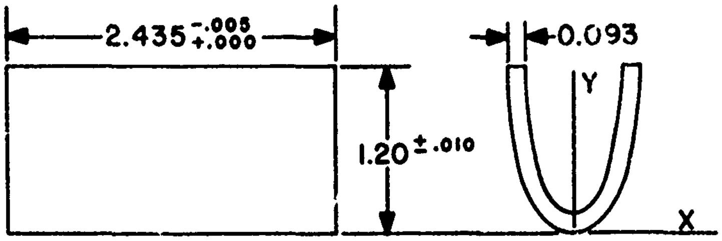


Figure 26. Rain and Dust Erosion Specimens Nos. 3 and 4 Incompletely Formed. Note the Darkened Tips Which Were Left Exposed to the Retort Walls

Figure 27. Subscale Airfoil Rain and Dust Erosion Specimens; 0.040 Inch A75 Titanium, 2.5 by 1.2 Inches Deep. At Front Right is Sample of Standard Aluminum Substrate

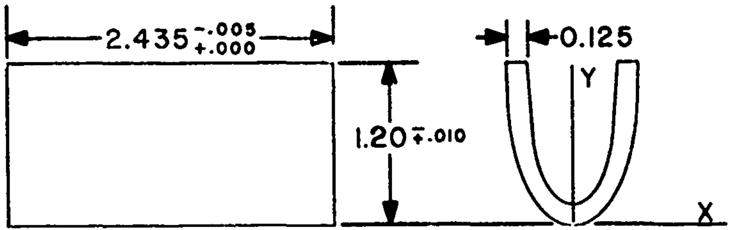


.0025 AIRFOIL - 4 INCH CHORD

DISTANCE FROM LEADING EDGE

% CHORD	ORDINATE (Y)	ABSCISSA (X)
.00	.00	.000
1.25	.05	.112
2.50	.10	.172
5.00	.20	.250
7.50	.30	.304
10.00	.40	.344
15.00	.60	.400
20.00	.80	.432
25.00	1.00	.439
30.00	1.20	.454

OUTER DIMENSIONS OF 0.093 INCH SPECIMEN
MATERIAL - GLASS EPOXY LAMINATE



.0025 AIRFOIL - 4 INCH CHORD

DISTANCE FROM LEADING EDGE

% CHORD	ORDINATE (Y)	ABSCISSA (X)
.00	.00	.000
1.25	.05	.158
2.50	.10	.218
5.00	.20	.296
7.50	.30	.350
10.00	.40	.390
15.00	.60	.446
20.00	.80	.478
25.00	1.00	.485
30.00	1.20	.500

OUTER DIMENSIONS OF 0.125 INCH SPECIMEN
MATERIAL-2024T4 ALUMINUM

Figure 28. Airfoils Used on Mach 1.2 Rain Erosion Test Apparatus, Wright-Patterson Air Force Base, Ohio

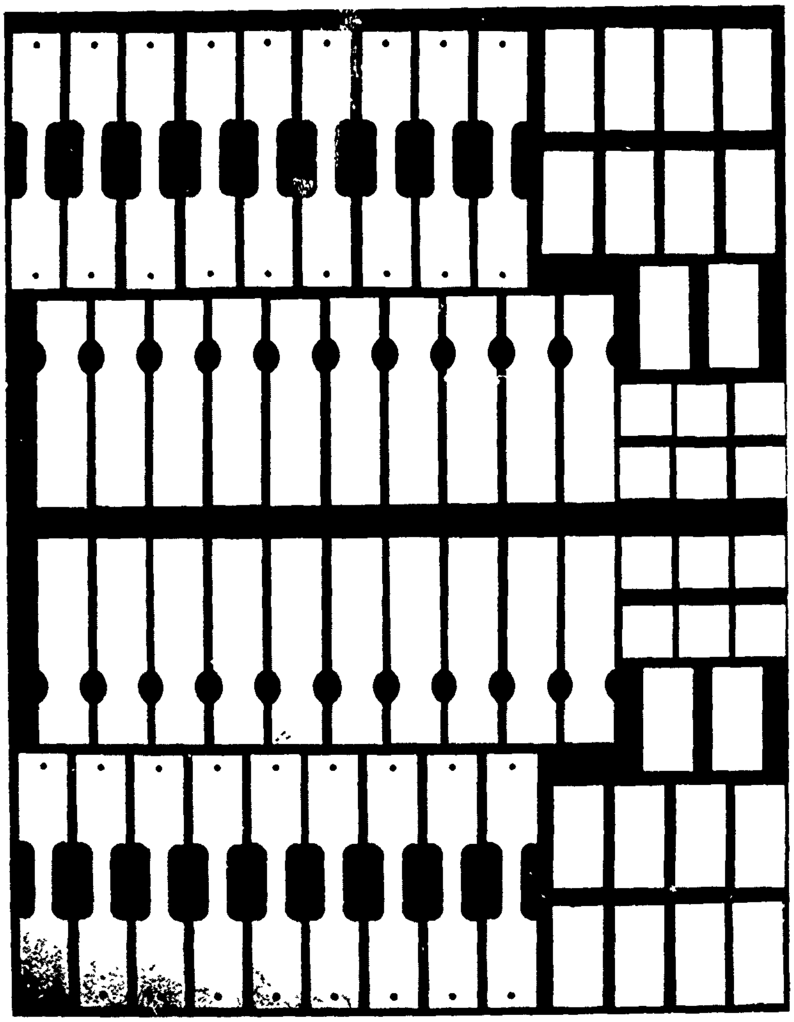


Figure 29. Borided Flat Test Specimens

1. The weight of coating achieved on each specimen per unit surface area was quite uniform. The total variation did not exceed nine percent on the A75 specimens and is about 15 perent on the Ti-6Al-4V specimens.

2. Without exception the A75 specimens acquired a heavier coating than the Ti-6Al-4V specimens under identical conditions. The A75 specimens gained an averge of 2.35 mg/cm^2 of surface area as compared to 1.97 mg/cm^2 for the Ti-6Al-4V specimens.

3. In order to account for the variations mentioned in the achieved coating weights, a correlation was sought between the weight of the bisque applied and the weight of the resultant coating on each specimen. The graphical relationships shown in Figures 30 and 31 demonstrate that although there is some scatter to the data, and certainly no straight-line relationship in evidence, a general trend does exist between bisque weight and coating weight for both alloys.

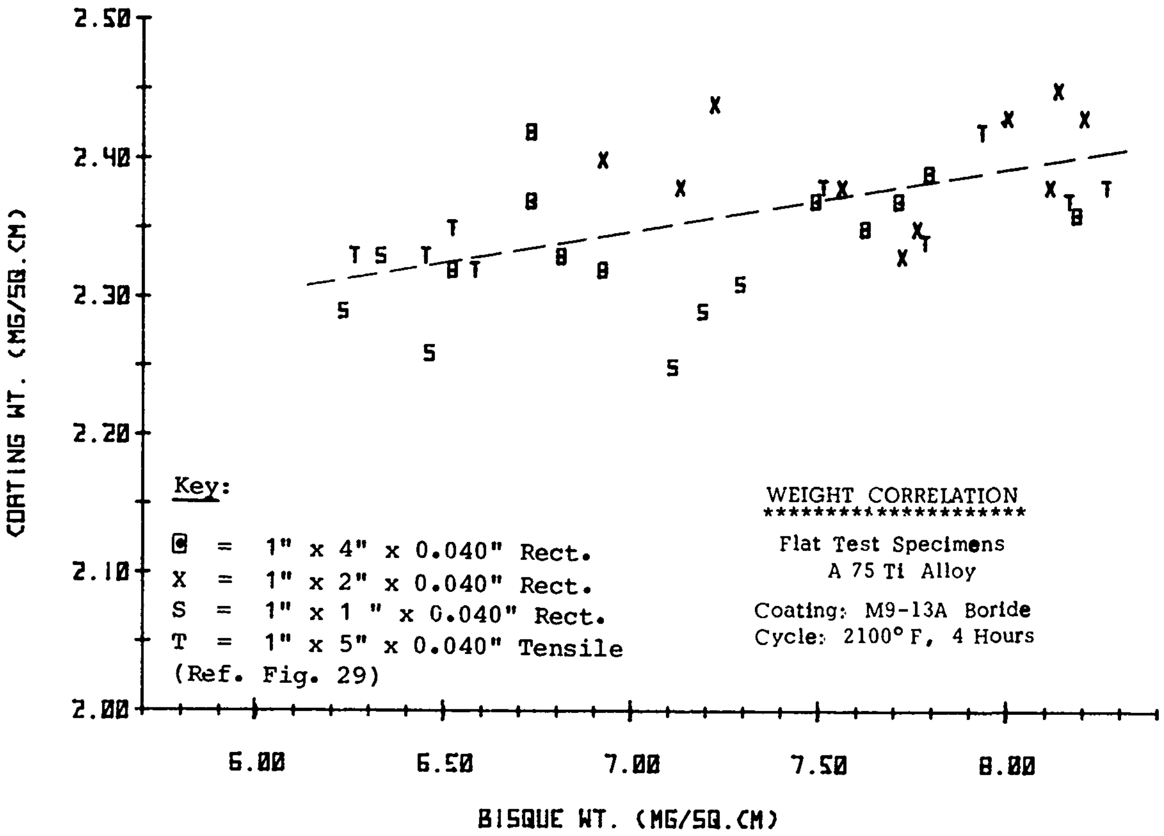


Figure 30. Bisque Versus Coating Weight Correlation for Borided A75 Titanium

At that point in the developmental work contact was made with personnel at Boeing-Vertol Company concerning Solide™ coated nose caps. They funded a special production run of whirl-arm erosion specimens and flat tensile fatigue specimens. The fatigue specimens were produced using older techniques without employing flat graphite mandrels which were not available at that time. Six UTTAS configuration whirl-arm specimens were coated using the newly acquired male mandrel and a specially made small female mandrel which was used to trap boron vapors during the boriding process and provided physical restraint to hold the pre-formed nose caps against the male mandrel. This resulted in no significant distortion from the proper airfoil profile in the finished borided parts. No linear restraint was introduced and each of the specimens was free to grow in length. The average measured before-to-after boriding growth was one percent in length. The coated whirl-arm specimens are shown in Figure 32. Specimens 1 and 2 from the first run were borided with Solar's M9-13 slip. In order to improve on the coating appearance the subsequent specimens were borided with a slightly modified slip designated M9-13A. This resulted in a cleaner and more uniform appearing coating.

During this period another early contact was made with helicopter industry personnel. Engineers from the Commercial Division of Hughes Helicopter requested five coated specimens of any airfoil shape for static erosion testing. They proved to be the first full depth specimens to be Solide™ coated:

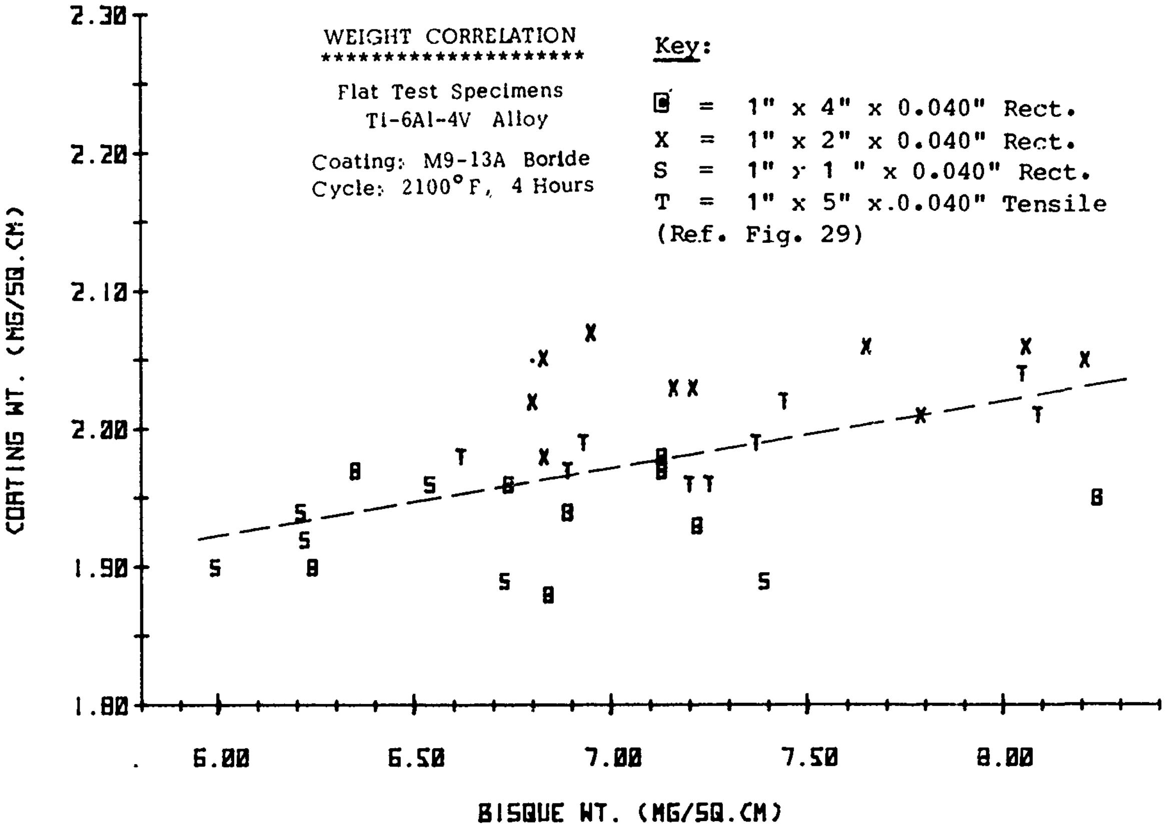


Figure 31. Bisque Versus Coating Weight Correlation for Borided Ti-6Al-4V Alloy

special 1 inch wide UTTAS configuration specimens of 0.040 inch Ti-6Al-4V alloy. Figure 33 shows the five specimens after coating. Hughes had requested them in order to test and compare them to other leading edge materials as an initial step toward eventual consideration of borided nose caps for use on production commercial helicopters manufactured by Hughes. Several other full depth test pieces (approx. 7 in. long) were coated during the same furnace run in preparation for a full scale 30 inch UTTAS nose cap. These specimens acquired an excellent coating with an average coating weight of 1.75 mg/cm^2 and no significant physical distortion.

Next the full scale 30 inch long nose caps were coated. Six Ti-6Al-4V UTTAS configuration caps were completed with excellent results. The coatings achieved were very good in appearance with an average coating weight gain of 1.92 mg/cm^2. Next, the A75Ti UH-1H nose caps were coated and creep formed using the special male and female graphite mandrels developed for the job. The results were, again, very good with fine looking coatings having an average weight gain of 2.22 mg/cm^2. Figure 34 shows several of the coated nose caps and a section of the UTTAS rotor blade.

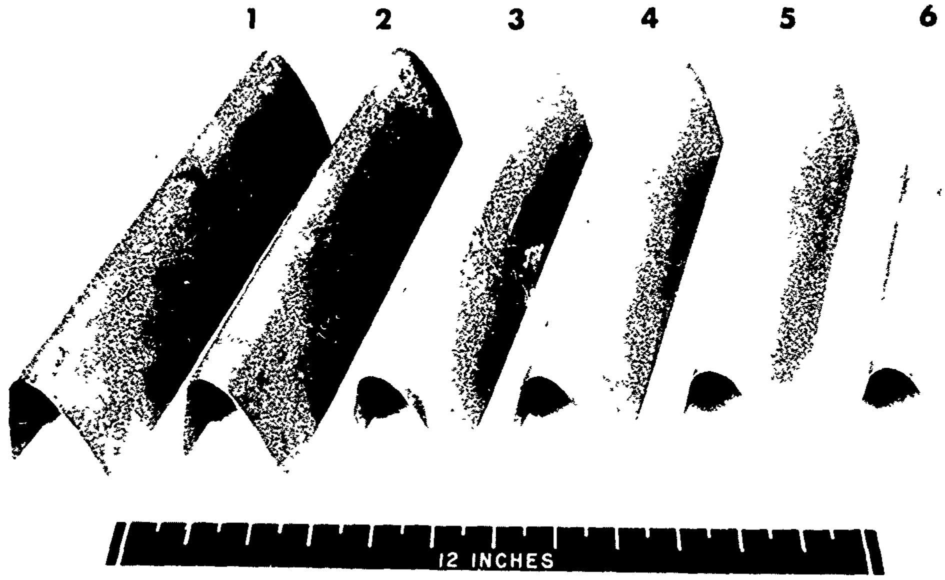


Figure 32. Whirl Arm Specimens - Boeing UTTAS Configuration; 0.040 Inch Ti-6Al-4V Alloy, 10 Inches Long

Several interesting phenomena were noted on these specimens. The achieved coating weights of the first three nose caps were directly proportional to the applied bisque, and the proportionality constant was about 0.22. This linear relationship was not so evident in earlier work with Ti-6Al-4V alloy. Varying amounts of bisque were applied to the parts prior to firing to evaluate the effect of applied bisque weight on resultant coating. The results are presented graphically in Figure 35. These values indicate that the optimum weight of bisque to be applied is 9.5-11.5 mg/sq.cm of surface area for Ti-6Al-4V alloy.

Another result worth noting concerned lengthwise expansion. Earlier work with smaller (16 in. long) parts for Boeing-Vertol indicated that a change in length of 1.6 to 2.2 percent could be expected during the coating process. Instead the maximum growth encountered was less than 0.5 percent with the initial full scale nose caps. Possibly connected to this unexpected phenomenon was the fact that several of the parts were found to be "rippled" or "corrugated" slightly at the trailing edges. Of the first four parts, this washboard distortion varied from negligible to a maximum of about 0.045 inch peak-to-peak. The relationship between linear growth and trailing edge distortion is not clear but evidence suggests that the two vary inversely. Tighter tolerance between the male and female mandrels has been shown to result in more uniform surface pressures on the part and more uniform expansion which minimizes corrugation type distortion. On each of the parts the nose (leading edge) is free of distortion where the highest pressure is felt from the weight of the mandrels.

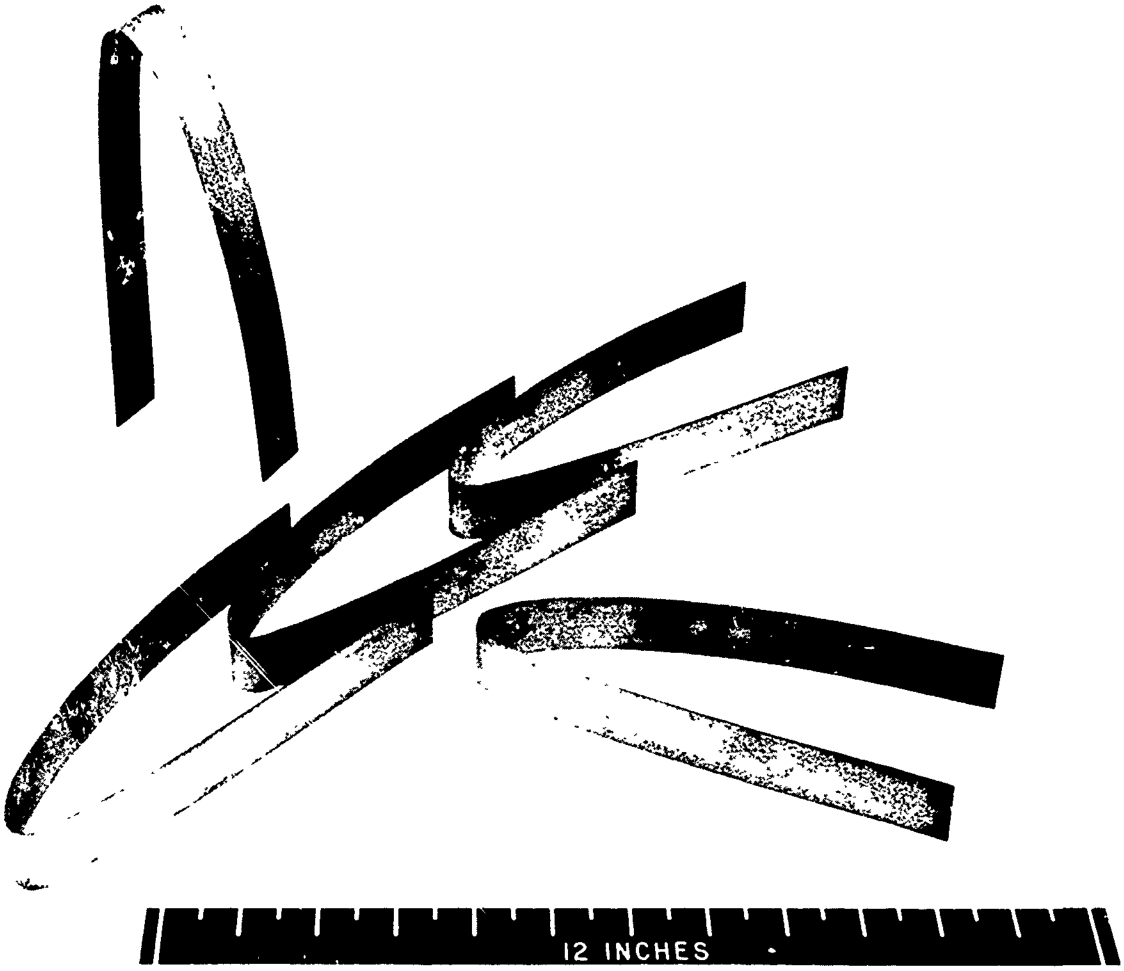


Figure 33. Static Erosion Specimens for Hughes Helicopter. Ti-6Al-4V Alloy, 0.040 Inch Thick, 1 Inch Wide, UTTAS Configuration

Standard full scale nose caps specimens were evaluated by metallographic analysis to ascertain that uniform coatings had been applied to all outside surfaces. Typical photomicrographs for leading and trailing edges appear in Figure 36 for an A75Ti UH-1H sample and in Figure 37 for a Ti-6Al-4V UTTAS sample.

Bonding

The final requirement of Phase II was to demonstrate that full scale nose caps could be successfully bonded to representative rotor blade sections. In addition, all test specimens except those for tensile testing had to be bonded.

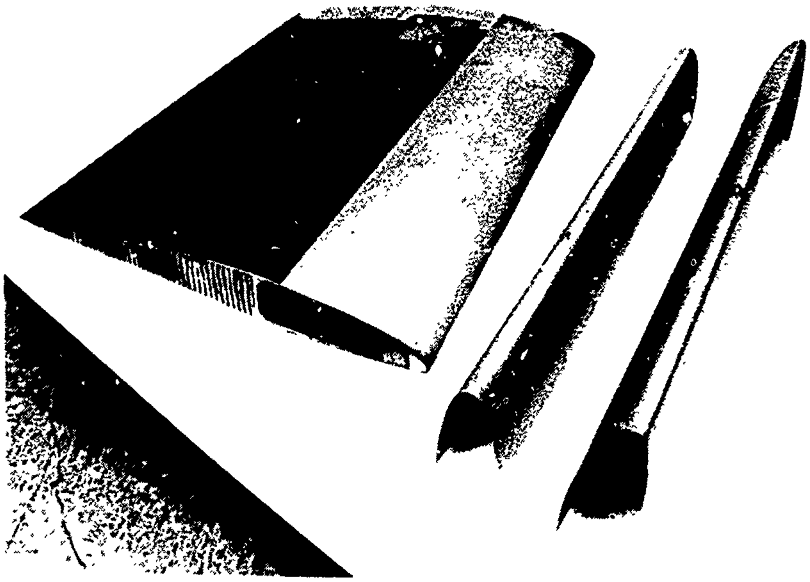


Figure 34. Full Scale Borided UTTAS and UH-1H Titanium Nose Caps

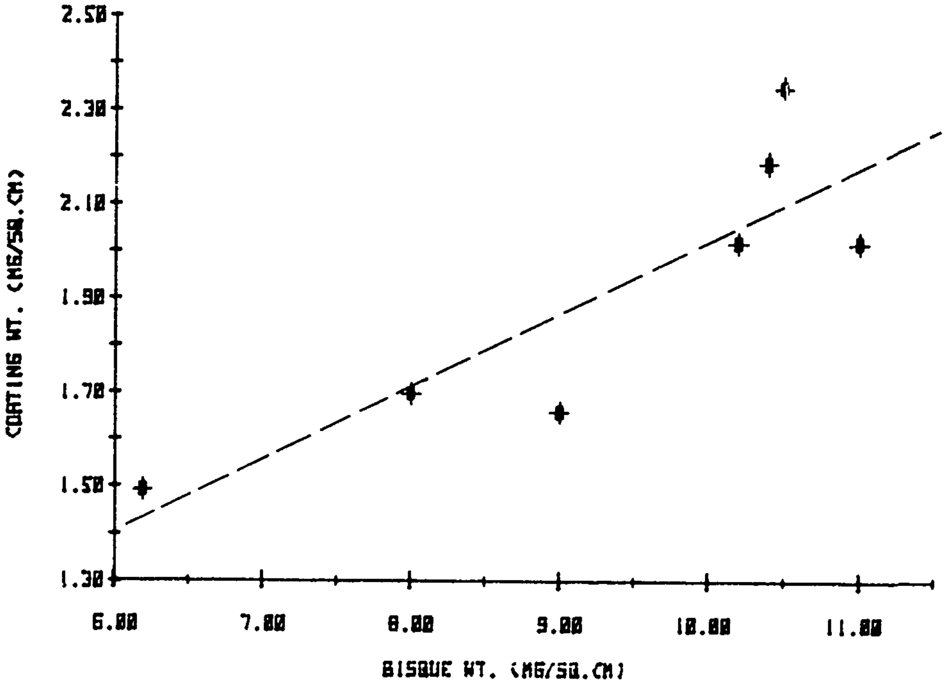


Figure 35. Coating Weight Correlation for Solide™ Coated UTTAS Nose Caps, Ti-6Al-4V Alloy

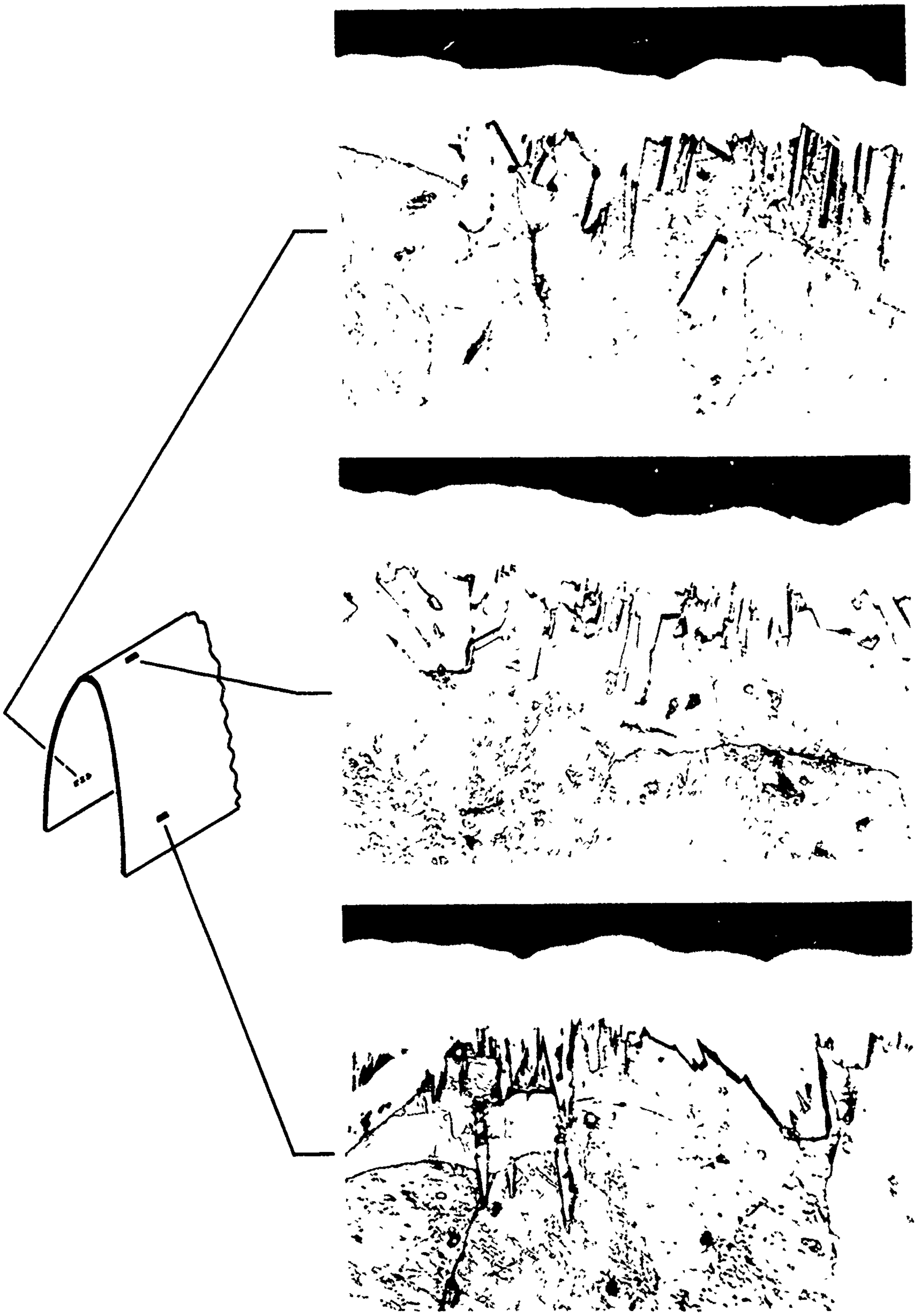


Figure 36. Standard Metallographic Sections, A75 Titanium UH-1H Full Scale Nose Caps; Magnification: 1000X

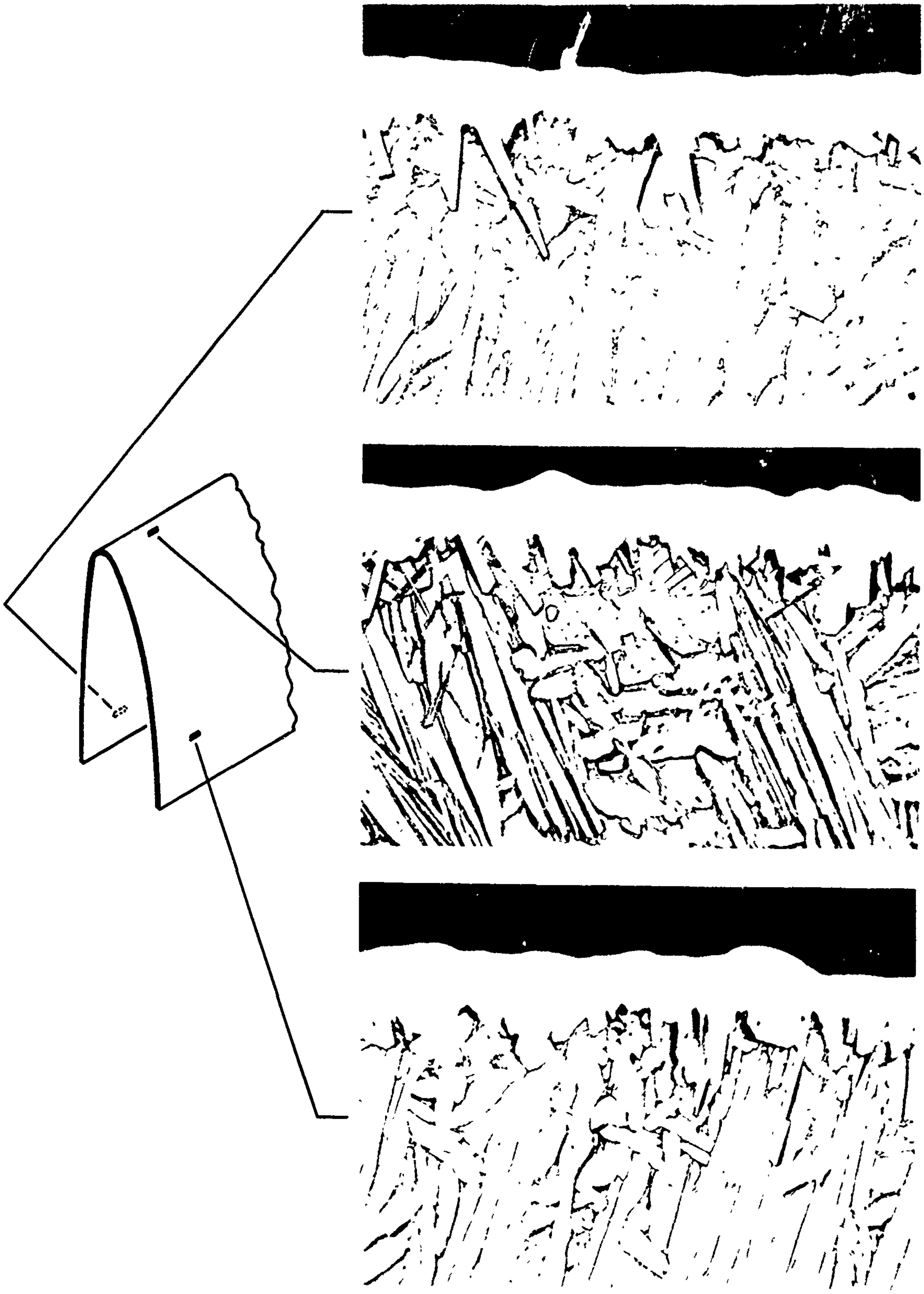


Figure 37. Standard Metallographic Sections, Ti-6Al-4V UTTAS Full Scale Nose Cap; Magnification: 1000X

Bonding of the 30-inch full scale UH-1H and UTTAS nose caps was performed by Teledyne Ryan Aeronautical of San Diego by subcontract. Each blade section and Solide™ coated nose cap was enclosed in an individual vacuum bag and then bonded in an autoclave to achieve the temperature and surface pressure required to cure the 3M Company AF-126-2 film adhesive which was used. The bonding results appeared excellent in the visual inspection. One of the coated nose caps bonded to a UTTAS fiberglass spar D-section appears in Figure 38. The smaller test specimens were bonded by Solar using the fixtures shown in the previous section and the same AF-126-2 adhesive.

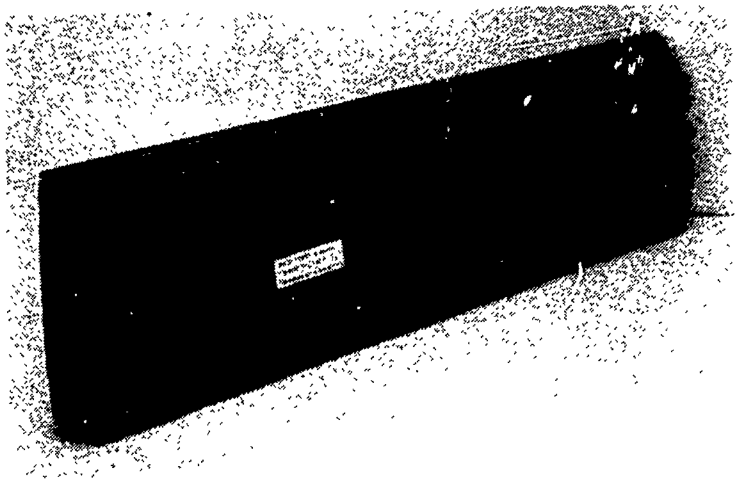


Figure 38. Solide™ Coated Nose Cap (Boeing Vertol UTTAS) Bonded to Fiberglass Spar D-Section

The completed full scale nose caps were bonded to rotor blade sections as follows:

(6) UH-1H, full depth, 0.040 inch A75Ti, 30 inches long

Bonded to 30-inch sections of salvaged UH-1H rotor blades (all-metal construction)

(3) UTTAS (Boeing-Vertol), full depth, 0.040 inch Ti-6Al-4V, 30 inches long

Bonded to 30 inches of new UTTAS fiberglass spar D-sections

(2) UTTAS, full depth, 0.040 inch Ti-6Al-4V, 30 inches long

Bonded to 30-inch sections of UTTAS blades (fiberglass-epoxy laminate construction)

(1) UTTAS (same as above) 19 inches long.

On November 3, 1977 four samples of the completed, full scale Solide™ coated nose caps were sent to AMMRC at the request of Mr. George Harris. These nose caps, bonded to actual rotor blade sections, are a portion of the 12 bonded final products of Phase II of the original contract. They met all original goals set forth at the outset of the program and demonstrated the feasibility of producing nose caps in sizes and configurations compatible with contemporary rotor design. The parts shipped were:

(2) Each 30-inch long Solide™ coated A75Ti nose caps bonded to salvaged sections of Bell UH-1H main rotor blades

(1) Each 30-inch long Solide™ coated Ti-6Al-4V nose cap bonded to a salvaged section of Boeing-Vertol UTTAS main rotor blade

(1) Each 30-inch long Solide™ coated Ti-6Al-4V nose cap bonded to an unused D-spar section of a Boeing-Vertol UTTAS blade.

Coating Removal

On several occasions interested personnel expressed their desire that Solide™ coated parts be uncoated on the inner (concave) surface. This was to avoid a possible problem of adhesive bonding to the coated surface. In an effort to ascertain the feasibility of coating only one side at a time, several experiments were performed on titanium test pieces using graphite tooling. Results were negative. Masking areas of the test specimens with molybdenum foil, ZrO_2, and/or bare graphite was attempted. In all cases warping and contaminated bare metal surfaces were obtained.

Another approach to the problem was attempted, namely, chemical stripping. Experiments were run in which the specimens were borided on all surfaces and then partially masked and subjected to acid bath stripping. Figure 39 shows the results of one coating and stripping operation. In the upper photo a test specimen of borided Ti-6Al-4V was masked on the right side and stripped on the left in an acid solution of $3HF-20HNO_3-77H_2O$ for 80 minutes. The microphotographs in the lower part of Figure 39 (1000X magnification) show the comparative results of the stripping action in the masked and unmasked regions. Total material removal in this example averaged 1.2 mil per side. The masked area can be seen to have maintained its boride coating in good condition. The method appeared feasible at that point although it was not pursued because no bonding problems had been encountered.

2.1.3 Phase III - Testing and Evaluation

The developmental program completed in March 1976 which was the predecessor to this program was based primarily on identification of coating processes and constituents plus comparison of substrate materials. Some testing was performed. Most was aimed at identification of coating properties and properties of substrate-clad combinations for the purpose of initial screening.

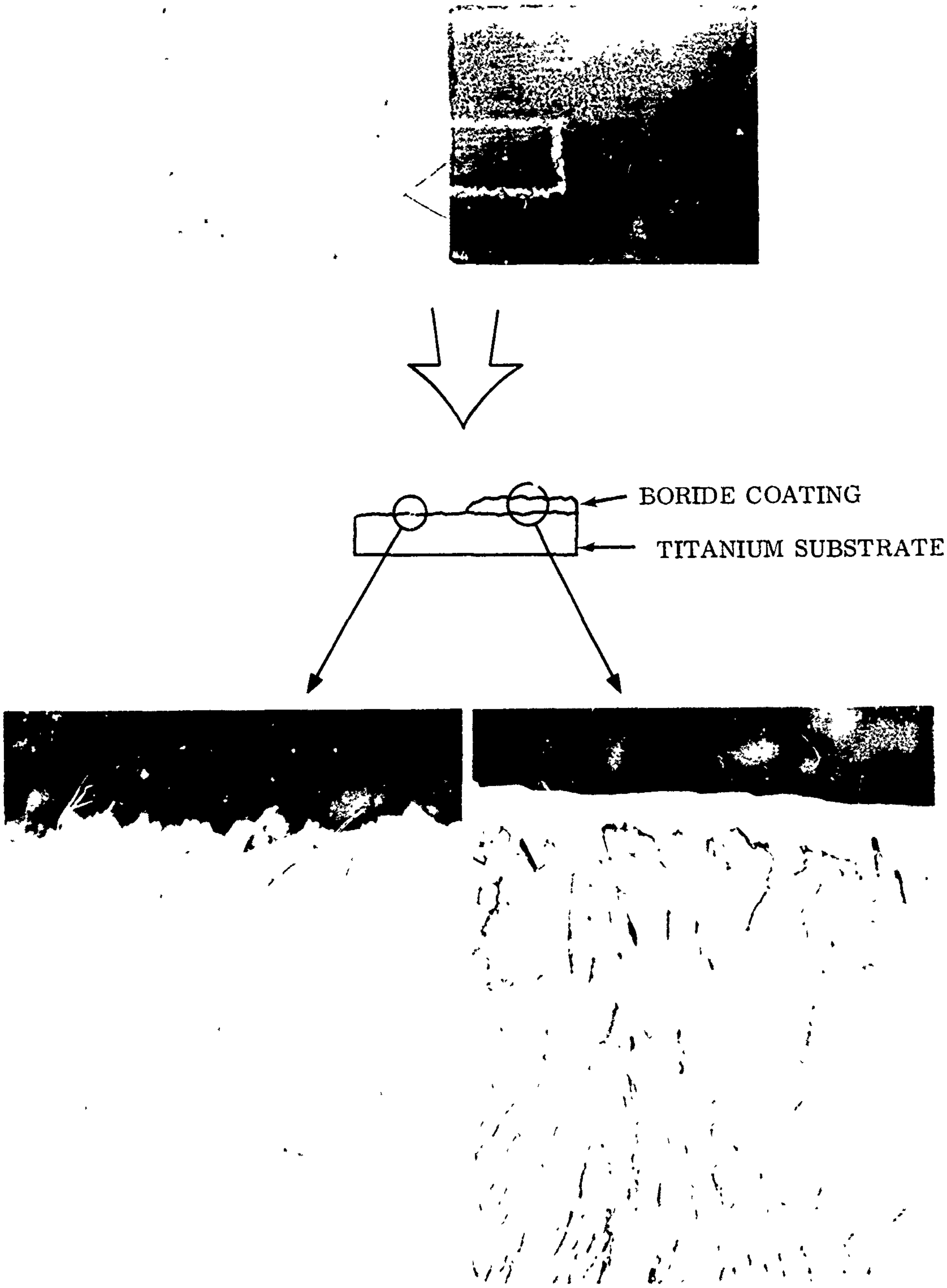


Figure 39. Results of Boride Stripping Experiment

The final testing of the optimum coating and substrate combinations included airfoil fatigue, impact, bonding, and erosion tests.

The present program, based primarily on development of improved, large scale manufacturing processes, also included a concentrated series of tests aimed at verifying the previous results and demonstrating that new tooling, coating processes, and scaleup were not detrimental to coating performance. The coating work performed in Phase II resulted in a full set of demonstration samples and test specimens, as detailed in Figure 25. Figure 40 shows how these specimens were used in the testing sequence of Phase III.

Erosion Tests

The erosion tests were the most critical of the tests performed because the function of Solide™ coated clads is the resistance of rain and/or dust erosion at subsonic impingement velocities. Erosion testing in general falls into two categories: 1) static, where the specimen is motionless and 2) dynamic, where the specimen is moved with a specified velocity into the path of near motionless particles or droplets. For water droplet erosion testing, dynamic testing is most common using whirl arms to achieve specimen velocity within a controlled rainfield. Droplet/specimen impacts are randomized as much as possible in a manner similar to actual rain storm conditions. For sand erosion testing both static and dynamic tests are commonly employed. Dynamic testing using whirl arms is more costly and certain variables are less controllable but this type of testing is essential for conditions requiring large particles at high (near sonic)impact velocities. Static tests are less expensive and the equipment required is less ponderous while greater control is possible over variables such as impingement angle and identification of types and quantities of impacting particles. Since the particles must be accelerated at stationary specimens, impact velocities and particle sizes have distinct upper limits and are difficult to measure with assurance in static test rigs.

For this program the initial dust ersoion test work was performed on Solar's static test rig using a vertical acceleration tube to achieve the selected impact velocities. Figures 41 and 42 show the facility. Later tests using whirl arm test rigs were performed as discussed in subsequent sections of this report.

Test conditions for Solar's dust erosion testing were the same as those used in the previous coating development program:

Particle type: Arizona road dust (primarily silica)
Particle size: 43-74 microns
Amount of particles: 45 gm per specimen
Particle velocity: 650-700 fps

In the past, flat specimens (1 in. by 2 in.) were used as erosion targets and impingement angles were controlled as shown in Figure 42. For this test effort airfoil leading edge specimens were coated and bonded to aluminum and

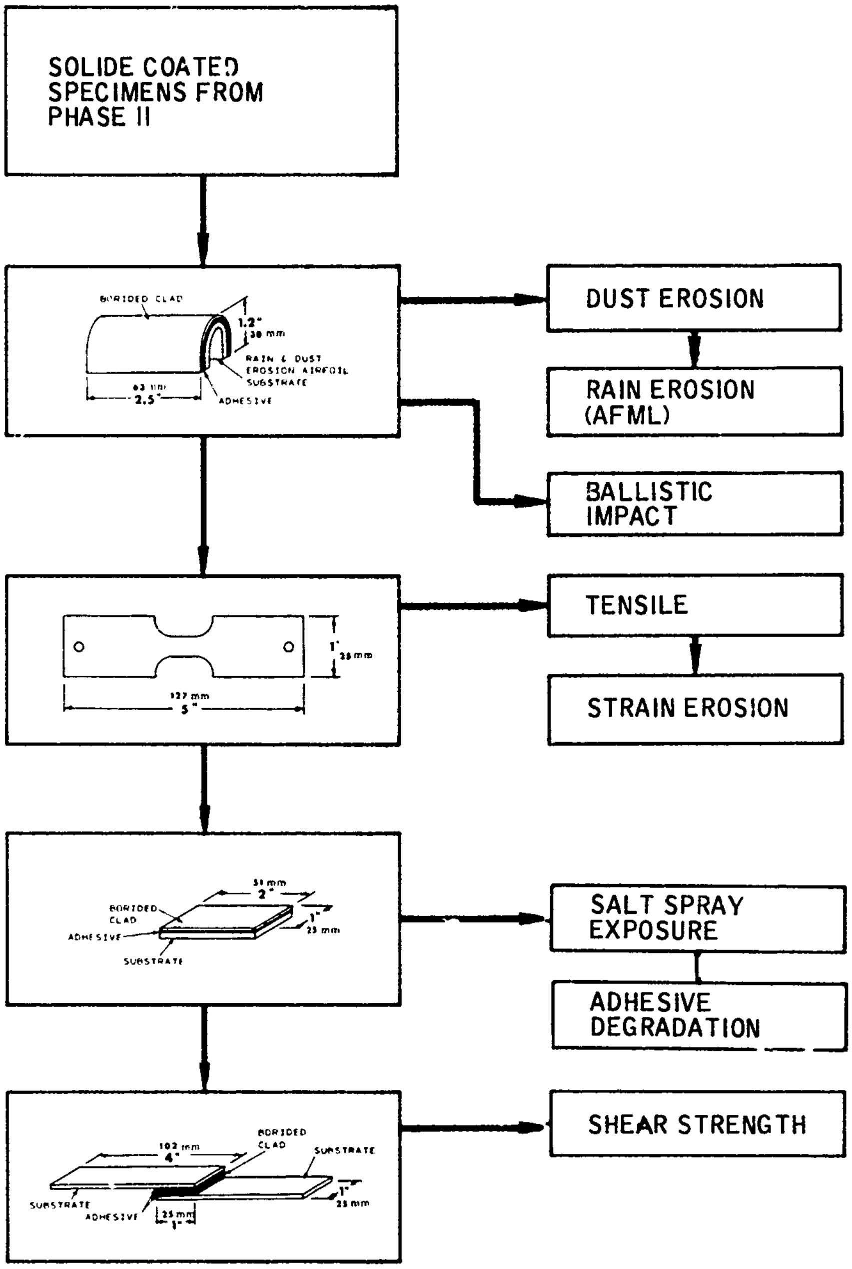


Figure 40. Phase III - Testing Sequence

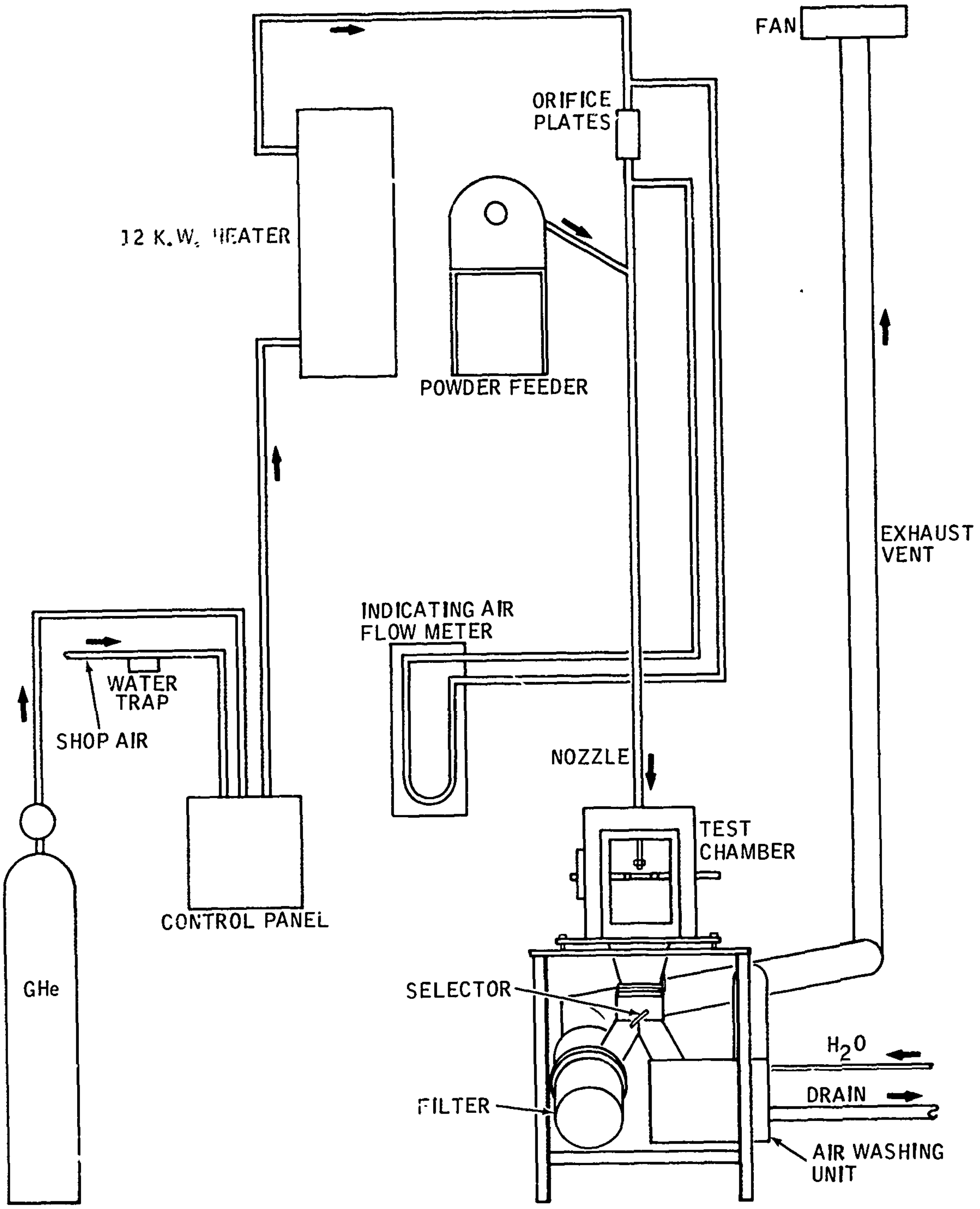


Figure 41. Schematic of Solar Dust Erosion Test Facility

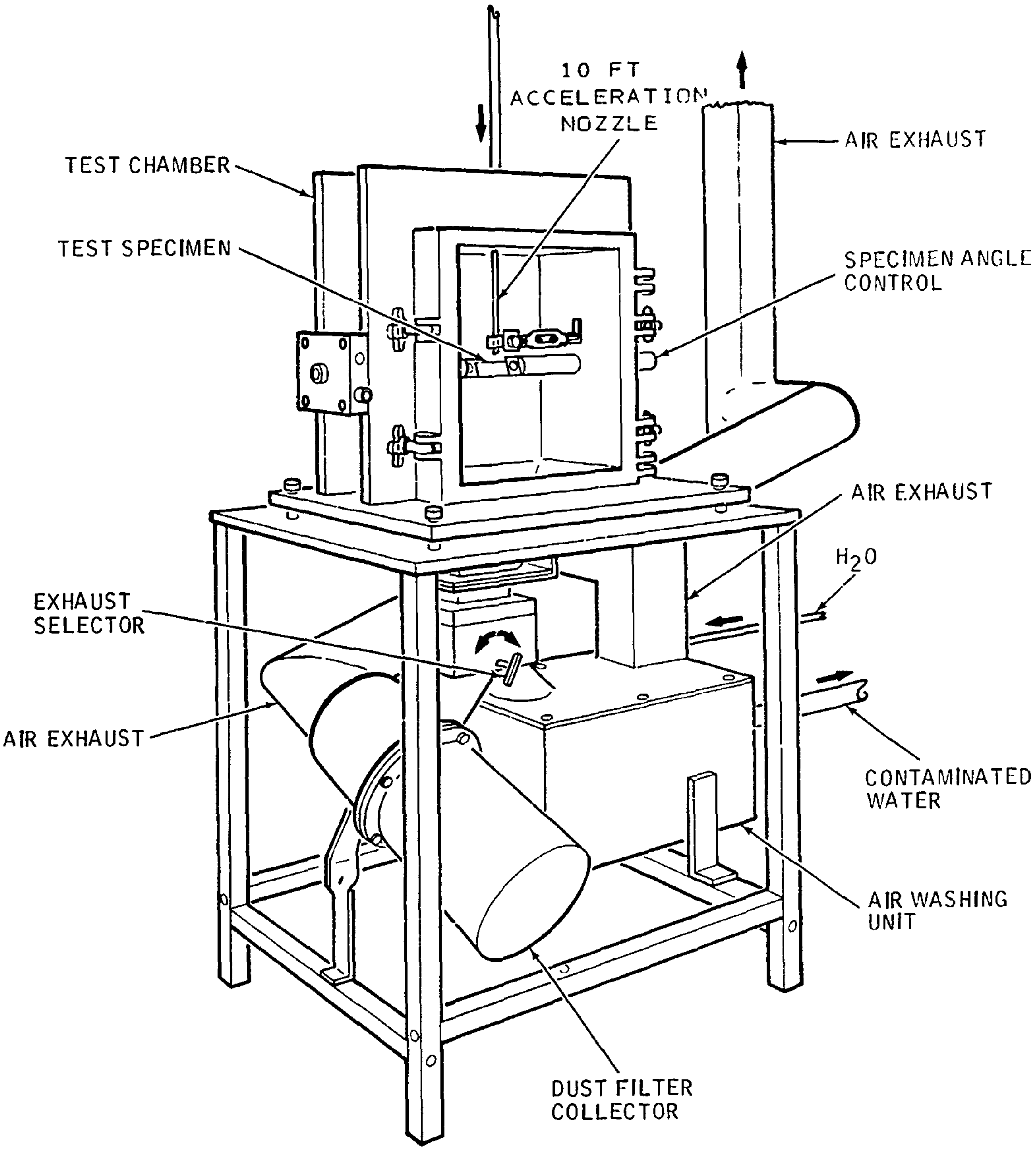


Figure 42. Closeup of Dust Erosion Test Chamber

fiberglass airfoils as described in the previous section. The specimens were positioned so that dust impingement occurred over a 3/8-inch diameter area directly on the nose of the specimen with a zero angle of attack. This resulted in effective impingement angles over the nose radius ranging from 90 degrees at the nose to approximately 45 degrees at the edges of the erosion zone. Also included in those tests were two special specimens. The first was a sample of electro formed nickel nose cap material now being used by Sikorsky. The second was a specimen which was hot formed to fit a standard fiberglass substrate after being coated. Several attempts were made to produce an acceptable airfoil erosion specimen which was coated in the flat condition with simple graphite slab tooling and then formed to any desired shape. If such a technique could be used to produce erosion resistant shapes it would indicate a breakthrough in cost reduction for the coating process on formed shapes.

Several pre-coated parts were used in an attempt to form a standard subscale rain and dust erosion specimen. The first attempt was done cold. In the cold state the titanium was much too brittle to be formed and cracked through after only slight bending. By heating with a gas torch the next specimen was successfully formed using a steel punch and die. Microphotographs showed that many cracks occurred in the coating as a result of bending but that the coating was intact in the areas adjacent to the cracks and elsewhere. The formed part was bonded to a standard subscale glass epoxy substrate and included in the rain and dust erosion tests. Previous tests on specimens with cracked coatings have indicated that dust erosion resistance is retained in spite of obvious coating damage. Figures 43 and 44 show an example of one of the earlier attempts in this vein. The dark coloration of the specimen in the areas not eroded was due to oxidation as a result of heating in air during the forming operation. The eroded area is light (the color of the boride coating) because the oxidation film was cleaned away in that area by the impinging dust particles.

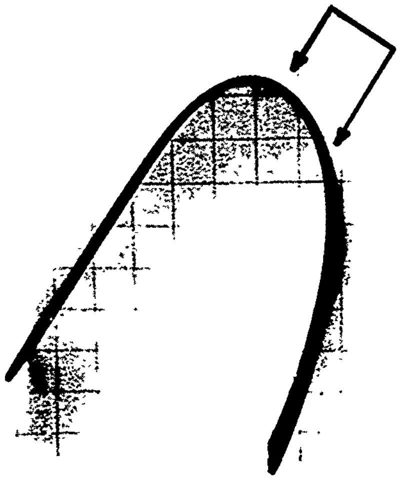


Figure 43.

A75 Titanium Specimen Hot Formed After Boride Coating

Actual Scale

Arrows Denote Location and Direction of Erosion Test

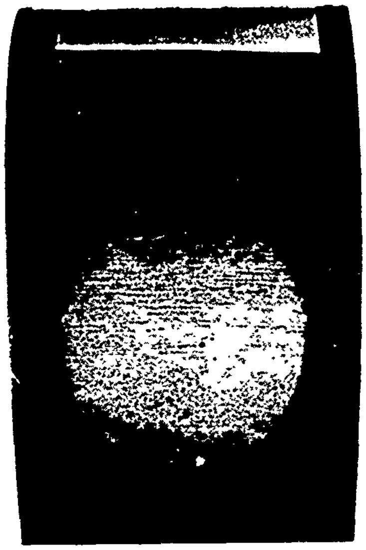


Figure 44.

Enlargement of Erosion Location

Note Cracks Visible in Coating

The weight loss results for all of the specimens included in the dust erosion tests are presented in Table 1. Figure 45 shows the relationship of the weight losses for the four different types of specimens tested. The results for the standard specimens, A75Ti on aluminum and Ti-6Al-4V on fiberglass, have been averaged. The Solide™ coated specimens were then sent to the Air Force Materials Laboratory at Wright-Patterson Air Force Base, Ohio for rain erosion testing.

A noticeable difference was evident between the dust erosion results of the A75Ti and the Ti-6Al-4V alloy specimens. This difference in erosion resistance was not found in any previous or later erosion testing. The Ti-6Al-4V results were in agreement with all previous data but the A75Ti results were not. The average weight loss for the six specimens was 2.5 mg. Since the area eroded was roughly one square centimeter this would suggest that the entire coating (average weight - 2.13 mg/cm^2) had been removed. Visual inspection of the specimens after testing did not indicate this. In the case of both the Ti-6Al-4V and the A75Ti specimens only a slight polishing of the coating in the erosion area was evident. No indication of coating removal could be found. The A75Ti specimens did, however, have a mottled surface residue which withstood normal cleaning but was removed during the erosion tests. The loss of this residue may have accounted for the unusually high erosion weight losses of these specimens.

Following the dust erosion exposure, the same specimens were sent on for rain erosion testing. For this program, as in the last, the rain erosion tests were performed by Mr. George Schmitt, Jr. at the Elastomers and Coating Branch, Nonmetallic Materials Division of the Air Force Materials Laboratory (AFML), Wright-Patterson AFB, Ohio. A description of the AFML rain erosion apparatus appears in Appendix A. The following conditions were used for the tests: Rainfall 1 inch/hour, droplet size 0.070 to 0.080 inch, test times 1 hour, specimen velocity 730 ft/sec (500 mph).

Table 1

Dust Erosion Test Results

Specimen		Coating	Substrate	Wt. Loss (mg)
Electro-Formed Nickel		--	--	29.4
Special A75Ti (Note 1)		M9-13A Solide	G-10 Fiberglass	16.3
Ti-6Al-4V	B	M9-13A Solide	G-10 Fiberglass	0.2
	C	"	"	0.5
	D	"	"	0.0
	E	"	"	0.8
	F	"	"	0.0
	G	"	"	0.6
	H	"	"	0.5
A75Ti	1	M9-13A Solide	2024 Aluminum	2.2*
	2	"	"	2.3
	3	"	"	2.6
	4	"	"	3.6
	5	"	"	2.3
	6	"	"	1.7

Note 1: Subscale airfoil specimen made by coating in a semi-cylindrical shape (radius = 1.5 in.) followed by hot forming to final airfoil shape (min. radius = 0.030 in.). The coating sustained visible cracks resulting from the forming operation.

* Abnormal results, see text.

The results of the rain erosion tests were similar to those run previously in that none of the specimens showed any visual evidence of erosion from the rain environment. No damage was observed on any of the borided surfaces or to the substrate underneath. There were no adhesion problems where the clads were bonded to either the aluminum or fiberglass-epoxy substrates.

In response to inquiries from engineers working for Pennsylvania Electric, Solar provided samples of Solide™ coated titanium and 430 stainless steel coupons for their evaluation. The Pennyslvania Electric group had a problem with erosion of large aluminum bladed fans in a coal fired generating plant. According to them, enough dust passes through electrostatic precipitators to require replacement of leading edge clads every six weeks. They tested Solide™ coated coupons along with a specimen of their standard clad material: stainless steel with 0.030 inch of hard chrome plating. The results reported to Solar are presented in Figure 46. (Note: Funding for this effort was not included in this contract. It is presented only as a matter of interest.)

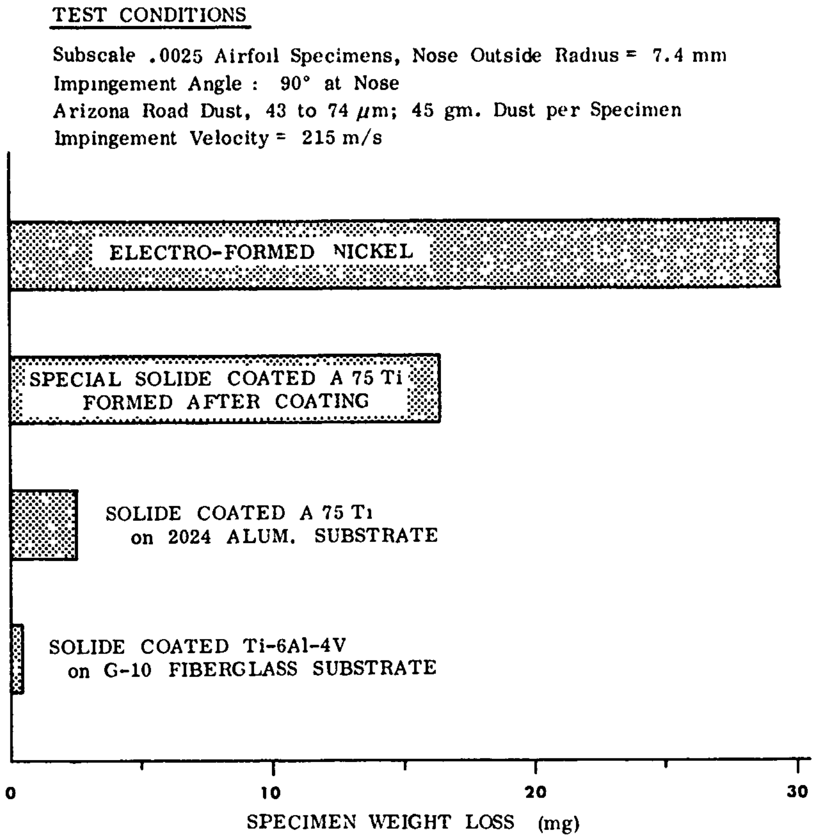


Figure 45. Dust Erosion Results for Subscale Airfoil Nose Cap Specimens; Average Values are Used for Multiple Specimens

The quantity of dust impinged during that test was more than 15 times as great as in the standard Solar dust tests. This is particularly significant because of the relatively thin coating on the clad, indicating very long life time under these specific erosion conditions, particularly for the coated titanium alloy, e.g., the ratio of material removed/material impacted is approximately 10^6.

Tensile Tests

Tensile tests were performed on standard flat tensile specimens coated on graphite mandrels, as described in Section 2.1.1. The specimens tested included annealed, uncoated baselines with as-coated, coated-annealed, and uncoated specimens which had gone through the coating heat cycle in a vacuum furnace. Figure 47 shows the corners of a pair of tensile specimens. The one on the left is in the annealed condition. The one on the right was run at 2100°F in a vacuum furnace for four hours. No etchant was used. Note the pronounced grain structure of the heat treated specimen. Its tensile strength was compared to annealed-coated and uncoated specimens to give an indication of the benefits of post-coating heat treatment.

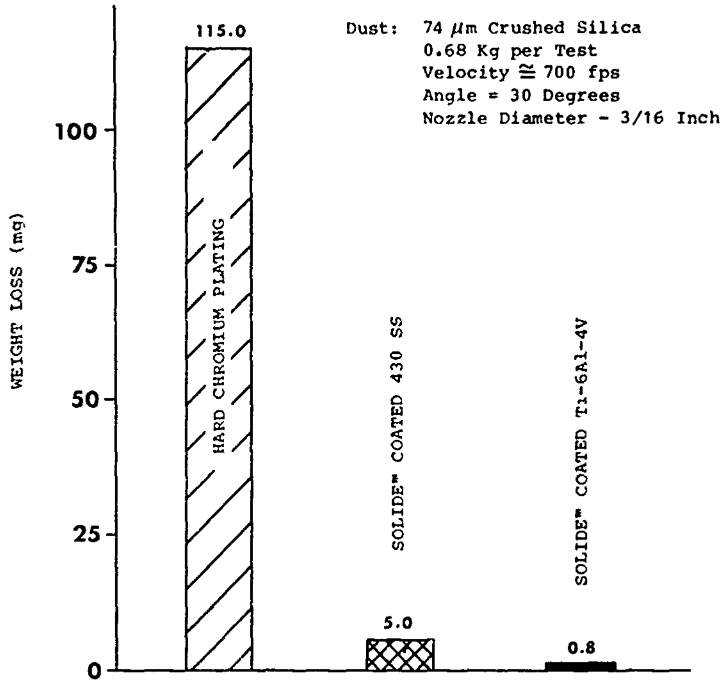


Figure 46. Pennsylvania Electric Company Dust Erosion Test Results

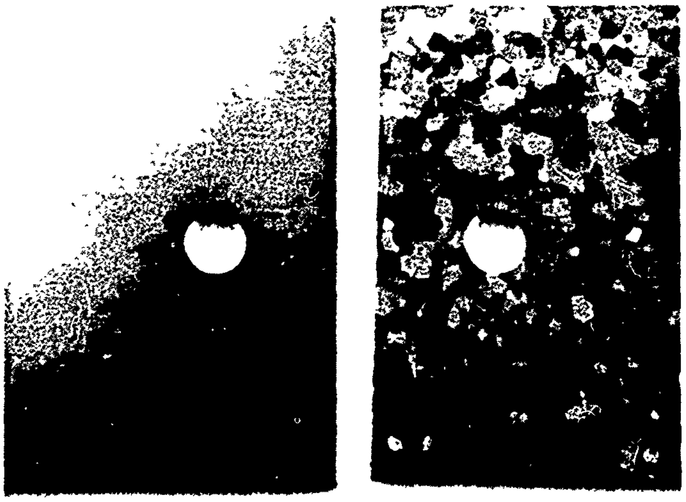


Figure 47.

Ti-6Al-4V Grain Growth

Left: Annealed Specimen

Right: Heat Treated at
2150°F in Vacuum,
4 Hours

Holes are 1/8 Inch Diameter

The results of the tensile tests are recorded in Table 2. Referring to the table, the values for annealed, uncoated specimens can be taken as baseline. Specimens exposed to the coating heat cycle but not coated showed a loss in yield strength, ultimate tensile strength, and ductility for both alloys. The coating heat cycle with actual coating formation displays a slight improvement in yield and ultimate tensile strength but a major loss in ductility. Annealing after the coating cycle shows very little effect on the tensile properties with or without an actual coating present.

Table 2

Tensile Test Results
Coating: Solide™

A75 Titanium (Average values for triplicate specimens)

Heat Cycle	Bare			Coated		
	0.2% Y.S. (ksi)	Ult. T.S. (ksi)	% Elong.	0.2% Y.S. (ksi)	Ult. T.S. (ksi)	% Elong.
Annealed[1]	82.0	102.4	28.7	--	--	--
Coating Cycle[2]	74.7	90.3	11.0	78.6	95.0	4.0
Coating Cycle + Anneal	87.2	93.5	6.0	83.6	97.8	5.0

Ti-6Al-4V (Average values for triplicate specimens)

Heat Cycle	Bare			Coated		
	0.2% Y.S. (ksi)	Ult. T.S. (ksi)	% Elong.	0.2% Y.S. (ksi)	Ult. T.S. (ksi)	% Elong.
Annealed[3]	137.2	141.2	15.2	--	--	--
Coating Cycle[2]	117.4	135.2	9.7	120.9	136.8	4.8
Coating Cycle + Anneal	123.6	133.6	7.8	123.7	137.7	5.0

[1] A75Ti: 1300°F in argon for 2 hours, air cool

[2] Bare specimens: 2100°F in vacuum furnace for 4 hours
furnace cool
Coated specimens: Normal coating procedure - 2100°F in argon
for 4 hours
Slow cool

[3] Ti-6Al-4V: 1350°F in argon for 4 hours
Furnace cool slow to 1050°F
1050°F for 10 minutes
Air cool

Strain-Erosion Tests

Three tensile specimens of each alloy were slated for a special strain limit/erosion examination. In that test tensile specimens were strained to the strain tolerance limit specified by Boeing Vertol for its rotor blades (2000 microinch/inch) and to two higher levels of strain and then submitted to a dust erosion test in the maximum strain location. Table 3 displays the results of the strain-erosion tests. Each specimen was pulled in a Tinius-Olsen tensile machine to the strain levels indicated and then removed. Permanent elongation of the 1-inch gage section was recorded. Each specimen was then subjected to a localized dust erosion test at 90 degrees in two different locations; once in the strained gage section and once in the unstrained end section. In all 12 erosion areas the weight change was negligible (less than ±1 mg net weight change). As a comparison, a bare piece of Ti-6Al-4V alloy tested under identical conditions (except at 30-degree impingement angle instead of 90 degree) lost 32.7 mg due to erosion. The conclusion is that a high substrate strain of even 10,000 microinch/inch did not impair the erosion resistant properties of the boride coating.

Table 3

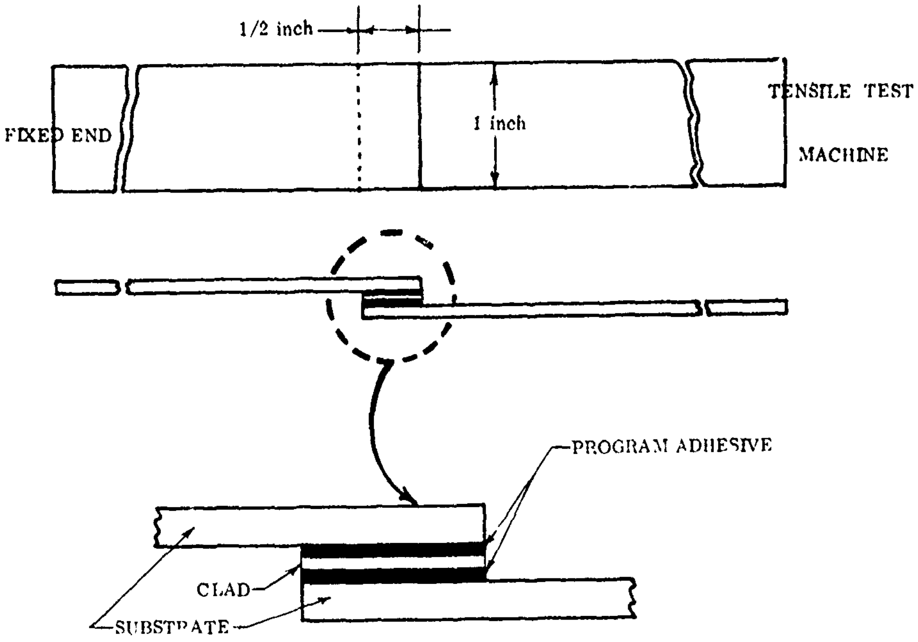
Strain-Erosion Test Results

Test Conditions: Arizona Road Dust, 43 to 74 μm
90° Impingement Angle
650 fps Particle Velocity
45 gm Dust per Specimen

Specimen Number	Alloy	Strain (μin./in.)	Perm. Elong. (mils)	Weight Change (mg) Strained Gage Section	Unstrained End Section
T-G	Ti-6Al-4V	2,000	0.00	-0.3	+0.4
T-7	A75 Ti	2,000	0.00	-0.2	+0.4
T-H	Ti-6Al-4V	5,000	0.00	-0.2	+0.3
T-8	A75 Ti	5,000	0.73	-0.2	+0.6
T-J	Ti-6Al-4V	10,000	1.92	0.00	+0.1
T-9	A75 Ti	10,000	5.26	-0.4	+0.5

Adhesive Shear Strength Tests

Several of the tests in Phase III of this program were intended to determine the adhesive bonding characteristics of the Solide™ coated clads. The shear strength tests utilized specimens, as detailed in Figure 48. The tests were conducted in accordance with ASTM Standard D1002-72 - Strength Properties of Adhesives in Shear by Tension Loading. The adhesive used was the program



ADHESIVE	SUBSTRATES	CLADS
(3M) AF126-2	1. 2mm 2024-T4 Aluminum	1. 1.02mm A75 Titanium
	2. 2.3mm G-10 Fiberglass	2. 1.02mm Ti-6Al-4V

Figure 48. Shear Strength Specimen Details

standard adhesive, 3M brand AF 126-2 Structural Adhesion film. The purpose of the tests in this case was to determine that Solide™ coated titanium would provide suitable surfaces for achieving high strength epoxy bonds when utilizing techniques and materials similar to those used in the aerospace industry. The results of the tests appear in Table 4 and are summarized graphically in Figure 49. Three specimen combinations were used with each of the two substrate/clad combinations. These were: 1) baseline specimens with two substrate sections bonded directly together, 2) substrates sandwiching an uncoated clad insert of titanium alloy, and 3) substrates sandwiching a coated clad insert, simulating actual noze cap/rotor blade materials.

As is evident from Figure 49, the G-10 fiberglass is a difficult surface to bond to. The specimens including a coated, or uncoated, titanium insert were actually stronger in shear than the baselines with no insert. The coating on the titanium resulted in essentially no change in bond shear strength as compared to the uncoated samples. The aluminum is a very good bond surface for AF-126-2 adhesive, as is seen from the high shear strengths demonstrated by the aluminum-to-aluminum baseline samples. The aluminum-titanium insert specimens could not match the baseline shear strength but it is apparent that the coated titanium inserts resulted in only a slight variation as compared to the uncoated samples. The conclusion that can be drawn from these data is that Solide™ coated titanium is as good as, or better than, uncoated titanium for adhesive bonding shear strength using this adhesive.

Table 4

Adhesive Shear Strength Test Results

Adhesive: 3M Brand AF-126-2
See Figure 48 for Specimen Details

Substrate Material	Clad Insert	Ultimate Shear Strength (psi)	Substrate Material	Clad Insert	Ultimate Shear Strength (psi)
2.36 mm G-10 Fiberglass	None	1500	2.03 mm 2024-T4 Aluminum	None	5885
		1265			5192
		1038			6140
		1509			5000
	Uncoated Ti-6Al-4V	1400			5406
		1843		Uncoated A75Ti	4314
	Solide Coated Ti-6Al-4V	1340			4340
		1633		Solide Coated A75Ti	4332
		1833			4113
		1840			4288
		1640			4167
		1962			3647

Salt Spray Test

To help evaluate the corrosion resistant properties of the Solide™ coated clad and bonding adhesive, a number of sample specimens were subjected to exposure in a salt spray cabinet in accordance with ASTM Standard B-117. The specimens were:

(10) 1 inch by 2 inch flat A75Ti Solide™ coated clads, 0.040 inch bonded to 2024 aluminum substrates.

(8) 1 inch by 2 inch flat Ti-6Al-4V Solide™ coated clads, 0.040 inch bonded to G-10 fiberglass substrates.

Adhesive: 3M brand AF-126-2 structural film adhesive.

Salt spray exposure time was 259 hours. The inspection following exposure revealed no evidence of any damage to either the adhesive or the fiberglass substrates. The aluminum substrates experienced severe corrosion. The A75Ti and Ti-6Al-4V coated clads were slightly discolored and had some salt deposits. The A75Ti/2024 aluminum combination specimens experienced a weight gain in each case averaging 0.0048 gm. The Ti-6Al-4V/G-10 fiberglass specimens gained an average of 0.0058 gm.

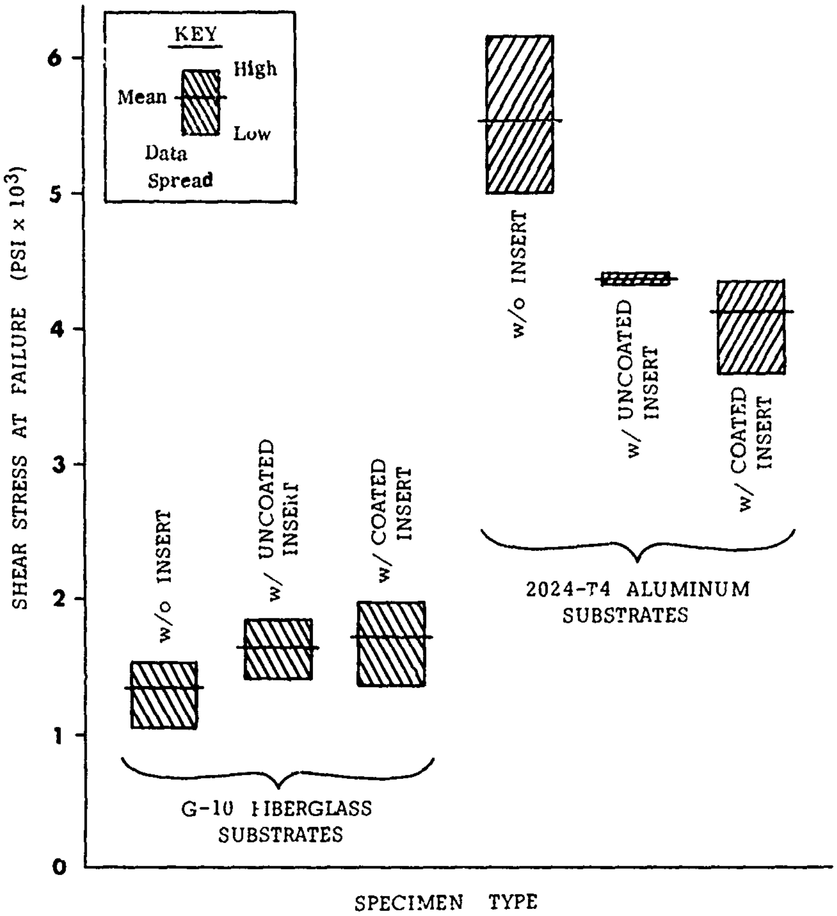


Figure 49. Adhesive Shear Strength Results

After exposure, cleanup, and weighing, the composite specimens were bonded to the mild steel tensile test fixtures shown in Figure 50 with 3M brand (Hi Temp) EC 2214 adhesive. They were then pulled to failure in a Tinius-Olsen tensile test machine. The results appear in Tables 5 and 6.

As can be seen in the tabulated data, the AF-126-2 adhesive after 259 hours of salt spray exposure was stronger than the EC 2214 adhesive in 16 of the 17 test samples. The types and locations of the failures concur with earlier shear strength bonding results. In general, the weakest bond was between the EC 2214 and the G-10 fiberglass. The next weakest was the EC 2214 to the aluminum: 3200 to 5175 psi. The best overall bond on the average was the salt exposed AF-126-2 to coated titanium.

These results verify that adequate bonding characteristics can be expected when using current aerospace adhesives with Solide™ coated clads.

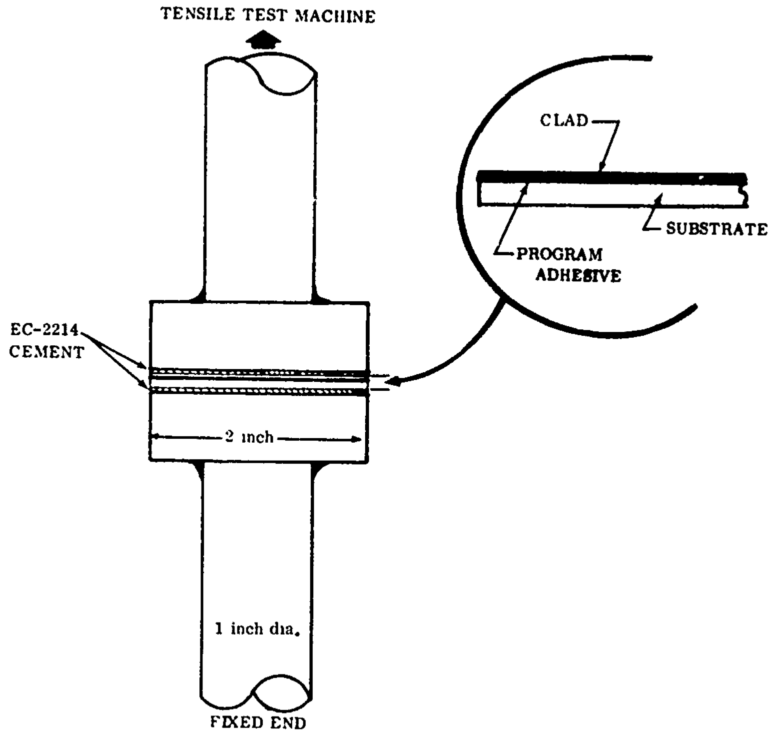


Figure 50. Adherence Test Setup for Specimens After Salt Spray Exposure

Ballistic Impact Tests

In order to evaluate the resistance of the Solide™ coating to single massive impacts, ballistic impact tests were performed. The apparatus used provided projectiles accelerated from an air rifle with nitrogen gas. Both steel ball and lead pellet projectiles were used. The following parameters were maintained:

Projectiles

0.22 caliber lead pellets, weight = 0.880 gm

0.188 caliber steel balls, weight = 0.440 gm

Impact velocity = (approx) 500 fps

Muzzle-to-target distance = 16.75 inches

Calculated impact energy (1/2 mv^2)

Lead pellets = 7.54 ft-lb
Steel balls = 3.77 ft-lb.

Table 5

Solide™ Coated A75 Titanium Bonded to 2024-T4 Aluminum

Spec. No.	Weight Gain During Salt Spray (mg)	Load At Failure (Adherence After Salt Spray) (psi)	Failure Type	Failure Location
1	9.8	3720	Cohesive	EC 2214 at Aluminum
2	7.4	3200	Adhesive	EC 2214 at Aluminum
3	3.0	--		Bad bond, EC 2214
4	4.3	5125	Cohesive	EC 2214 at Aluminum
5	5.9	3790	Cohesive	EC 2214 at Aluminum
6	7.0	4985	Cohesive	AF-126-2
7	1.2	4925	Cohesive	EC 2214 at Solide Titanium
8	2.8	5250	Cohesive	EC 2214 Both Sides
9	2.8	5175	Cohesive	EC 2214 at Aluminum
10	4.3	4450	Cohesive	EC 2214 at Aluminum
Average	4.8.	4513		

Figure 51 shows the two projectile types and a typical target specimen. The lead pellet, left, is twice as massive as the steel ball but its hollow design causes it to undergo complete deformation at impact, thus absorbing most of the impact energy. The steel ball with less mass transferred more energy to the target. Figures 52 and 53 are closeups of typical impact sites. In Figure 52 the target is Solide™ coated Ti-6Al-4V bonded to a G-10 fiberglass epoxy subscale airfoil form. The coating suffered cracks in the immediate vicinity of the impact and the fiberglass backing material underwent marked splitting and separation of the laminations. In Figure 53 the clad is Solide™ coated A75Ti bonded to a 2024 aluminum alloy substrate. The extent of impact damage is noticeably less than the fiberglass backed specimen and no damage was visible to the aluminum itself.

Table 6

Solide™ Coated Ti-6Al-4V Bonded to G-10 Fiberglass

Spec No.	Weight Gain During Salt Spray (mg)	Load at Failure (Adherence After Salt Spray) (psi)	Failure Type	Failure Location
A	5.8	3875	Cohesive Structural	EC 2214 G-10
B	5.4	2760	Cohesive Structural	EC 2214 G-10
C	6.0	3865	Structural	G-10
D	6.9	2890	Adhesive Structural	EC 2214 G-10
E	6.9	2825	Adhesive	EC 2214 at G-10
F	5.4	3310	Adhesive	EC 2214 at G-10
G	4.6	3580	Structural	G-10
Average	5.9	3301		

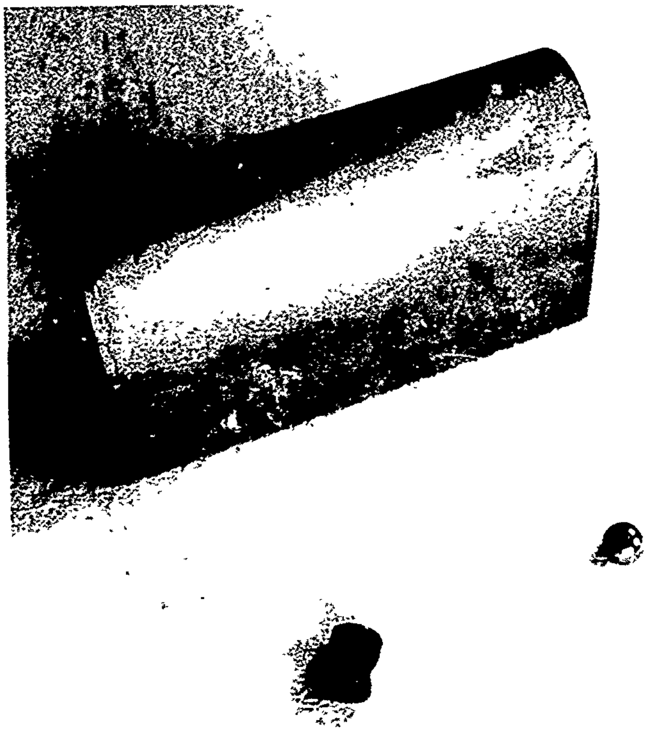


Figure 51.

Ballistic Impact Specimen and Projectiles

Lead Pellet (Left) and Steel Ball

Figure 52.

Impact Site on Solide™ Coated Ti-6Al-4V Bonded to G-10 Fiberglass

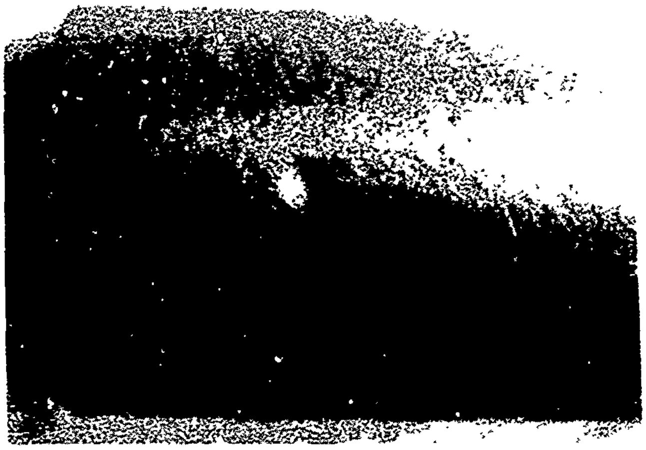


Figure 53.

Impact Site on Solide™ Coated A75 Titanium Bonded to 2024 Aluminum

2.1.4 Phase IV - Procurement Data Package

In accordance with contract provisions a Procurement Data Package has been prepared under separate cover. It contains all information resulting from the work performed in this program which is pertinent to manufacturing of Solide™ coatings and application of coated clads to rotor blades or similar structures.

Included in the data package are descriptions of:

- Equipment requirements
- Process and quality control specification
- Jig and fixture requirements

- Operational shop practice specifications
- Physical test procedures and specifications

Solar will make available to industry on a commercial basis the slurry for Solide™ coating.

2.1.5 Cost Estimate

A cost estimate was prepared in June 1978 itemizing the anticipated costs of fabricating Solide™ coated erosion resistant nose caps for Army helicopter rotor blades. The estimate which is included as Appendix B is based on current coating techniques expanded to large scale production requirements. This would be essentially the worst case, assuming no improved mass production coating techniques are utilized.

Both titanium and stainless steel were included as substrate materials in the cost estimate. The helicopter systems chosen as examples for production rate requirements and typical rotor blade geometries were Sikorsky's new Blackhawk (UTTAS) and Bell's UH-1H. The estimate covers the period 1978 to 1987 on a yearly cost-per-part basis.

The total estimated cost for either substrate material is given but no difference is indicated for the type of helicopter. The geometries, raw material requirements and labor time are essentially the same for either of the two rotor blade types evaluated.

The final estimate of cost for SAE 430 stainless steel nose caps with a 0.002-inch thick Solide™ coating ranges from $44.55 each in 1978 to $63.12 each in 1987. A70 titanium nose caps with a 0.0005-inch thick Solide™ coating range from $76.02 each in 1978 to $110.67 each in 1987. Refer to Appendix B for more details.

2.2 TESTING BY HELICOPTER MANUFACTURERS

Research for the Army by Solar into the applicability of ceramic coated clads for rotor blade erosion protection was initiated in 1974 in response to an unsolved existing material problem. Visits to the rotor blade overhaul center at the Naval Air Rework Facility, North Island Naval Air Station demonstrated how extensive the problem is with the Navy's helicopter fleet whose operations in sandy environments is less prevalent than with the Army's fleet. Despite this research by Solar and the need by the in-the-field helicopters, no direct link had been established between the laboratory and the Army fleet. Effective transfer of the new technology mandated awareness and acceptance of the product by the major manufacturers of Army helicopters.

With the timely awards of the UTTAS and AAH contracts to Sikorsky Aircraft and Hughes Helicopter, respectively, a natural opportunity occurred to introduce the new technology to Army contractors at a time when prototype design of new rotor systems was underway. Accordingly, Solar made contact with rotor design and material engineering personnel at Hughes and Sikorsky. Both organizations provided quotations and test plans for evaluating Solide™ coated titanium and SAE 430 specimens as potential rotor blade leading edge material candidates. Later, Bell Helicopter Textron expressed interest and also provided a quotation and test plan. All three testing programs were included in two extensions to the original program. The test specimens fabricated, tests performed and results and conclusions are described in the following sections. The actual test reports and details on apparatus and methods from Hughes, Sikorsky and Bell are included as Appendices C, D, and E, respectively.

2.2.1 The Hughes Program

The objective of the Hughes test program was to evaluate Solide™ coated samples by direct comparison with their baseline material, hard anodized aluminum. Hughes uses a whirl arm test rig for both sand and rain erosion simulation. Test specimens are fixed to the outboard 18 inches of the leading edge of Hughes Model 500D (military designation OH-6A) stub rotor blades. Hughes required 12 total specimens as follows:

	Solide™ Coated 430 SS (0.040")	Solide™ Coated A75Ti (0.040")
Rain tests	2	2
Dust tests	2	2
Bonding studies	2	2
plus spares		
	6	6

In order to produce 18-inch long airfoil specimens suitable for bonding to Hughes test rig rotor blades, special tooling had to be fabricated. The titanium specimens were fabricated using the same coating/creep forming tecnique developed to produce the large scale Bell UH-1H titanium nose caps. The two-piece (male and female) graphite mandrel set made especially for the job is shown in Figure 54 along with a coated titanium specimen and a cross-section of the Model 500D rotor blade. Six coated A75Ti specimens were produced for Hughes. One of these was given an extra thick coating, i.e., approximately 0.001 inch rather than 0.0005 inch, by extending the process cycle.

Coating the SAE 430 alloy specimens for Hughes required a specially made three-piece mild steel fixture which is shown in Figure 55. Six coated SAE 430 specimens were produced in the manner shown. As with the titanium specimens, one SAE 430 specimen was made with a double thick coating produced by a longer-than-standard furnace cycle. Preliminary experimental work at Solar had

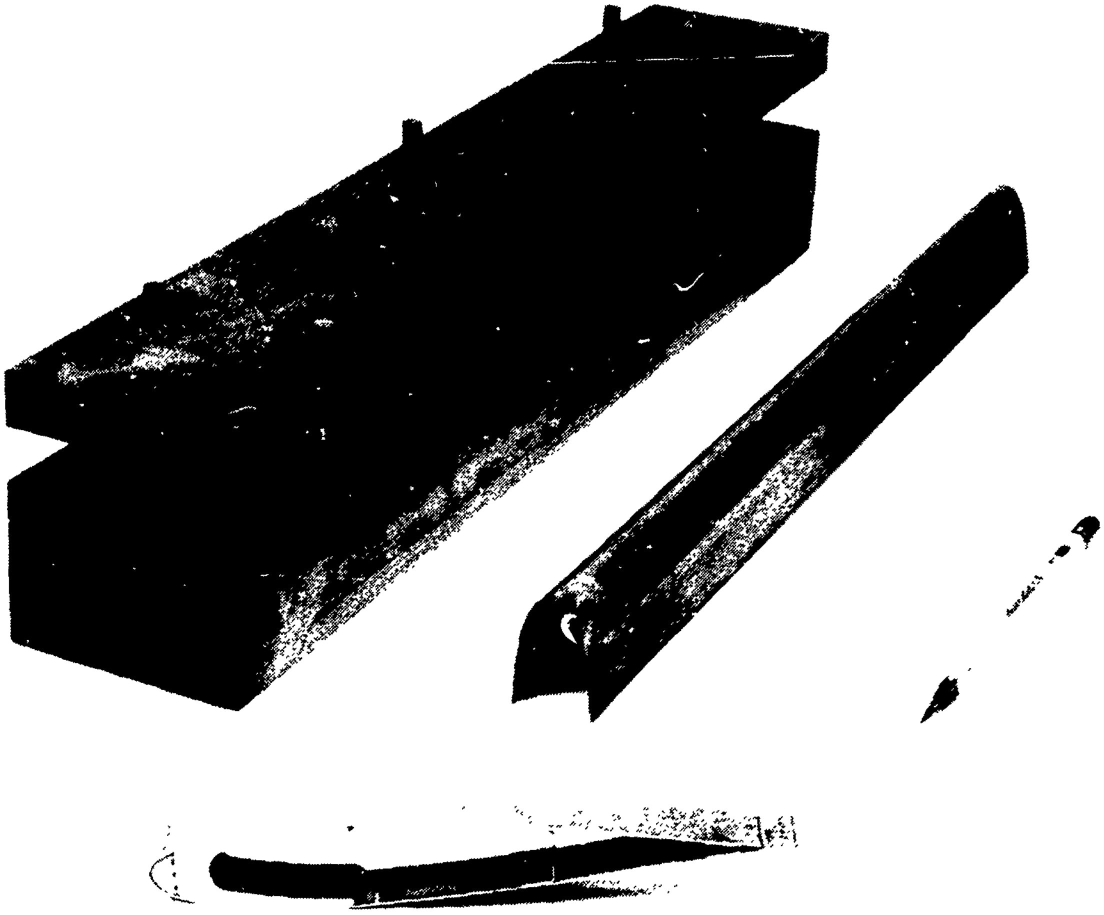


Figure 54. Hughes Titanium Test Specimen, Graphite Mandrels and Rotor Blade Section

ndicated that these thicker coatings have the potential to resist erosion to arger particles, which is critical in the case of very hard coatings that xhibit fracture thresholds for erosion damage. By providing Hughes with pecimens having normal and thicker-than-normal coatings, a relationship between oating thickness and erosion resistance was sought.

he complete set of specimens delivered to Hughes is listed below.

For Preliminary Bonding Studies

(2) Solide™ coated A75 titanium with 0.0005-inch thick coating
(2) Solide™ coated 430 stainless steel with 0.002-inch thick coating

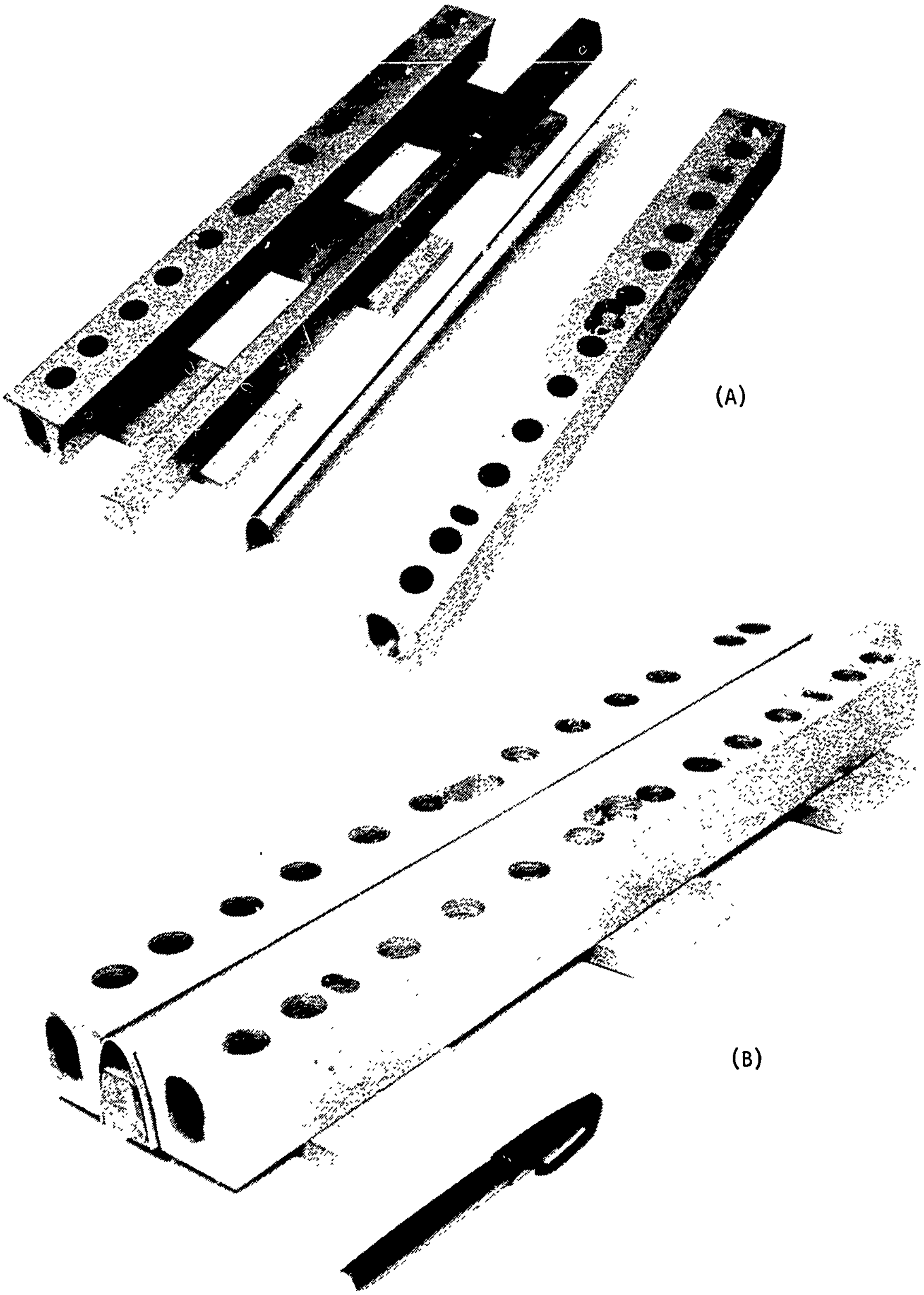


Figure 55. Mild Steel Fixture for Coating Hughes SAE 430 Specimens

For Dynamic Whirl Arm Erosion Tests

(3) Solide™ coated A75 titanium with 0.0005-inch thick coating
(3) Solide™ coated 430 stainless steel with 0.002-inch thick coating
(1) Solide™ coated A75 titanium with 0.001-inch thick coating
(1) Solide™ coated 430 stainless steel with 0.004-inch thick coating

Hughes' whirl arm test rig consists of a hydraulically driven pair of stub rotor blades on a stationary stand within a circular fenced enclosure. The blade assemblies are 39.75 inches long and are mounted so that the tips travel in a horizontal plane at a radius of 54 inches and 50 inches above the concrete floor. Specimens are bonded and mechanically fastened to the leading edges of the blades.

Rain erosion test conditions to simulate 100 knot level flight in a 1 inch/hour rainfall are accomplished by setting the rig to run at 900 fps tip speed with a zero pitch angle. Simulated rain comes from a suspended horizontal pipe array above the rig. The pipes are located 1 foot apart with 0.039-inch diameter orifices, on 1-foot centers, through their lower walls. Thise pipes are connected to a reservoir, at the center, maintaining a constant 3-inch head of water at the orifices. Head height and orifice size were determined b separate laboratory tests to produce the desired droplet size and flow rate. The average droplet diameter is 1900 microns, with the largest 2375 microns and the smallest 595 microns. Seventy-four percent of the droplets are 1800 to 2100 microns mean diameter. The suspended pipe array is driven in a circular path, on a 4.25 inch radius about the center of blade rotation at approximately 0.3 cps. This permits the droplets of water from each orifice to cover an area of approximaely 1 square foot at the blade plane of rotation. With a measured flow rate of 146 in.^{3}/hr from one orifice, this results in a 1 in./hr "rainfall". The simulated rain, of tap water, covers an area approximately 43 feet in diameter.

Sand erosion conditions simulate take-offs and landings over deserts or beaches. The test blades are rotated at 750 fps tip speed with blade pitch set at +7 degrees (L.E. up). Sand is placed in two open rectangular boxes (3.5 x 24 x 72 inches) located on the floor under the blades. Sand is drawn out of two wooden boxes by the blasting action of the positive pitch blade setting. "Gordon" No. 50 and No. 30 silica sand is mixed in the boxes to produce approximately the following particle size distribution:

Particle Size (microns)	Percent by Wt. Finer Than Size Indicated
1000	100.0
833	97.4
589	94.2
495	82.5
354	46.2
246	9.3
147	0.37
74	0.02

Several samples of sand were taken at the test site and analyzed at Solar. The sand from the boxes prior to testing was found to be coarse and quite uniform, ranging in size from 500 to 1000 microns in diameter. A sample collected in a cup about 15 feet from the test rig and 4 to 5 feet above the ground contained a high proportion of particles in the 700 to 800 micron range. Particles of this size are about 15 times larger in diameter and, therefore, over 3500 times more massive than the standard, 43-74 micron Arizona road dust used in Solar's erosion tests. The sand in the boxes is dispersed at a rate of about 125 lbs/min. No attempt is made to determine which particles within the sand mixture or the quality of sand particles that actually contact the test specimens.

Hughes evaluates candidate materials on the basis of life expectancy ratio as compared to the life expectancy of hard anodized aluminum which is given an arbitrary value of one. Test life in minutes is determined by visual inspection at four minute intervals when the test is stopped to add sand to the boxes. The test is terminated when subjective visual evidence suggests the test specimen is no longer flightworthy.

2.2.2 The Sikorsky Program

Sikorsky Aircraft Division of United Technologies in Stratford, Connecticut proposed a test and evaluation program to subject Solide™ coated Ti-6Al-4V and SAE 430 stainless steel specimens to a variety of laboratory type tests. Their evaluation approach was aimed at achieving a thorough preliminary characterization of Solide™ coated materials and comparing their functional properties to Sikorsky's standard erosion resistant material - electroformed nickel.

Their proposed test sequence included adhesive bonding compatibility, tension-tension fatigue, impact and static erosion tests. Sikorsky also performed metallographic examinations of coating-substrate conditions for both alloys.

All specimens required for Sikorsky's test program were flat sheet in thicknesses ranging from 0.010 to 0.125 inch. No airfoil shaped erosion specimens were requested by Sikorsky since they do not use rotor arm erosion test methods. Table 7 lists the tests, specimen details, and number of specimens supplied to and tested by Sikorsky.

The required titanium test specimens were given Solide™ coatings in two furnace runs. Coatings achieved were a minimum of 0.0005-inch thick using the customary time-temperature conditions and flat graphite mandrels as described in Section 2.1.1. The SAE 430 specimens were produced using specially developed flat mandrels of 3/8-inch thick Type 304 stainless steel which proved successful after unsuccessful attempts to coat the 430 specimens had been performed using 410 stainless steel mandrels and a run using no mandrels in a refractory alloy lined retort. Coatings achieved were 0.002-inch thick or more.

Sikorsky's rotor design personnel devoted a portion of their evaluation testing to examination of the bonding ability of Solide™ coatings using their Narmco Metlbond M1113 adhesive system. Bonding tests included: stress durability, where bonded specimens were tested under 2200 psi shear loading in a 140°F,

Table 7

Specimens Tested by Sikorsky

Test	Specimens Requested by Sikorsky	Shape and Thickness	Material	Specimens Supplied by Solar	Specimens Supplied by Sikorsky
Stress Durability	(12) Coated	1"x5.5" rect.	Ti-6-4	15	9
	(4) Uncoated	x 0.063" thick	Ti-6-4	4	2
	(12) Coated	1"x5.5" rect.	430 SS	12	9
	(4) Uncoated	x 0.125" thick	430 SS	4	2
Shear	(6) Coated	1"x4" rect.	Ti-6-4	16	3
	(4) Uncoated	x 0.125" thick	Ti-6-4	4	
	(6) Coated		430 SS	12	3
	(4) Uncoated		430 SS	4	
T-Peel	(6) Coated	1"x6" rect.	Ti-6-4	6	3
	(6) Coated	x 0.010" thick	430 SS	7	3
Fatigue*	(6) Coated	2.25"x9.25" rect.	Ti-6-4	6	6
	(6) Coated	x 0.125" thick	430 SS	6	6
Impact	-	1"x6" rect.	Ti-6-4	Various coated & uncoated	2
	-	x 0.125" thick			
		(14) total inputs			
Erosion	(6) Coated	2"x6" rect.	Ti-6-4	8	6
	(6) Coated	x 0.020" thick	430 SS	6	6
		(min. 3 tests	E-F Nickel	-	3
	Uncoated	per specimen)	Ti-6-4	-	6
	Uncoated		430 SS	-	6

* Sonntag fatigue specimens supplied by Sikorsky, coated by Solar.

95 percent humid environment for 10 hours minimum; shear, where bonded specimens were tested for ultimate shear strength per ASTM D1002; and T-peel, where the peel strength of bonds were tested per ASTM D1876.

Tension-tension fatigue tests were performed using Sonntag fatigue specimens tested at 1800 cpm with a stress ratio of $R = +0.10$ for 10^7 cycles or until fracture. The results of these tests provided a direct comparison between coated and uncoated fatigue strength.

Sikorsky fabricated a static erosion test rig specifically for this program. Their setup involved a commercial sand blast machine with air stream acceleration of sand particles. Sand velocity was estimated by theoretical analysis to be 750 fps. Unused silica sand was used for each test and introduced from a hopper at a rate of 37 cubic inches per minute.

A complete matrix of tests were run varying particle sizes (100, 150, 250 μm) and impingement angles (15°, 90°) on coated and uncoated samples of both alloys (SAE 430, Ti-6Al-4v) plus electroformed nickel specimens for comparison. All specimens were 0.020-inch flats adhesively bonded to 0.187-inch aluminum plates to simulate abrasion strips bonded to rotor blades.

2.2.3 The Bell Program

Bell Helicopter Textron in Fort Worth, Texas proposed a test program to compare Solide™ coated specimens against their baseline standard material, 301 half-hard stainless steel. Bell's rotor blade test facility consists of a twin bladed whirl arm rig for both sand and rain exposure. Their standard specimen is an airfoil shape contoured to fit the rig rotor blades. Each specimen is 2.225 inches long by 1.75 inches deep. Four specimens are included in each test run mounted two to a blade, side by side, at the blade tips. One standard and one test specimen is mounted on each blade with one of each as the outboard specimen.

Bell provided pre-formed test specimens to Solar for coating. Twelve 0.070-inch Ti-6Al-4V alloy and twelve 0.048-inch SAE 430 alloy specimens were supplied to yield eight coated specimens of each alloy. Solar fabricated custom mandrels designed to allow for coating six specimens at a time. Figure 56 shows the mild steel mandrels for the SAE 430 specimens. Figure 57 shows the simplified graphite mandrel pair for coating the titanium specimens. Also shown in the figure are a standard 301 stainless specimen and a pair of Solide™ coated specimen with the coated clad bonded to a standard base. All 24 Solide™ coated specimens were produced in four furnace runs. The eight best of each alloy type were sent to Bell for testing.

The following is a summary of the coating conditions and results for the 16 specimens to be tested.

Alloy	Ti-6Al-4V	SAE 430 Stainless Steel
Number of specimens	8	8
Substrate thickness	0.070 inch	0.048 inch
Coating temperature	2150°F	1700-1750°F
Time at temperature	16 hours	8 hours
Tooling used	Graphite mandrels	Mild steel mandrels
Average coating weight	3.16 mg/sq.cm	5.73 mg/sq.cm
Approximate coating thickness	0.8 mils	3.5 mils

Bell produced (16) "standards" which were identical airfoil specimen fabricated of half-hard 301 stainless steel.

Details and photographs of Bell's test rig appear in Appendix C along with the report of the test results. The whirl arm is rotated in a vertical plane (horizontal axis of rotation) at 3600 rpm to achieve a tip speed of approximately 750 fps. For the sand test Clemtex No. 4 grade sand is released at 3 to 4 lbs/min. directly onto the oncoming test specimens. Clemtex No. 4 sand ranges from 43 to 841 micron particle size with 98.8 percent in the 150-353 micron range. Bell's whirl arm rig differs considerably from Hughes' in that with the Bell apparatus for dispersing the sand it is possible to determine that most, if not all, of the sand impacts the whirl arm.

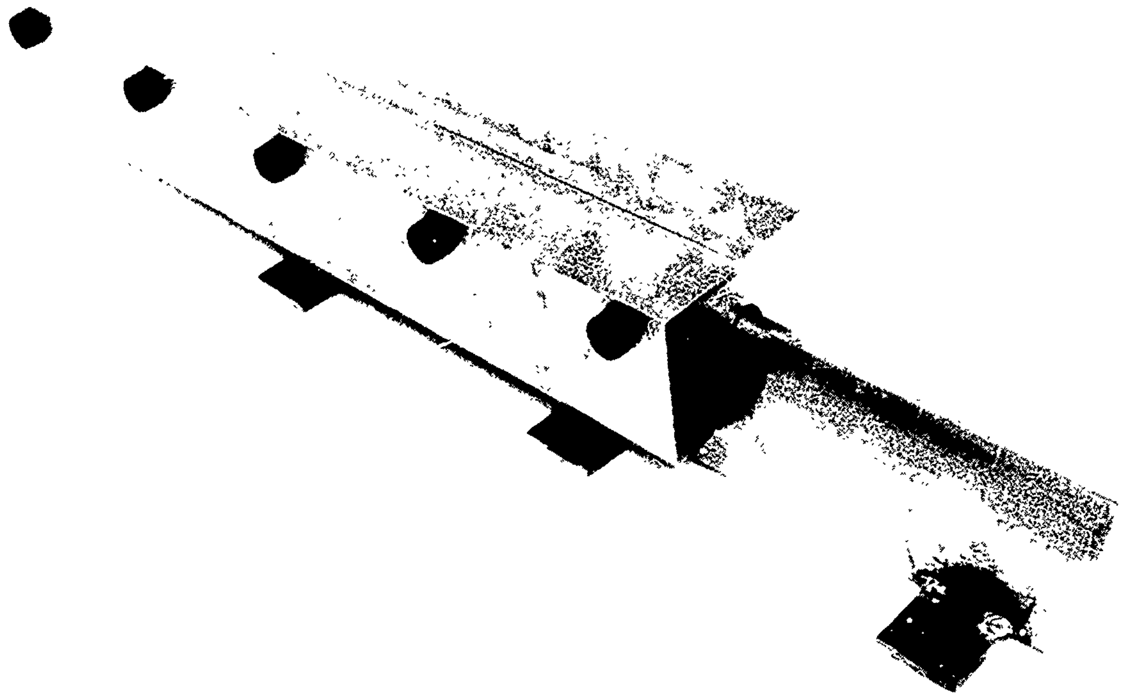


Figure 56. Mild Steel Mandrel Pair for Coating SAE 430 Specimens - Bell Helicopter Whirl Arm

For the rain tests, a number of hypodermic needles provide a simulated 1 inch/hour rainfall in the plane of the blades. The droplet size range was not specified but was described as having been empirically determined to best represent actual rain drops.

Bell evaluates test results on a strictly comparative basis using specimen weight loss due to erosion as the measuring stick. Each sample is given a rating of merit determined by a weight loss ratio as compared to the weight loss of the 301 stainless steel standard specimens in the same test run. No consideration is given, however, to location, type or degree of erosion damage.

The sand tests were run first and a large quantity of sand became trapped in the test rig enclosure. During each of the rain tests which followed immediately, some sand was inadvertently vibrated loose and impacted the test specimens along with the water droplets, resulting in combination rain/sand erosion effects.

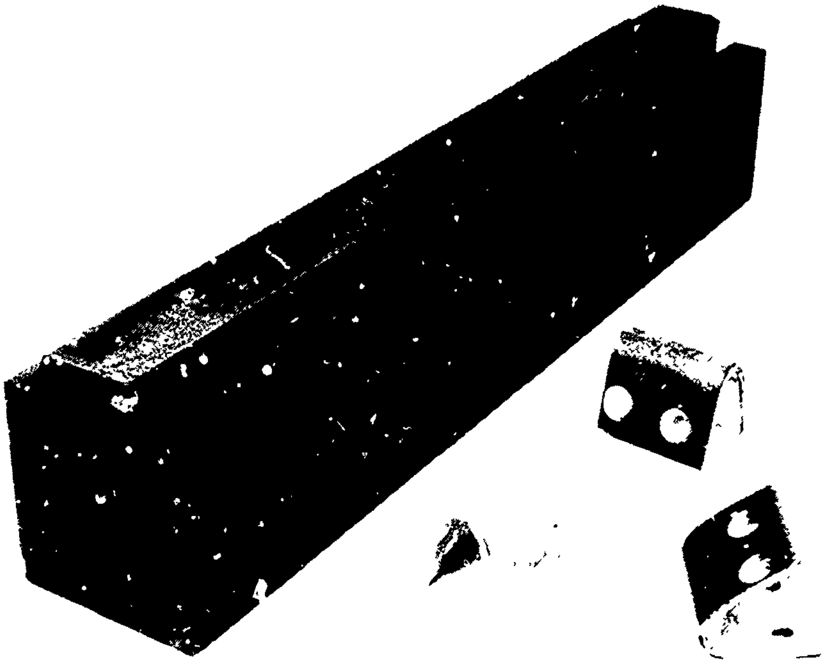


Figure 57. Whirl Arm Test Specimens and Graphite Coating Mandrel for Bell Helicopter Tests

2.2.4 Summary - Helicopter Manufacturers Test Results

Table 8 summarizes the tests and results of the material evaluation programs performed by rotor blade design engineers at Hughes Helicopter, Sikorsky Aircraft and Bell Helicopter. All three companies tested coated specimens of both program alloys, Ti-6Al-4V and SAE 430 stainless steel. Both Hughes and Bell chose to test airfoil shaped specimens in whirl arm (dynamic) rain and sand erosion test rigs for which company-standard tests had previously been developed. Both Hughes and Bell tested adhesive bonding of test specimens to backup structures only enough to satisfy themselves that the specimens could be safely tested. Sikorsky performed a more conventional material evaluation and qualification program including metallographic examination and fatigue testing plus static erosion testing developed especially for this program. They also thoroughly tested adhesive bonding compatibility.

All three companies concluded that Solide™ coated erosion strips do not meet present requirements for rotor blade service due to the failure of the coating to withstand impacts by particles 100 μm or greater in size at impingement angles of 45 degrees or greater at velocities of 750 fps. Rain erosion resistance of Solide™ coatings was deemed excellent and adhesive bondability was satisfactory. Only the Sikorsky engineers wished to pursue the possibility of utilizing the exceptional low angle particle erosion resistance of Solide™ coatings on titanium for erosion protection of rotor blade tip caps.

Table 8

Helicopter Manufacturers' Test Results

Manufacturer	Test	Description	Results	
			SAE 430 SS	Ti-6Al-4V
Hughes Helicopters Culver City, CA	Adhesive bonding	Airfoil bell peel test	Acceptable bonds	
	Whirl arm rain erosion	900 fps; 1 in./hr rainfall	Coating removed at leading edge in 15 minutes.	No erosion in 10 hours.
	Whirl arm sand erosion	750 fps; silica sand up to 800 μm	Coating removed at leading edge in 3 minutes.	
Sikorsky Aircraft Stratford, CT	Adhesive bonding	Stress durability, shear and T-peel	Bondability of coated samples equivalent to bare metal using Metlbond M1113.	
	Fatigue	Sonntag tension-tension	Fatigue strength of coated samples about 50% of uncoated metal.	
	Impact	4.5 ft-lb impact by 1/4" diameter hardened ball	Unsupported coated specimens showed signs of brittleness. Coating remained intact for supported specimens.	
	Static sand erosion	Calc. 750 fps, silica sand 100, 150, 250 μm. 15° and 90° impingement angles.	Coating removed or pitted at leading edge at 90° or 15° angles.	Coating removed at leading edge at 90°. No erosion at 15°.
Bell Helicopters Textron Ft. Worth, TX	Whirl arm sand erosion	750 fps; silica sand up to 850 μm.	Coating removed at leading edge in 30 seconds for angles greater than 45°.	
	Whirl arm rain erosion	750 fps; 1 in./hr rainfall	Inconclusive: Pitting erosion at leading edge in 1 hour due to sand contamination.	

3

CONCLUSIONS

The goals of this program were: 1) to continue the cladding development work using Solide™ coated titanium and stainless steel begun under Contract No. DAAG46-74-C-0054 and scale up the process to sizes that would demonstrate fabrication and utilization feasibility for helicopter main rotor blades, and 2) to assist major helicopter manufacturers in evaluating Solide™ coated clads as potential improved materials for rotor blade erosion protection.

The coating process for full scale, formed sheet metal airfoil nose caps up to 30 inches long by 7 inches deep was sucessfully demonstrated. Three of the four major helicopter manufacturers were provided with test specimens made to their specifications for evaluation.

The following conclusions from the 48-month effort can be drawn:

1. Solide™ coatings can be successfully applied to airfoil shaped nose caps for helicopter rotor blades.

   The scaleup requirement of the program was achieved by designing and using graphite and mild steel mandrels which enabled the large airfoil shapes to be accurately maintained during the coating process. In addition, it was demonstrated that 0.040-inch titanium nose caps could be accurately coated and creep formed to final shape in one process using graphite mandrel pairs. Consistent coating quality was achieved repeatedly on a variety of specimen shapes and sizes. Substrate materials included SAE 430 stainless steel, commercially pure titanium (A70 or A75) and Ti-6Al-4V alloyed titanium.

2. Solide™ coated clads are adaptable to rotor blade design criteria.

   Samples were made which demonstrated that coated airfoils could be produced with appropriate nose radii and shapes suitable for modern rotor systems. Additionally, bonding and environmental compatibility tests were conducted. Solide™ coated materials met all adhesive bonding requirements with properties as good as or better than comparable metal surfaces. Corrosion resistance to a salt water environment proved excellent for coated titanium while coated SAE 430 is poor. Coated titanium specimens demonstrated exceptional resistance to spalling after ballistic impacts or stress conditions beyond the elastic limit of the substrate material.

3. Solide™ coated titanium is recommended over Solide™ coated stainless steel for rotor applications.

Both alloys can be successfully given hard, continuous ceramic coatings but titanium-base alloys achieve harder, better bonded coatings and are recommended in applications where titanium is acceptable in place of stainless steel. The higher raw material cost of titanium over stainless steel can be compensated for by the significantly harder, more erosion and corrosion resistant coating which can be achieved. Additionally, titanium parts can be produced employing the previously described combination coating/creep forming process while stainless steels cannot. Titanium alloys are finding increased acceptance as leading edge material candidates for the new generation composite rotor designs (Ref. 3).

Neither alloy is recommended in the coated condition for critical structural applications without a detailed analysis of mechanical design properties of the coated alloys. Process development of the coatings to date has been aimed at achieving consistently high coating quality to be used in a cladding application. Further development work will be necessary to maintain or improve mechanical properties such as high tensile strength and fatigue life for applications with those requirements.

4. Solide™ coated airfoil specimens have demonstrated exceptional resistance to rain erosion.

In separate rain erosion tests conducted by the Air Force Materials Laboratory, Hughes Helicopter and Bell Helicopter Textron, Solide™ coated airfoil samples proved to be virtually impervious to rain droplet erosion under conditions where many metals and elastomers (especially aluminum and polyurethane) suffer severe erosion damage. Only in the Bell test was any measured erosion effect observed and that was due to sand particle contamination of the rain erosion tests which yielded combination erosion effects.

5. Solide™ coated airfoil specimens are exceptional in resistance to sand erosion at low impingement angles.

Figure 58 displays a relationship between sand erosion damage and impingement angle commonly found in the technical literature (Refs. 4, 5). Erosion rates of brittle materials decrease rapidly as impingement angle decreases and are a function of hardness of the material. The TiB_2 surface of Solide™ coatings on titanium have been found to have a hardness in excess of 2700 KHN which is harder than any man-made substance except boron carbide and synthetic diamond (Ref. 6). Several researchers have pointed out that most materials exhibit a combination of both brittle and ductile modes with the total damage being the sum of the two modes (Ref. 4). Solar's experience with very hard coatings supports this thesis and additionally suggests that ductile mode erosion becomes a virtually insignificant factor for the hardest surfaces.

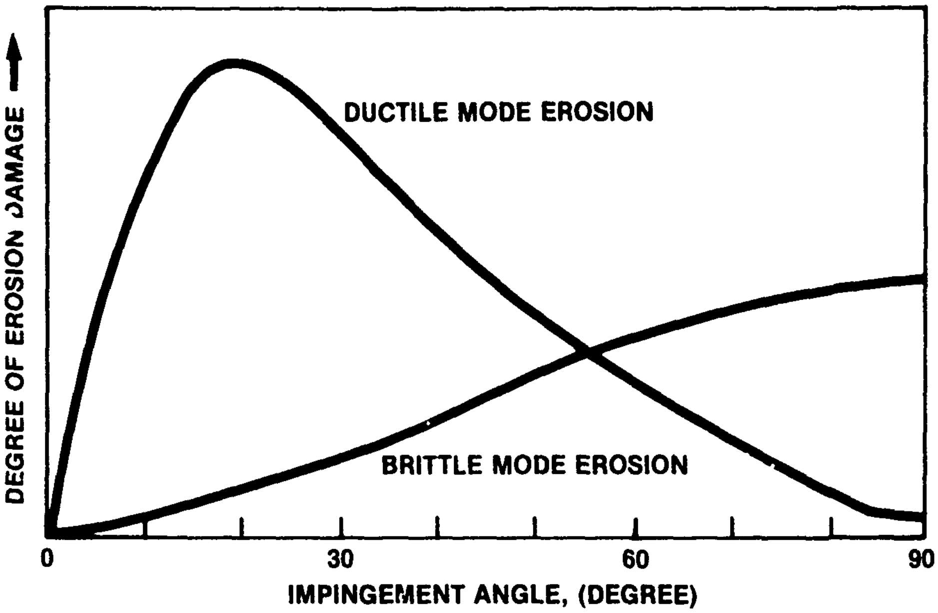


Figure 58. Erosion Behavior Versus Impingement Angle

All of the erosion tests performed under this program verified the impervious nature of Solide™ coatings (especially on titanium) to erosion by sand or dust at low angles. (Low impingement angles are defined here as less than 30 degrees. Erosion effects at impingement angles between 30 and 45 degrees were not specifically investigated. This may be considered a transitional zone between low and high angle erosion.) In the whirl arm tests conducted by Bell the standard uncoated 301 stainless steel specimens manifested erosion damage which was nearly uniform over the entire surface exposed to particle impacts. The Solide™ coatings in the same test (Fig. 59) suffered coating removal and substrate erosion in the high angle region but showed no signs of damage in the low angle regions which comprised approximately 85 percent of the exposed surface. Similar results were observed in Hughes' whirl arm and Sikorsky's static erosion tests. Sikorsky's project engineer was sufficiently impressed to include in his test report a recommendation that Sikorsky continue investigation of Solide™ coated titanium for possible use as rotor blade tip caps on the Blackhawk (YUH-60A) where low angle erosion is a serious problem.

6. Solide™ coated clads do not meet present requirements of the helicopter industry based on results of erosion screening tests.

Ceramic solid materials or coatings (such as Solide™) and some elastomers exhibit resistance to erosion damage by a mode which can be described as threshold behavior. Below a given level of impact energy, threshold-type materials are essentially immune to erosion, especially when the target material hardness is significantly greater than that of the impacting material (TiB_2 is about three times harder on the Knoop scale than common silica sand). However,

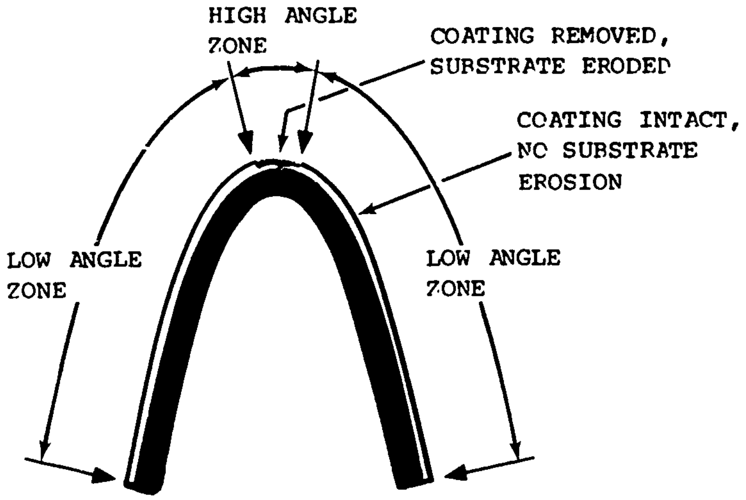


Figure 59.

Typical Solide™ Coated Whirl Arm Specimen Showing Common Erosion Pattern

in the case of a very thin, intermetallic compound coating, the energy of the particles can be sufficiently high to shatter the coating from surface to substrate and result in complete coating removal. A commonly used analogy is the case of a rock through a glass window.

Solide™ coatings on dozens of test specimens survived erosion tests on Solar's static test rig and remained free of erosion damage due primarily to the fact that the size of the selected standard dust (Arizona road dust, 43-74 micron) did not enable any particle to achieve an impact energy above the coating's failure threshold. The threshold impact energy was, however, achieved in tests by the helicopter manufacturers when larger particles (up to 1000 microns) impacted airfoil specimens in regions where the impingement angle was 45 to 90 degrees.

Static and whirl arm sand erosion tests by helicopter manufacturers consistently produced coating failure and removal at the leading edge of Solide™ coated airfoil specimens or at 90-degree impingement angles on flat specimens. In all of these sand erosion tests any amount of coating removal at the leading edge (nose) of the specimens was deemed sufficient to declare failure of the specimen. Hughes did continue several tests after initial coating removal at the nose occurred and noted that coating removal tended to limit itself away from the nose after which erosion losses were limited to high angle bare-metal erosion of the exposed substrate material.

4

RECOMMENDATIONS

1. It is clear that sand erosion has been, and will continue to be, a significant problem facing rotor blade designers and helicopter users. However, the exact nature of that problem has not yet been clearly defined in a manner agreed upon by helicopter manufacturers, helicopter maintenance personnel and erosion researchers. In order to develop improved materials or rotor designs to withstand in-flight particle erosion, it will become more and more essential to specify conditions actually encountered by helicopter rotor blades in service. Particles which cause the erosion damage must be specifically identified in terms of material and shape as well as sizes. If only a selected portion of a natural distribution of different sized particles are commonly found to impact rotors, that portion must be identified. Solar recommends that appropriate investigation be performed to empirically determine the exact conditions through actual measurements in the field.

   Lacking an exact definition of rotor service conditions involving sand erosion has led the helicopter manufacturers to adopt and rely upon "accelerated" erosion tests which are inappropriate for testing materials which exhibit "threshold" relationships between erosion damage and particle impact energy.

   All of the erosion tests in this program employed by Hughes Helicopters and Bell Helicopter Textron were of the "accelerated" variety. This was achieved by increasing particle impact energy by using high introduction rates of large (up to 1000 microns) or very hard (Al_2O_3) particles. For comparison testing of different ductile materials increasing particle impact energy to accelerate erosion and reduce test time is a reasonable, cost effective procedure.

   It is not reasonable to use similar techniques when testing threshold-type materials such as Solide™ coatings. Polyurethane also has been found to exhibit threshold behavior (Ref. 7).

   Figure 60 is an idealized log-log plot of erosion damage as a function of particle/target impact energy. Except at very low energy levels, erosion of metals and other ductile materials can be considered as proportional to impact energy which in turn is a quite complex function of the variables noted in the figure. The S curve in Figure 60 displays the threshold (vertical portion of the curve) typical of Solide™ coated metal with a particular coating thickness. Increasing the energy levels of impacts to speed up test results runs the risk of providing impact

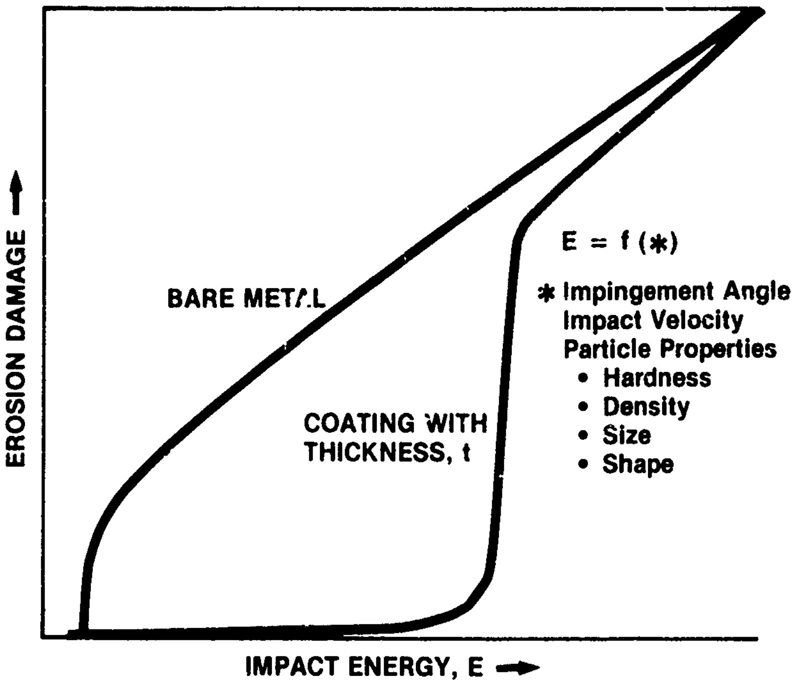


Figure 60. Erosion Behavior of Threshold Type Materials Versus Bare Metals

energies in excess of the specified coating threshold. This will quickly result in massive damage to the coating which would not have occurred at lower impact energy levels over any reasonable length of time.

The conclusion to be drawn is that the most valid tests for candidate leading edge materials should be under conditions closely approximating actual contitions where they would be used with particular attention given to the choice of the erosion media in regard to particle type, size, introduction rate, velocity, and angle of impingement. Proper consideration should always be given to the mechanism by which a specific material resists erosion when devising a test for that material.

In testing for long-term erosion effects an appropriate compromise must be achieved between the cost advantages of accelerated testing and the inevitable inaccuracies that such test procedures introduce.

2. A standardized erosion test method should be developed according to standards established by ASTM, Military Specification, or other appropriate agencies. No such standard now exists for helicopter rotor blades or other rotating airfoil machinery which suffer similar erosion problems. Such a test should include methods for evaluating the full spectrum of materials under consideration including metals, ceramics, intermetallics, plastics and elastomers, taking into account the different means by which each is able to resist erosion.

3. The Solide™ coatings, especially on titanium, in this program displayed erosion resistance to rain, large sand particles at low angles and small particles at high angles which was remarkable for such thin coatings. Relationships between erosion resistance and coating thicknesses, while not exhaustively studied, did suggest strongly that erosion resistance varies proportionally with coating thickness. This indicates that ceramic type coatings or shields could provide adequate erosion resistant performance if they were thicker than those tested while still being very thin in comparison to other rotor blade materials of construction. The Solide™ coatings in this research effort were limited to about 1 mil for titanium or 4 mils for SAE 430 stainless steel due to inherent process limitations. However, other ceramic type erosion protectors or other processes for creating thicker Solide™ coatings could be developed, using the results of this program as a guide. Solar recommends that the Army seriously consider prospects for research and development along these lines.

4. Sikorsky Aircraft rotor design personnel determined that coating failure at high angles eliminated Solide™ coated abrasion strips for possible usage on the leading edges of Sikorsky helicopters. However, based on satisfactory results in tests of erosion at low angles (15°), Sikorsky recommended that more work be done to further qualify Solide™ coated titanium for enhancement of erosion resistance on rotor blade tip caps of Sikorsky's Blackhawk airships where only low angle impacts occur.

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APPENDIX A

AFML RAIN EROSION APPARATUS

APPENDIX A

AFML RAIN EROSION APPARATUS

The apparatus at AFML, on which the subsonic rain erosion tests on borided alloys were conducted, includes an 8-foot diameter propeller blade made of 4340 steel, mounted horizontally and powered by a 400 horsepower electric motor. It is capable of attaining variable speeds up to Mach 1.2 at the blade tip where the specimens are inserted.

The speed of the equipment is regulated by a thyristor power supply from which rigid control is possible. A revolution counter is utilized for monitoring velocity, and vibration pickups are used for gauging specimen balance and smooth operation. The rotating specimens were observed from a closed circuit television camera and a stroboscopic unit synchronized with the blade revolutions. This system enables the observer to note the exact moment of coating failure (i.e., penetration to the substrate or loss of adhesion).

Mounted above the blade is the water system used to simulate the rain environment. The 8-foot diameter, 1-inch aluminum pipe ring is equipped with 96 equally spaced hypodermic needles to yield a rainfall simulation of 1 inch per hour. The hypodermic needles are No. 27 gauge, which produces rain droplets of 1.5 to 2.0 mm diameter, as determined photographically. The water system, when operated with low pressure in the spray ring, enables a stream of water drops to impinge on the material specimens without distorting the drops.

The specimen configurations were conformal specimens of aluminum and laminated glass epoxy with the borided alloys bonded to them. The conformal specimens are employed extensively because they are easy to coat and their low drag and light weight permit efficient operation of the apparatus.

A schematic of the AFML apparatus used in this investigation is shown in Figure A-1.

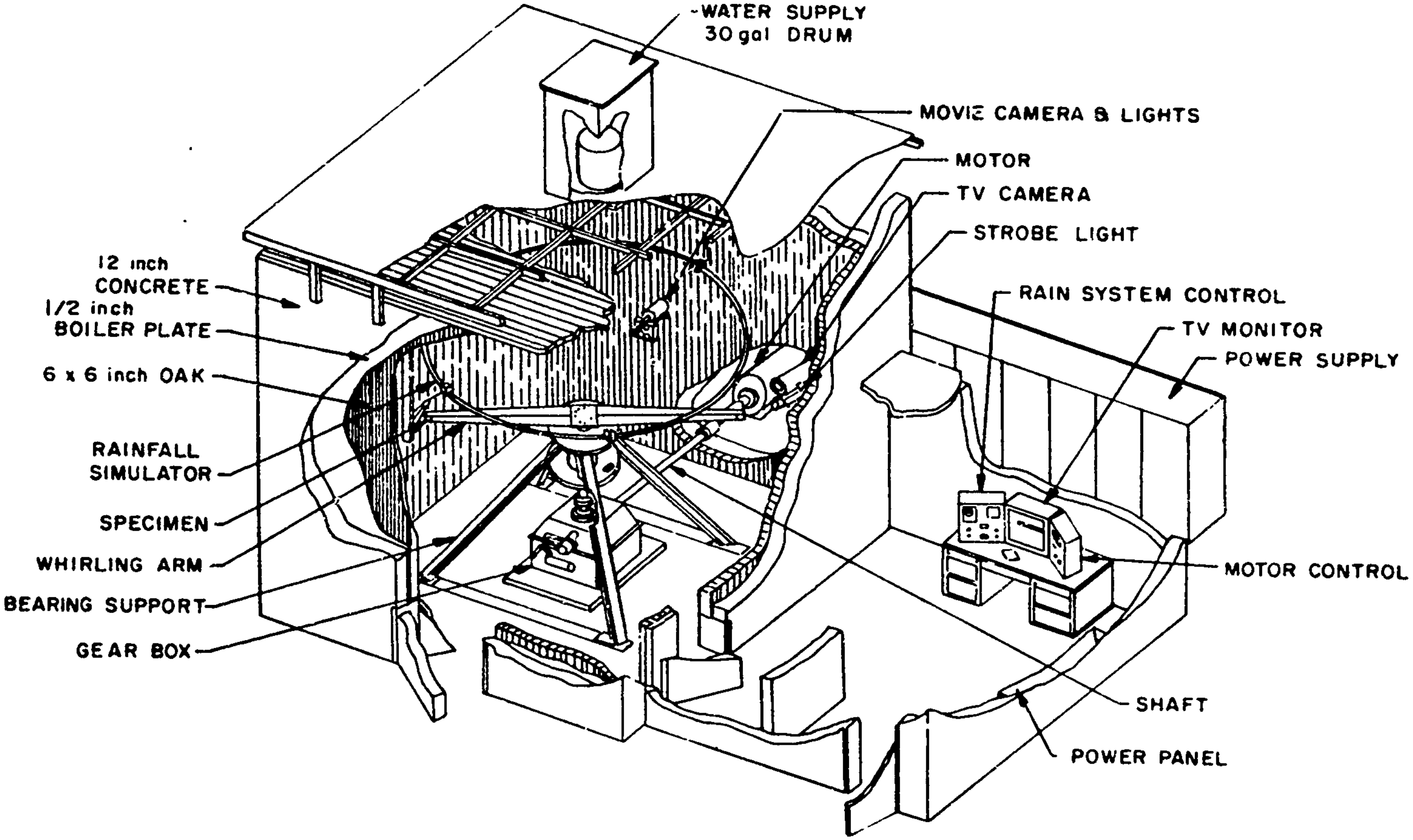

Figure A-1. Schematic of AFML Rotating Arm Rain Erosion Apparatus

APPENDIX B

COST ESTIMATE FOR THE INITIAL PRODUCTION OF SOLIDE™ COATED EROSION RESISTANT NOSE CAPS

APPENDIX B

COST ESTIMATE FOR THE INITIAL PRODUCTION OF SOLIDE™ COATED EROSION RESISTANT NOSE CAPS

AMMRC Contract DAAG46-76-C-0033

Solar Sales Order 6-4511-7

This is an estimate of the costs to fabricate Solide™ coated erosion resistant nose caps for helicopter rotor blades. Current laboratory production techniques were used as the basis for all estimates of labor and tooling. The Sikorsky Blackhawk (UTTAS) and Bell UH-1H helicopter systems were arbitrarily chosen as examples to establish a representative production rate requirement as well as typical dimensions. Both of the coating systems now under development by Solar are included in the estimate: Solide™ coated titanium and Solide™ coated stainless steel (SAE 430).

ASSUMPTIONS

The following assumptions have been made in order to set an economic framework for this cost estimate.

- The facility at which the nose caps are to be produced would be an extension to an existing manufacturing establishment. Normal plant facilities such as water, shop air, electricity, hand tools and so on are assumed to be present without additional expense other than an hourly overhead rate.

- Pre-formed, bare metal nose caps are assumed to be available as raw material. The expense of the metal in sheets (0.040 inch A70 titanium or SAE 430 stainless steel) is included in this estimate but not the cost of hot or cold forming the blank sheet metal pieces to the rotor blade leading edge shape.

- The Solide™ coating to be applied is assumed to be 0.002 inch thick on SAE 430 and 0.0005 inch thick on titanium.

- Either of the two coating systems may be used but it is assumed that only one is required during any given production period.

EXPLANATION OF THE ESTIMATING FACTORS

The following paragraphs explain the individual details used to arrive at these total cost figures (refer to Tables B-1 through B-8).

Estimated Demand for Parts (Table B-1)

The current average monthly demand by AVSCOM for rotor blades for the UH-1H aircraft in the Army fleet is 113 per month (1356 per year). This rate has been assumed to remain constant over the next ten years for the purposes of this cost estimate. A design for a nose cap suitable for the UH-1H rotor blade calls for a single piece 42 inches long with a depth along the chord of about 5 inches.

The estimated production rate of nose caps for Sikorsky's Blackhawks is based on the announced production rate of helicopters over the next ten years.

Enough parts are included in the estimate to allow for 25 percent spares continuously plus replacement parts at the rate of three percent per month for aircraft produced in previous years as the total fleet grows. Additionally, the present design for the Blackhawk rotor blades call for a three-piece nickel abrasion strip with the longest piece 41 inches long. Thus, this cost estimate allows for three Solide™ coated nose cap sections for each Blackhawk rotor blade.

The estimate for raw material usage and labor time is a composite of all of these nose cap types disregarding the actual numbers of each design.

Capital Equipment (Table B-2)

The capital equipment required to produce Solide™ coated nose caps using current techniques is included in this estimate. Some equipment which would be required but probably already available (e.g., welding equipment, overhead hoists, etc.) has not been included. All of the items have been estimated to have a ten-year life expectancy for the purposes of amortization. The furnace has been depreciated at a rate typically used by Solar for production heat treating furnaces. For all other capital equipment, straight line depreciation has been employed.

Tooling (Tables B-3, B-4, B-5)

Major tooling costs have been broken down into three parts: perishable tools (retorts), graphite mandrels (for producing titanium nose caps), and steel mandrels (for stainless steel nose caps). Retorts are estimated on a basis of the number of parts run before the retort must be completely replaced. The number of mandrels required varies from year to year as the demand for finished parts varies. Mandrels on hand must equal the estimated daily production so that each mandrel is used once a day. The replacement costs have been spread out by depreciating the initial costs in a straight line over the anticipated life of each new mandrel.

Raw Material (Table B-6)

Raw material costs are estimated at current prices and re-estimated for each future year at the material inflation rates for the specific type of material taken from the Chase Inflation Planner.

Labor/Overhead (Table B-7)

Labor rates are based on an arbitrary current man hour labor cost of $8.00 per hour plus an overhead rate of $15.00 per hour. These rates are increased in each future year by estimated labor inflation factors from the Chase Inflation Planner.

Summary - Total Costs (Table B-8)

Table B-8 is a summary of total costs tabulated on a per-part basis and given in terms of factory production costs only. Profits, fees, handling charges, etc., are not included. The production efficiency brings about an optimum labor rate in the fourth year, but inflationary factors take over and push the estimated costs steadily upward thereafter.

Table B-1

Estimated Demand For Nose Caps For Sikorsky Blackhawk and Bell UH-1H Helicopters

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
• Blackhawk Blades for new Craft + 25% spares	75	280	645	840	840	840	900	900	215	--
Total blades in fleet + 25% spares	75	355	1000	1840	2680	3520	4420	5320	5535	5535
Replacement blades at 3% per month	0	27	128	360	662	965	1267	1591	1915	1915
Total annual blade demand (new & replace.)	75	307	773	1200	1502	1805	2167	2491	2130	2130
Nose cap demand (at 3 per blade)	225	921	2319	3600	4506	5415	6501	7473	6390	6390
• UH-1H Annual blade demand	1356	1356	1356	1356	1356	1356	1356	1356	1356	1356
Total: Blackhawk + UH-1H	1581	2277	3675	4956	5862	6771	7857	8829	7746	7746
• Total annual nose cap production rate (incl. 5% rej.)	1660	2391	3859	5204	6155	7110	8250	9270	8133	8133
Monthly rate	138	199	322	434	513	593	688	773	678	678
Approx. daily rate	7	10	16	22	26	30	34	39	34	34

Table B-2

Capital Equipment

Year	Parts Req'd Annually		Furnace	Spray Booth	Spray Guns (4)	Ball Mill	Vacuum Pump and Drive	Cleaning Tanks	Misc.	Total Cost Per Part
		Initial Cost	24,300	800	400	700	1680	350	1000	
1978	1660	% Decprciation Annual cost Cost per part	10.5 2552 1.54	10.0 80.0 0.05	10.0 40.0 0.02	10.0 70.0 0.04	10.0 168.0 0.07	10.0 35.0 0.02	10.0 100.0 0.06	1.83
1979	2391	% Depreciation Annual cost Cost per part	18.8 4568 1.91	10.0 80.0 0.03	10.0 40.0 0.02	10.0 70.0 0.03	10.0 168.0 0.07	10.0 35.0 0.01	10.0 100.0 0.04	2.11
1980	3859	% Depreciation Annual cost Cost per part	15.7 3815 0.99	10.0 80.0 0.02	10.0 40.0 0.01	10.0 70.0 0.02	10.0 168.0 0.04	10.0 35.0 0.01	10.0 100.0 0.03	1.12
1981	5204	% Depreciation Annual cost Cost per part	13.7 3329 0.64	10.0 80.0 0.02	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.03	10.0 35.0 0.01	10.0 100.0 0.02	0.73
1982	6155	% Depreciation Annual cost Cost per part	11.8 2867 0.47	10.0 80.0 0.01	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.03	10.0 35.0 0.01	10.0 100.0 0.02	0.56
1983	7110	% Depreciation Annual cost Cost per part	9.8 2381 0.33	10.0 80.0 0.01	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.02	10.0 35.0 0.01	10.0 100.0 0.01	0.40
1984	8250	% Depreciation Annual cost Cost per part	7.8 1895 0.23	10.0 80.0 0.01	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.02	10.0 35.0 0.01	10.0 100.0 0.01	0.30
1985	9270	% Depreciation Annual cost Cost per part	5.9 1434 0.15	10.0 80.0 0.01	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.02	10.0 35.0 0.01	10.0 100.0 0.01	0.22
1986	8133	% Depreciation Annual cost Cost per part	3.9 948 0.12	10.0 80.0 0.01	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.02	10.0 35.0 0.01	10.0 100.0 0.01	0.19
1987	8133	% Depreciation Annual cost Cost per part	2.1 510 0.06	10.0 80.0 0.01	10.0 40.0 0.01	10.0 70.0 0.01	10.0 168.0 0.02	10.0 35.0 0.01	10.0 100.0 0.01	0.13

Table B-3

Tooling - Graphite Mandrels With Two-Year Life

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Total tools req'd this year	7	10	16	22	26	30	34	39	34	34
Used tools still functional at start of year	0	7	3	13	9	17	13	21	18	16
Total tools to be purchased this year	7	3	13	9	17	13	21	18	16	18
Material price inflation rate	--	5.0	5.5	5.5	5.5	6.1	4.5	4.5	4.5	5.0
New tool cost (each) $	4,250	4,463	4,708	4,967	5,240	5,560	5,810	6,071	6,344	6,661
Total cost for new tools	29,750	13,389	61,204	44,703	89,080	72,280	122,010	109,278	101,504	119,898
Annual cumulative tool expense at 50% annual deprec.	14,875	21,570	37,297	52,954	66,892	80,680	97,145	115,650	105,391	110,701
Number of parts produced this year	1,660	2,391	3,859	5,204	6,155	7,110	8,250	9,270	8,133	8,133
Cost per part	8.96	9.02	9.66	10.18	10.87	11.35	11.78	12.48	12.96	13.61

Table B-4

Tooling - Steel Mandrels With Five-Year Life

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Total tools req'd this year	7	10	16	22	26	30	34	39	34	34
Used tools still functional at start of year	0	7	10	16	22	19	27	28	33	30
Total tools to be purchased this year	7	3	6	6	4	11	7	11	1	4
Material price inflation rate	--	5.0	5.5	5.5	5.5	6.1	4.5	4.5	4.5	5.0
New tool cost (each) $	750	788	831	877	925	981	1025	1071	1119	1175
Total cost for new tools	5250	2364	4986	5262	3700	10,791	7175	11,781	1119	4700
Annual cumulative tool expense at 20% annual depreciation	1050	1523	2520	3572	4312	5421	6383	7742	6913	7113
Number of parts produced this year	1660	2391	3859	5204	6155	7110	8250	9270	8133	8133
Cost per part	0.63	0.64	0.65	0.69	0.70	0.76	0.77	0.84	0.85	0.87

Table B-5

Perishable Tools - Retorts

Year	Mat'l Inflation Rate (%)	New Retort Cost	Life Expectancy	Cost Per Part
1978	-	3235	1000 parts	3.23
1979	5.0	3396	1000 parts	3.40
1980	5.5	3584	1000 parts	3.58
1981	5.5	3781	1000 parts	3.78
1982	5.5	3989	1000 parts	3.99
1983	6.1	4232	1000 parts	4.23
1984	4.5	4422	1000 parts	4.42
1985	4.5	4621	1000 parts	4.62
1986	4.5	4829	1000 parts	4.83
1987	5.0	5070	1000 parts	5.07

Table B-6

Raw Materials

Year	A70 Titanium, 0.040 Inch				SAE 430 SS, 0.040 Inch				M9-13 Coating Slurry			
	Mat'l Infl. Rate (%)	Cost Per Sheet	Parts Per Sheet	Cost Per Part	Mat'l Infl. Rate (%)	Cost Per Sheet	Parts Per Sheet	Cost Per Part	Mat'l Infl. Rate (%)	Cost Per Pint	Parts Per Pint	Cost Per Part
1978	-	293.35	10	29.33	-	61.94	10	6.19	-	19.26	5	3.85
1979	9.2	320.34	10	32.03	6.7	66.09	10	6.61	5.0	20.22	5	4.04
1980	6.1	339.88	10	33.99	9.2	72.17	10	7.22	5.5	21.33	5	4.27
1981	4.6	355.51	10	35.55	8.2	78.09	10	7.81	5.5	22.50	5	4.50
1982	4.5	371.51	10	37.15	6.7	83.32	10	8.33	5.5	23.74	5	4.75
1983	3.8	385.63	10	38.56	5.5	87.90	10	8.79	6.1	25.19	5	5.04
1984	3.9	400.67	10	40.07	5.0	92.30	10	9.23	4.5	26.32	5	5.26
1985	4.1	417.10	10	41.71	4.8	96.73	10	9.67	4.5	27.50	5	5.50
1986	4.2	434.62	10	43.46	4.4	100.99	10	10.10	4.5	28.74	5	5.75
1987	4.3	453.31	10	45.33	4.2	105.23	10	10.52	5.0	30.18	5	6.04

Table B-7

Labor/Overhead

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Estimated annual labor/ burden inflation	--	6.5	6.5	6.4	6.2	6.1	5.9	6.1	6.3	6.0
Number of parts this year	1,660	2.391	3,859	5,204	6,155	7,110	8,250	9,270	8,133	8,133
Full time crew required	1.0	1.5	2.1	2.5	3.0	3.5	4.0	4.3	4.0	4.0
Total annual manhours	2,080	3,120	4,368	5,200	6,240	7,280	8,320	8,944	8,320	8,320
Labor/burden rate	23.00	24.50	26.09	27.76	29.48	31.28	33.13	35.13	37.34	39.58
Total labor/ burden expense	47,840	76,440	113,961	144,352	183,955	227,718	275,642	314,203	310,669	329,306
Cost per part	28.82	31.97	29.53	27.74	29.89	32.03	33.41	33.89	38.20	40.49

Table B-8

Summary: Total Costs Per Part

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Capital equipment	1.83	2.11	1.12	0.73	0.56	0.40	0.30	0.22	0.19	0.13
Perishable tools	3.23	3.40	3.58	3.78	3.99	4.23	4.42	4.62	4.83	5.07
Graphite mandrels	8.96	9.02	9.66	10.18	10.87	11.35	11.78	12.48	12.96	13.61
Steel mandrels	0.63	0.64	0.65	0.69	0.70	0.76	0.77	0.84	0.85	0.87
A70 titanium, 0.040"	29.33	37.03	33.99	35.55	37.15	38.56	40.07	41.71	43.46	45.33
0.040" SAE 430 SS	6.19	6.61	7.22	7.81	8.33	8.79	9.23	9.67	10.10	10.52
M9-13 coating slurry	3.85	4.04	4.27	4.50	4.75	5.04	5.26	5.50	5.75	6.04
Labor/overhead	28.82	31.97	29.53	27.74	29.89	32.03	33.41	33.89	38.20	40.49
Cost Per Part Total titanium	76.02	82.57	82.15	82.48	87.21	91.61	95.24	98.42	105.39	110.67
Total 430 SS	44.55	48.77	46.37	45.25	48.22	51.25	53.39	54.74	59.92	63.12

APPENDIX C

HUGHES HELICOPTERS FINAL REPORT
FOR
SOLAR CERAMIC COATING TESTS

Hughes Helicopters

HH 78-160

FINAL REPORT
FOR
SOLAR CERAMIC COATING TESTS
AT HUGHES HELICOPTERS

June 1978

HUGHES HELICOPTERS
Culver City, California

PREFACE

This final report was prepared by Hughes Helicopters (HH), Division of Summa Corporation, Culver City, California for Solar Division of International Harvester, San Diego, California under P.O. 9980-43072-505. The subcontract was issued under Army (AMMRC) Prime Contract DAAG-46-76-C-0033.

Tests were performed in May 1978 at Test Site No. 3, Hughes Helicopters, Culver City, California.

George Harris of AMMRC, Ross Sherwood of Army Engineering at HH, David Huey and Al Stetson of Solar, and Alex Kam and Chuck Emigh of HH witnessed the sand test performed on May 16, 1978.

SUMMARY

This report summarizes the results of tests conducted on leading edge erosion protection materials utilizing the Hughes Helicopters rain/sand erosion test facility. The specimens were mounted on special test blades cut down from Model 500D main rotor blades and were whirled at closely controlled rpm in specified rain and sand environments.

The abrasion strips were fabricated by Solar Division, International Harvester, Inc. Four specimens had a ceramic coating on a Titanium (Ti-6Al-4V) substrate and four had the same ceramic coating on a SAE 430 stainless steel backing.

Compared with the aluminum Model 500D blade as a baseline, the ceramic coating on stainless steel is inferior in the test rain erosion environment. The coating on titanium showed no erosion in rain.

In the sand environment, the coatings on both substrates were worn off in a very short time. However, for the substrates, the 430 stainless steel had better sand erosion protection than titanium.

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INTRODUCTION

This report presents the results of erosion tests conducted on the test configured OH-6A main rotor blades. The tests were conducted between April 24 and May 20, 1978, at the Hughes Helicopters (HH) Structure Test Facility in Culver City, California.

TEST OBJECTIVES

The test objective was to determine the rain and sand erosion resistance characteristics of ceramic coatings on titanium (Ti-6Al-4V) and SAE 430 stainless steel abrasion strips.

TEST SPECIMENS

The main rotor blade test specimens were 39.75 inches in overall length, erotion test portion was 18 inches of the length (Figure 1). The blade length was selected to avoid excess centrifugal force on the erosion strips when conducting the simulated rain test at 900 feet per second tip speed. The abrasion strips were furnished by Solar, Division of International Harvester, Inc., and were bonded by Hughes to the test blades with EA9628 Class II adhesive tape. Screws were installed along the trailing edge of the strips for safety purposes (Figure 1).

A bell peel test was performed to verify adequate peel strength of the adhesive tape.

TEST SETUP

RAIN EROSION TEST

The blade specimens were mounted to a two-bladed hub fixture with standard aircraft attach pins. The hub was driven by a hydraulic motor whose power supply was portable unit placed outside the protective cage of the test site. The rain spray rig (Figure 2) was supported 25 feet above the blade fixture (Figure 3) and oscillated approximately 0.3 rpm to spray water evenly from each pipe orifice at a cumulative rate of 1.00 inch per hour.

SAND EROSION TEST

Two open rectangular boxes (3.5 by 24 by 72 inches) (Figure 4) were placed on the ground and located at the three-quarter radius of the rotor plane. The longitudinal axes of the boxes were positioned tangent to the radius circle. Each box holds approximately 600 pounds of a sand mixture made of 4:1 ratio No. 50 and No. 30 grade sand.

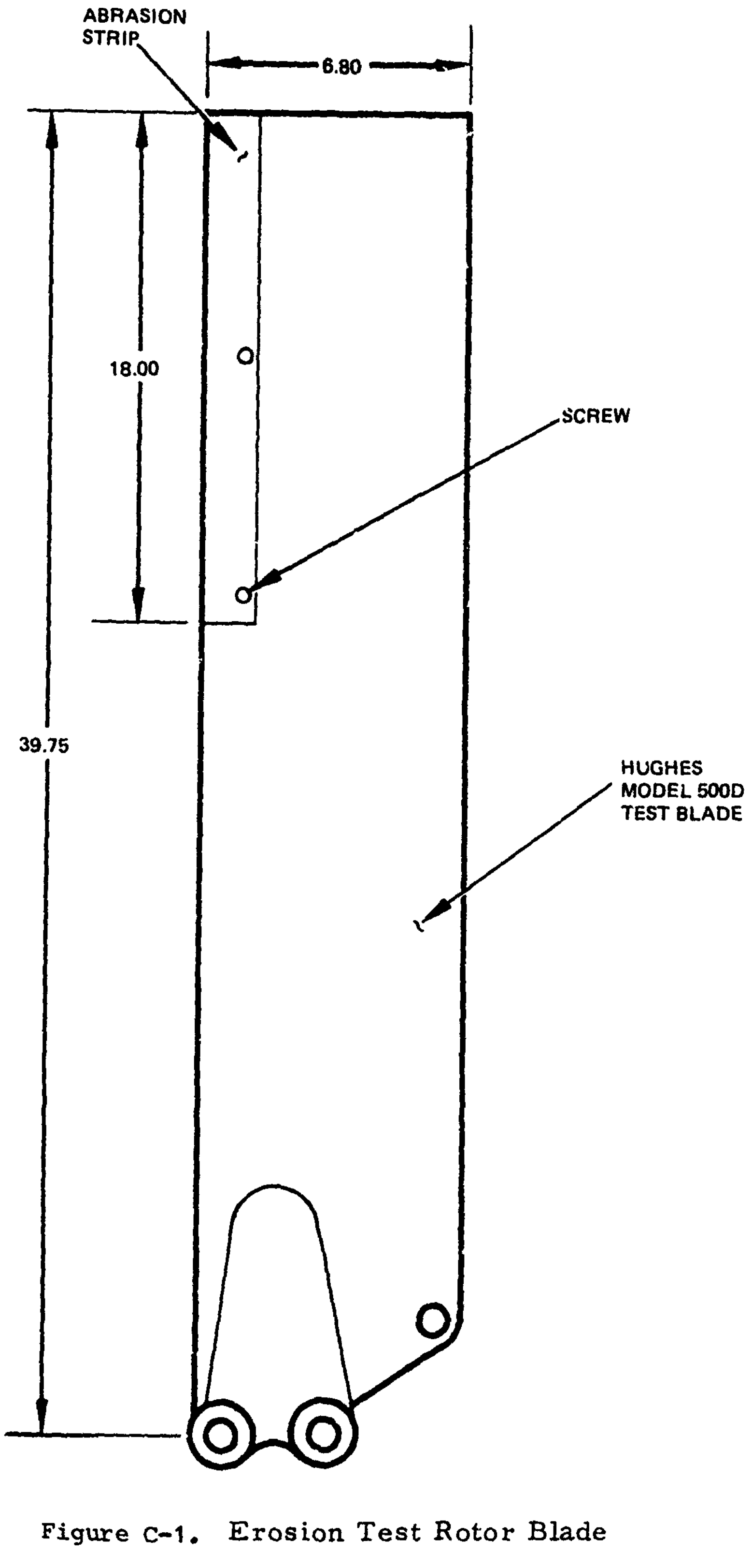

Figure C-1. Erosion Test Rotor Blade

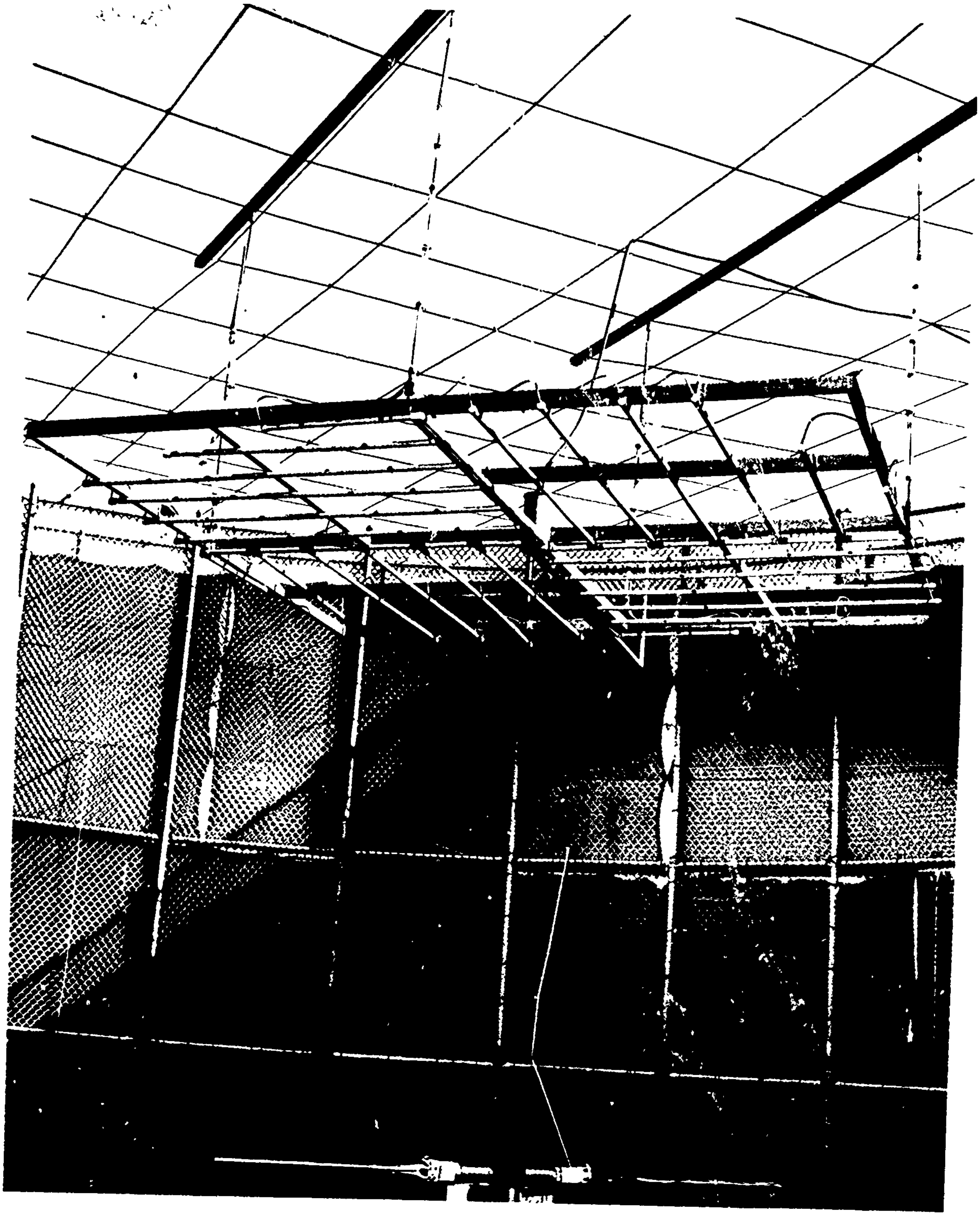

Figure C-2. Rain Rig for Rain Test

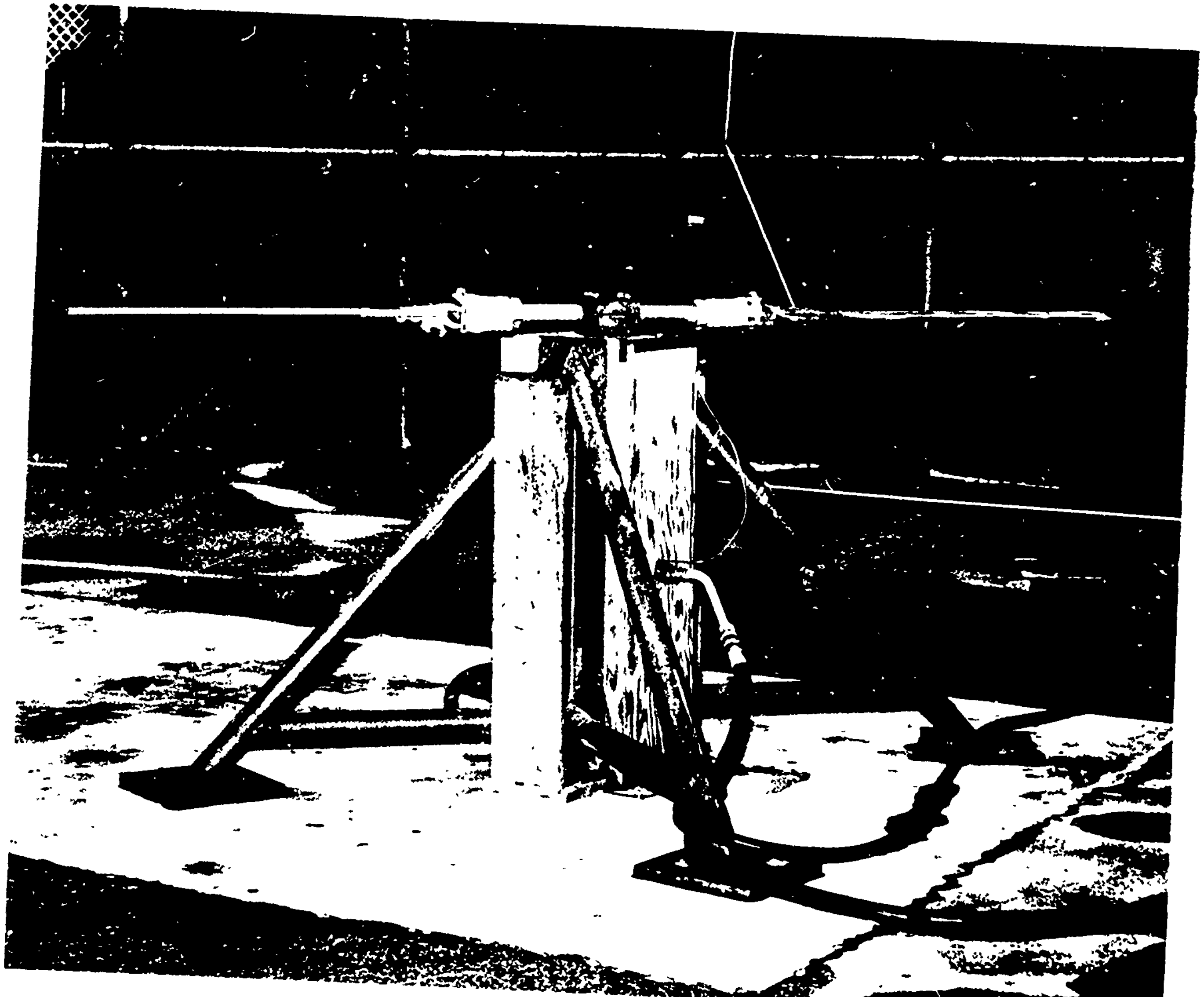

Figure C-3. Rain/Sand Test Stand

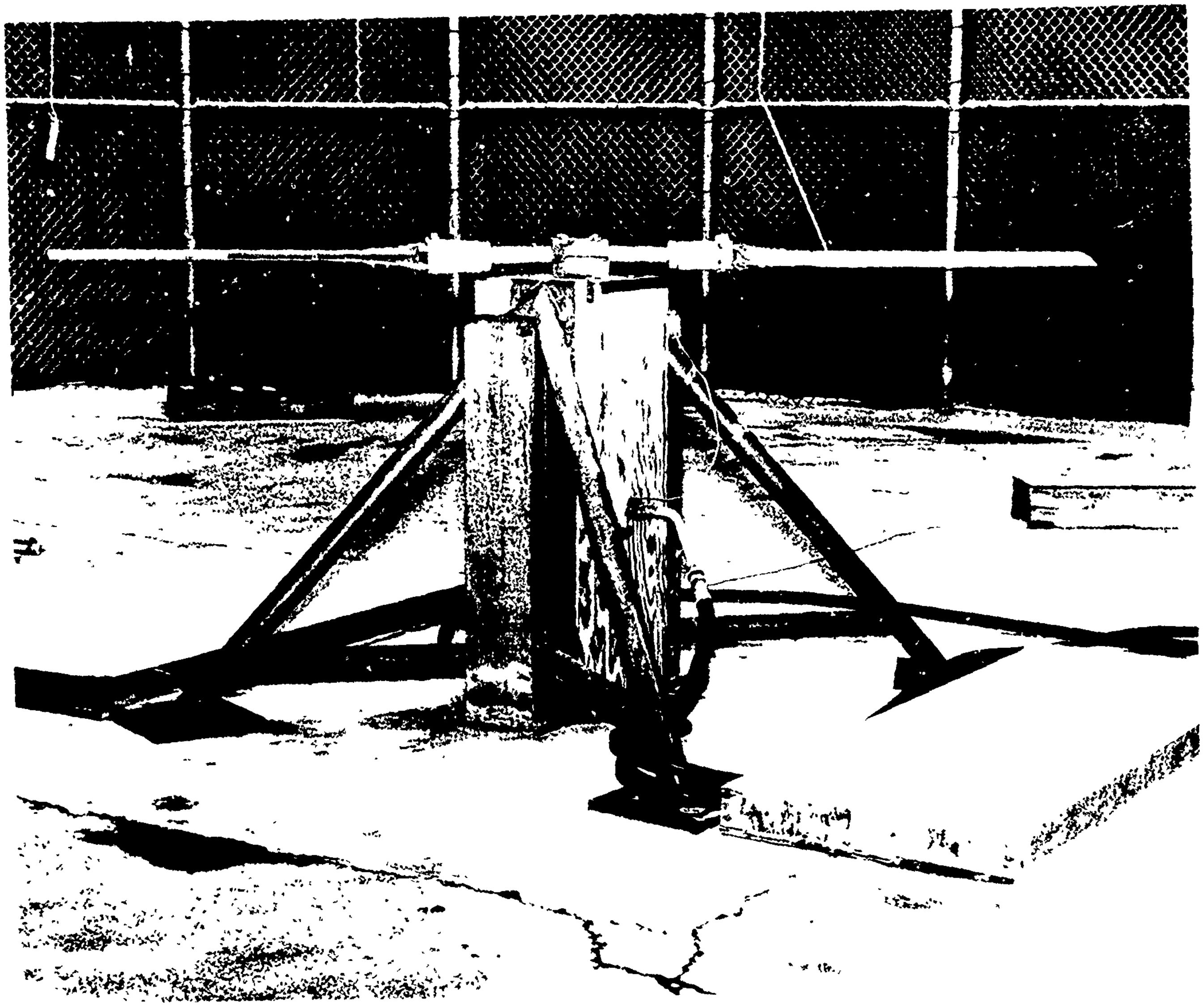

Figure [illegible]. Sand Box for Sand Test

TEST PROCEDURE

RAIN EROSION TEST

Each blade was mounted on the hub with a collective pitch at the tip of zero degree to simulate a 100-knot level flight condition. The water pressure was adjusted to provide a rainfall of 1.00 inch per hour. The rain spray rig was checked to ensure an even water flow from all pipe orifices. With the spray rig oscillating at approximately 0.3 rpm for even raindrop dispersal, the rotor was rotated at a tip speed of 900 fps.

SAND EROSION TEST

The collective pitch for each blade was set at +7 degrees at the tip to simulate a hover condition. The sand boxes were filled to the top and leveled with the required 4:1 weight ratio of sandgrade prior to each test run. The rotor was rotated at a tip speed of 750 fps. Each run lasted 3 to 4 minutes. The data from the tests are listed in Table I for the eight specimens. The same data are shown in bar chart form in Figure 5.

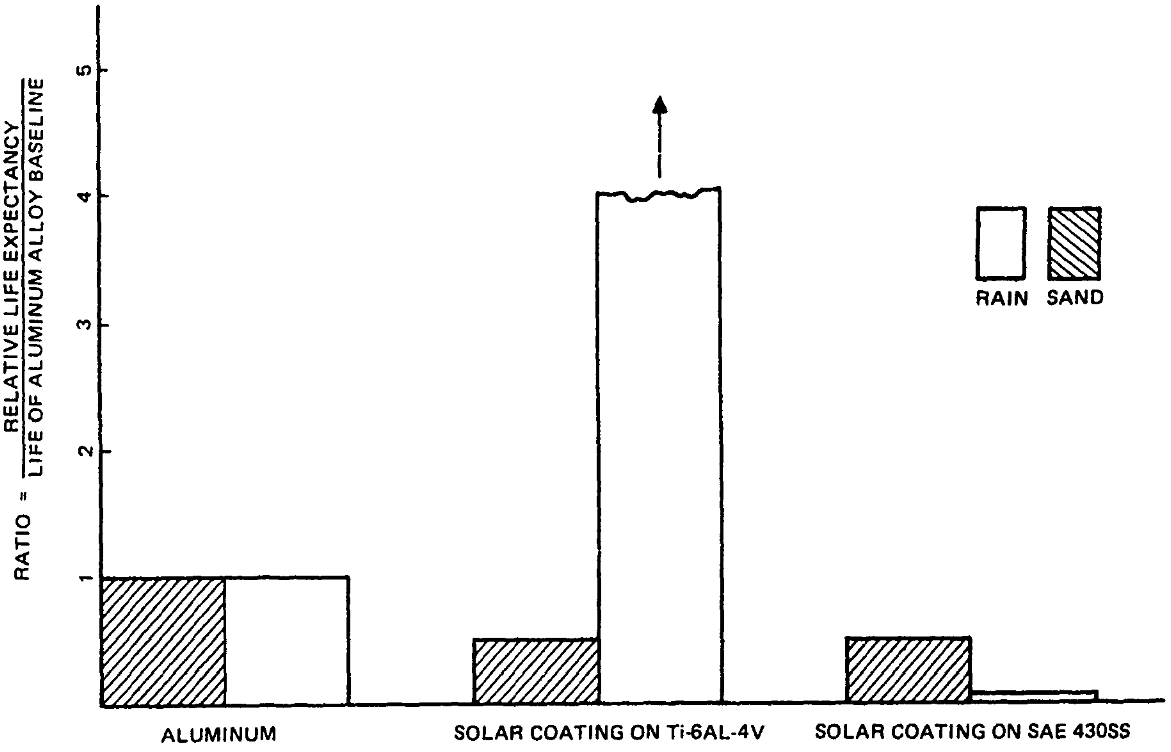

Figure C-5. Erosion Test Results

Table C-1. SOLAR TESTING RESULTS

Blade No.	Materials With Solar Coating	Environment	Tip Speed (fps)	Pitch (degrees)	Test Time (minutes)	Remarks
1	430 Stainless Steel	Rain Rate 1 in/hr	900	0	15	Coating failed along leading edge.
2	430 Stainless Steel	Rain Rate 1 in/hr	900	0	15	Coating failed along leading edge.
3	Ti-6Al-4V	Rain Rate 1 in/hr	900	0	600	Test duration no erosion.
4	Ti-6Al-4V	Rain Rate 1 in/hr	900	0	600	Test duration no erosion.
5	430 Stainless Steel	Sand 125 lb/min	750	+7	3	Coating wore off the leading edge to metal.
6	430 Stainless Steel	Sand 125 lb/min	750	+7	3	Coating wore off the leading edge to metal.
7	Ti-6Al-4V	Sand 125 lb/min	750	+7	3	Coating wore off the leading edge to metal.
8	Ti-6Al-4V	Sand 125 lb/min	750	+7	3	Coating wore off the leading edge to metal.

DISCUSSION

The coating on SAE 430 stainless steel wore off in approximately 15 minutes in the rain test but no further erosion occurred after that. For the coating on titanium, no erosion occurred after 10 hours of rain environment testing. This test showed that the ceramic coating on the titanium was far better than the same coating on stainless steel.

In the sand environment, the coatings on both stainless steel and titanium wore off in about the same time (see Figures 6 and 7). After the coating wore off, the titanium started to erode, and with another run the blades were removed because of the erosion rate (see Figures 8 and 9).

For the stainless steel, the erosion rate of the metal is a lot slower than titanium. The strip was exposed for 23 minutes before blade removal due to splitting of the blade trailing edge.

All test speciments were sawed off and send back to Solar for further investigation.

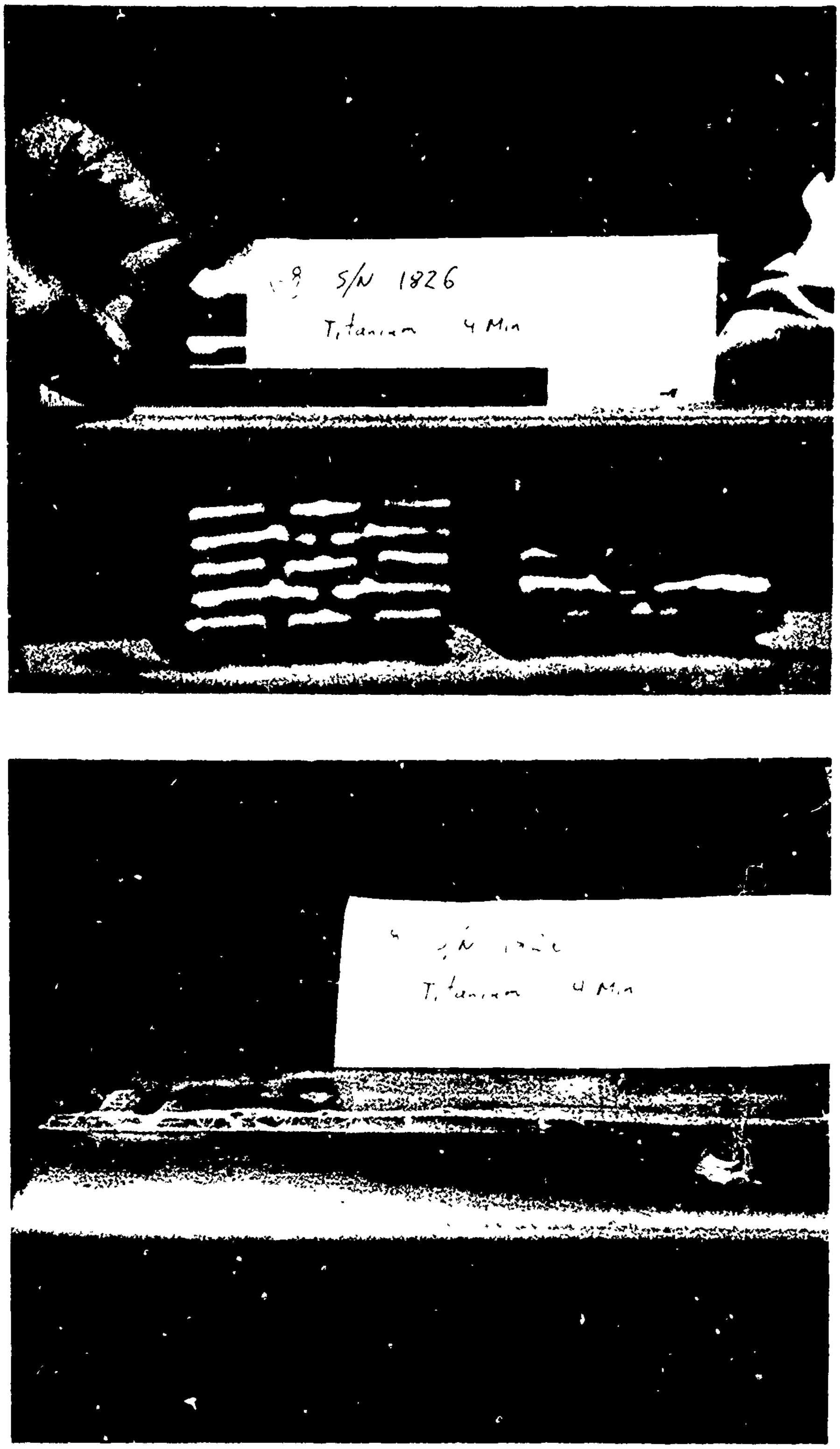

Figure C-6. Titanium after 4 Minutes — Sand Test

Figure C-7. Titanium after 4 Minutes — Sand Test

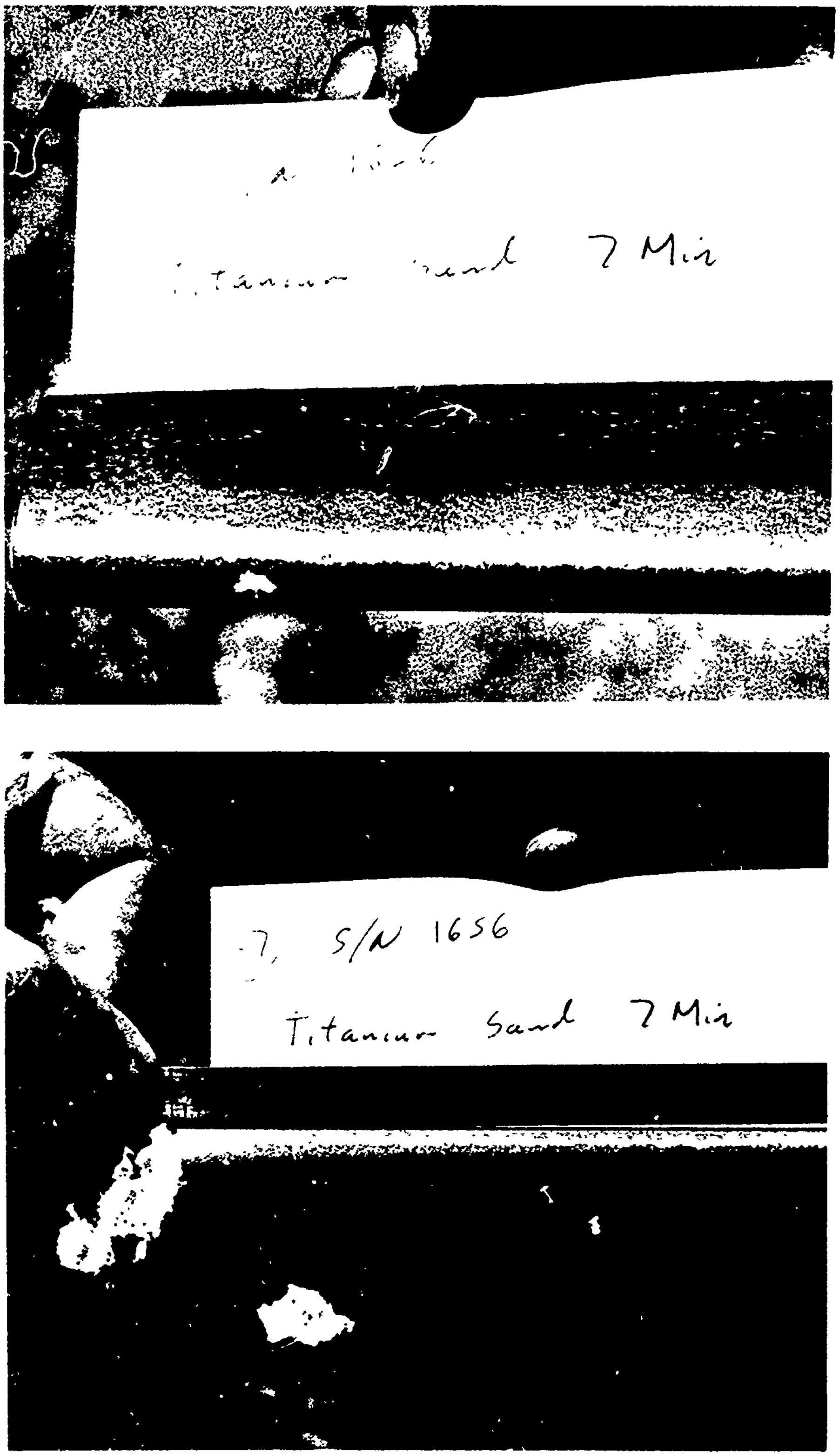

Figure 8. Titanium after 7 Minutes

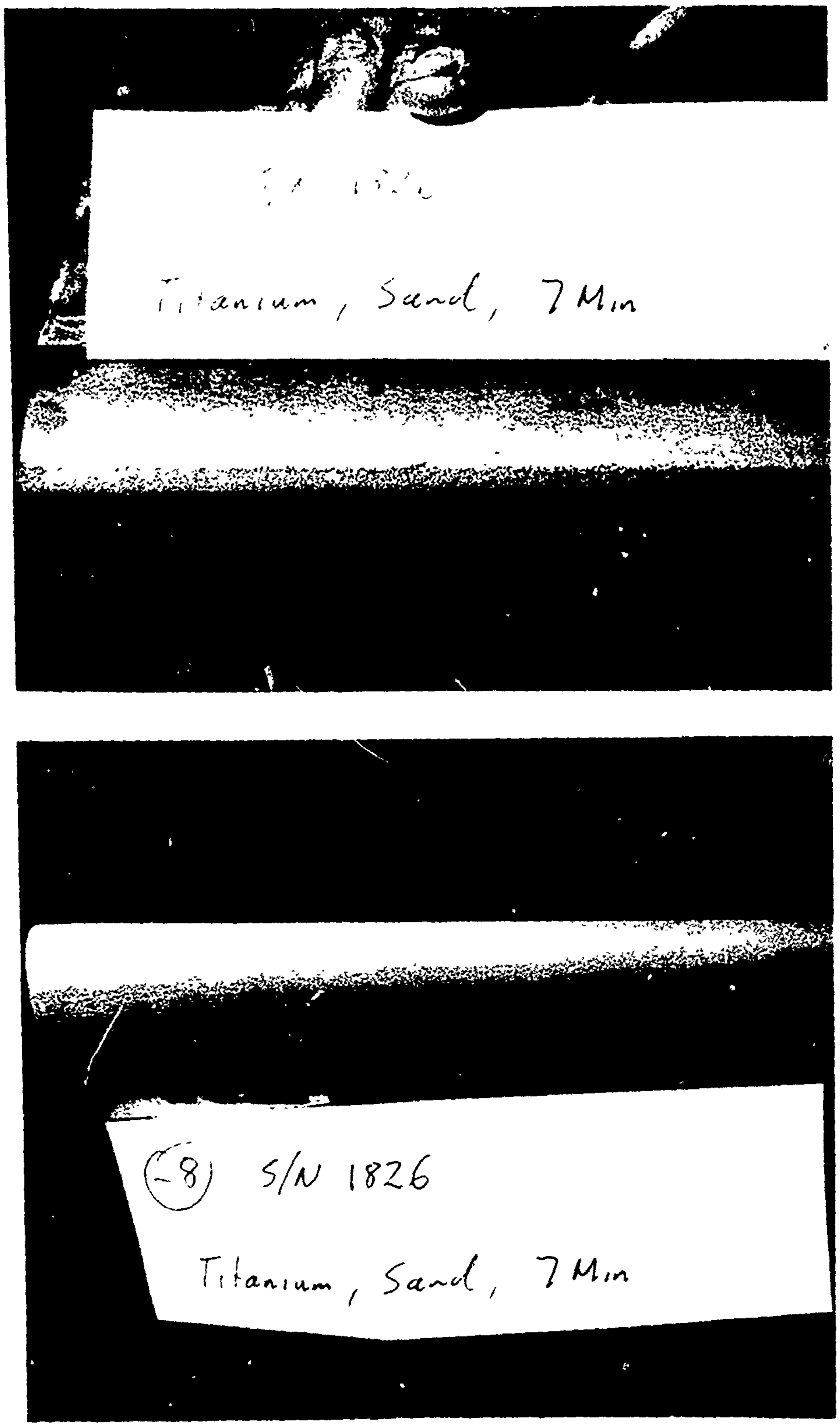

Figure C-9. Titanium after 7 Minutes

CONCLUDING REMARKS

The coating wore off the 430 stainless steel leading edges in approximately 15 minutes in rain. After that there was no further erosion from rain. The coating on Ti-6Al-4V alloy had no sign of rain erosion after 10 hours of testing.

The coatings on both titanium and stainless steel were worn through in 3 minutes in the sand erosion environment.

After the coatings were worn through, a few more test runs were made to determine the erosion resistance of the backing materials. The Ti-6Al-4V alloy backing was found unsatisfactory in the sand environment. However, the 430 stainless steel was considerably better. After 23 minutes in the sand environment, the trailing edge of the test blade split apart. The test was terminated for safety reasons.

The tests showed that the ceramic coating on both substrates gave unsatisfactory protection in the sand environment. It gives better protection with the titanium than with the stainless steel in the rain environment.

APPENDIX

LABORATORY TEST RESULTS

Hughes Helicopters HH 78-160

DEPARTMENT 13-91 STRUCTURES TEST LABORATORY
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FINAL SUMMARY REPORT

TITLE: Main Rotor Blade Erosion Test ETR: R-BT-16
TEST ENGINEER: W. A. Christiansen EXT. 4042 MJO 3986 APPROVED: G. Korkosz G. Deveaux

DATE	TEST EVENTS

May 5 thru
May 16,1978

INTRODUCTION

This report presents the results of erosion tests conducted on main rotor abrasion strips between May 5, 1978 and May 16, 1978. The tests were conducted at the Hughes Helicopters Structures Test Facility, Culver City, California.

OBJECTIVE

The objective of the test program was to determine the rain and sand erosion characteristics of the ceramic coating applied to 430 stainless steel and titanium abrasion strips.

TEST SPECIMENS

The test specimens were eight 369 main rotor blades shortened to 39.75 inches with ceramic coated metalic abrasion strips bonded to the leading edge with EA 9628 Class II adhesive. The blades were numbered from one to eight, corresponding to procedure instructions given in Engineering Test Request R-BT-16. Refer to Table I for composition of erosion strips.

TEST SETUP

Rain Erosion Tests - The blades were mounted onto a two-bladed hub fixture with standard aircraft attach pins (Figure 2). The hub was driven by a hydraulic motor with fluid pressure supplied by a portable unit located outside the protective cage. Rotor tip speed was regulated by a pressure regulator on the portable unit, while constantly monitored with a frequency counter. A rain spray rig (Figure 1) supported 25 feet above the blade fixture provided the required rainfall rate of 1 in/hr and nominal raindrop diameter ranges as specified in MIL-STD-210B, Article S.1.11.3.

Sand Erosion Tests - The same hub fixture and rotor tip speed regulation system was used for the sand erosion tests as was used in the rain erosion tests. Two rectangular boxes (3.5 x 24.0 x 72.0 inches) were placed on the ground with their longitudinal axes tangent to the 3/4 radius of rotor disk. #50 and #30 grade sand were used in a ratio of 4:1, respectively, to achieve

Distribution: A. Kam; R. E. Head; D. Huey; J. F. Needham; D. Mancill
N. J. Mocerino; R. E. Moore

STRUCTURES TEST SUMMARY REPORT Page 2 of 5

TITLE:	Main Rotor Blade Erosion Test	ETR: R-BT-16

DATE	TEST EVENTS

#40 grade (see Figure 2).

PROCEDURE

The procedure followed was per Engineering Test Request No. R-BT-16.(Appendix A). Inspection interval time was increased during testing blades No. 3 and 4, after several inspections indicated that these specimens would last the full 10-hour maximum duration of the test. Failure of the coating was defined as the point where visual inspection revealed that the coating had worn through to the metalic abrasion strip.

RESULTS

Results of test are tabulated in Table I.

This completes the requirements of Engineering Test Request No. R-BT-16.

TABLE I

MAIN ROTOR BLADE EROSION TEST

No.	Composition	Environment	Tip Speed (fps)	Pitch	Test Time	Results
1	430 S.S 3 mil coating	Rain 1 in/hr	900	0°	15 Min.	Coating Failed
2	430 S.S. 3 mil coating	Rain 1 in/hr	900	0°	15 Min.	Coating Failed
3	Titanium 3 mil coating	Rain 1 in/hr	900	0°	600 Min.	Coating Intact
4	Titanium 3 mil coating	Rain 1 in/hr	900	0°	600 Min.	Coating Intact
5	430 S.S. 5 mil coating	Sand #40	750	$+7^{\circ}$	3 Min.	Coating Failed
6	430 S.S. 3 mil coating	Sand ##40	750	$+7^{\circ}$	3 Min.	Coating Failed
7	Titanium 5 mil coating	Sand #40	750	$+7^{\circ}$	3 Min	Coating Failed
8	Titanium 3 mil coating	Sand #40	750	$+7^{\circ}$	3 min	Coating failed

Hughes Helicopters

A.M. KAM /
A G. HIRKO /
B. McCRACKEN /
B. KATHERMAN /
FILE /

STANDARDS, MATERIALS AND PROCESS ENGINEERING

LABORATORY REPORT

PE R&D

NO 61042

PART NUMBER ____ PART NAME ABRASION STRIPS SOLAR CERAMIC
SUBMITTED BY A.M. KAM ORG CODE # 11-20 EXTENSION 5521
NUMBER OF SAMPLES 4 LOT SIZE ____ MJO 3986 CC 113
FORM 9778 DATE 3/5/78 ITR NO ____ P.O. ____ R R ____
FORM 9778 NUMBER LWR 9780 MICRO NUMBERS ____
WO/SO NO. ____ HEAT OR LOT NO ____
VENDOR ____ HEAT TREAT CO. ____
REASON FOR TEST ACCEPTANCE HP16-30

BLUE PRINT REQUIREMENTS	RESULTS OF LABORATORY EXAMINATION					
	BELL PEEL					
	STAINLESS STEEL 430			TITANIUM		
	#1	#2	#3	#1	#2	#3
BELL PEEL 30 PIW (MIN)	72	75	50	57	52	65
	% COHESIVE					
% COHESIVE 75% (MIN) HP16-30 ADHEREND OVER .020"	100%	95%	95%	100%	90%	100%

CONFORMANCE PARTS MEET HP16-30 REQUIREMENT PREPARED BY L BROWN
DATE 3/31/78

APPROVED BY ____ K A COLLINS DATE 3-31-78 APPROVED BY ____ A G HIRKO DATE 3-31-78

FORM 9130 (REV 8/77)

Hughes Helicopters

APPENDIX D

SIKORSKY AIRCRAFT FINAL REPORT
ON
TESTING OF SOLAR M9-13 EROSION RESISTANT COATING

SIKORSKY AIRCRAFT Division of UNITED TECHNOLOGIES

TITLE TESTING OF SOLAR M9-13 EROSION RESISTANT COATING

DOCUMENT NUMBER SER-510027

PREPARED UNDER Subcontract P.O. 9991-37419-T05 and
Sikorsky Letter Agreement CA/ODF-79-312

DOCUMENT DATE February 1980

PERIOD COVERED April 1979 to February 1980

THIS DOCUMENT IS APPLICABLE TO THE FOLLOWING AIRCRAFT MODEL(S) AND CONTRACT(S):

MODEL General

Prime CONTRACT DAAG46-76-C-0033
Issued to Solar Turbines International
by Army Materials and Mechanics
Research Center (AMMRC)

PREPARED BY John Longobardi 2/8/80 J. Longobardi

CHECKED BY Charles Galli 2/26/80 C. Galli

APPROVED BY 2/26/80 P. Ogle

REV	CHANGED BY	REVISED PAGE(S)	ADDED PAGE(S)	DELETED PAGE(S)	DESCRIPTION	DATE	APPROVAL

SUMMARY

This report summaries the results of sand erosion, adhesive and fatigue tests performed on flat ceramic coated and baseline uncoated specimens. The tests were conducted for Solar Turbines International to evaluate Solar's M9-13 boride erosion resistant coating on Ti-6Al-4V and SAE 430SS specimens. The purpose of the program was to determine the suitability of the coating for use as an erosion resistant material on the leading edge of helicopter rotor blades.

Specimens for the tests were fabricated by both Solar and Sikorsky Aircraft; all coated specimens were supplied by Solar. A total of 92 specimens were tested for the program. Fifty-four specimens were Ti-6A-4V and SAE 430SS Solar coated and the remainder were baseline, uncoated Ti-6A-4V, SAE 430SS and eletroformed nickel. All testing was performed at Sikorsky Facilities.

For **erosion** tests at 90^{0} impingement angle, using 100μ to 250μ sand, the coatings on Ti-6Al-4V and SAE 430SS specimens wore through (or pitted) to the substrate in less than one minute. Total wear on the coating and substrate surfaces for Solar coated Ti-6Al-4V and SAE 430SS specimens was better than baseline Ti-6Al-4V and SAE 430SS specimens, up to 100μ sand. Solar coated materials however were inferior to electroformed nickel for all sand grain sizes (100μ, 150μ and 250μ). At 15^{0} impingement angle, Solar coated Ti-6Al-4V and SAE 430SS were erosion free and were superior to the baseline Ti-6Al-4V, SAE 430SS and electroformed nickel specimens. Stress durability, peel and shear tests demonstrated that Solar's coating is receptive to Narmco Metlbond M1113 adhesive system utilized for rotor blade/abrasion strip bonding. The fatigue strength of Solar's coated Ti-6Al-4V and SAE 430SS specimens was reduced to 50% of standard uncoated Ti-6Al-4V and SAE 430SS specimens. There was also evidenced of brittleness and flaking of the M9-13 coating from fatigue and direct impact tests.

However, based on favorable sand erosion results at 15^{0} impingement angle and Solar coating/Metlbond M1113 adhesive capability, further development is warranted. The coated material should be considered for indirect erosion resistance in areas where fatigue and direct impact are minimized. Such an area is on the sides of the rotor blade tip cap.

FOREWORD

This final report was prepared by Sikorsky Aircraft, Division of United Technologies, Stratford, Connecticut. It was performed for Solar Turbines International, San Diego, California under Solar Subcontract P.O. 9991-37419-T05 and Sikorsky Letter Agreement CA/ODF-79-312. The Prime Contract, DAAG46-76-C-0033, was issued to Solar by Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts under the technical direction of George Harris, of the Ceramics Division at AMMRC.

The cognizant personnel of this sub-contract program were George Harris of AMMRC and David P. Huey and A.R. Stetson of Solar, from Sikorsky Aircraft: John Longobardi, Program Manager, Peter Ogle, Rotor System Section Head and John Lucas, Chief of Metals, Structures and Materials Branch.

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INTRODUCTION

The helicopter industry has noted from experience that erosion from sand and rain can significantly reduce the serviceable life of rotor blades. Since the advent of composite blades, there is even a greater need for erosion protection materials over past generation metal blades. Steel and aluminum blades at least provided some inherent protection against erosion and required a minimum of erosion protection. Composite blades, however, have far less resistance to erosion and require far greater leading edge protection.

Presently there are several erosion protection materials utilized by helicopter manufacturers. Polyurethane is generally good in desert or arid surroundings but poor in rain; Haynes Alloy, electro-formed nickel and stainless steel 301/302, are excellent in rain but not as good as polyurethane in the sand. There are other materials; unfortunately however, there is no one material which can be considered optimum for all climatic and environmental conditions.

There is a continuing need for research and development in an effort to obtain more idealized erosion resistant materials. The primary purpose for testing Solar's M9-13 borided coating on SAS 430SS and Ti-6Al-4V specimens was to evaluate the sand erosion resistance of the coating for use on helicopter rotor blades. The secondary purpose was to obtain basic information on the adhesive bonding qualities, fatigue data, and metallurgical properties of the coating, also important if the coating is to be utilized on rotor blades.

The rudimentary results of the test program indicate there should be further investigation for application of Solar's M9-13 borided coating.

SAND EROSION TESTS

TEST OBJECTIVE

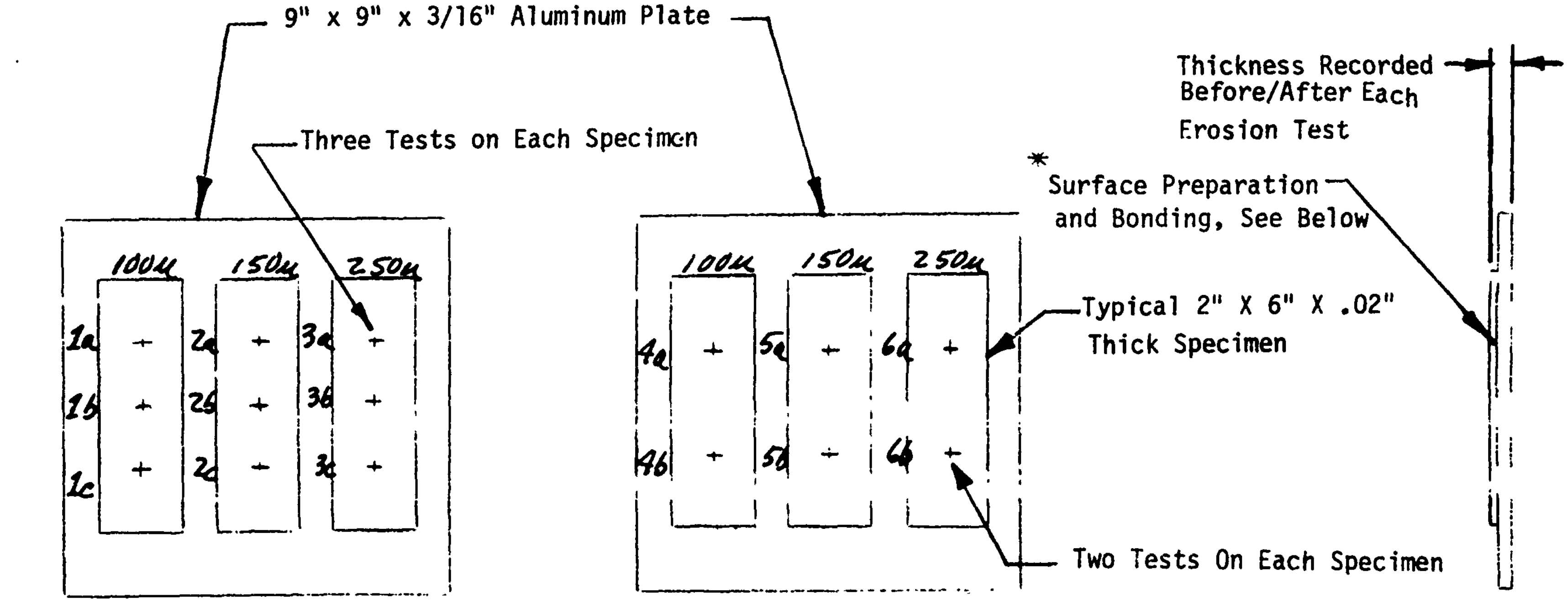
The objective was to determine sand erosion resistance characteristics of Solar's borided ceramic coating on Ti-6Al-4V and SAE 430 stainless specimens to evaluate its potential use on helicopter rotor blade abrasion strips.

TEST SPECIMENS

The test specimens were 2" x 6" x .020" flat sheets, consisting of both Solar ceramic coated and baseline uncoated Ti-6Al-4V and SAE 430SS materials. (The Solar coatings were .0005" thick for the Ti-6Al-4V specimens and .002" thick for the SAE 430SS specimens). There were also a limited number of electroformed nickel specimens. The specimens were bonded to 9" x 9" x .187" thick anodized aluminum plates, Figure 1, in accordance with Sikorsky Standards using Narmco Metlbond M1113 adhesive. The total thickness of the .020" specimens, .005" adhesive glue line and .187" plate, approximated the stiffness of abrasion strips bonded to blades. The purpose was to obtain a similar impingement effect from the sand during the test that would occur on a normal abrasion strip in flight. A total of 33 test specimens bonded to 9 aluminum plates (hereafter referred as panels) were tested. Four of the panels contained Solar's ceramic coated specimens, (two coated SAE 430SS and two coated Ti-6Al-4V). The remaining five panels consisted of baseline, uncoated specimens (two uncoated SAE 430SS, two uncoated Ti-6Al-4V and one electroformed nickel). The overall thickness of each panel was measured by micrometer, prior to test, in the designated erosion areas and recorded. Similar measurements were taken at the conclusions of the tests to determine the amount of erosion wear.

TEST SET-UP

The panels were fastened to a holding fixture and positioned 3" away from a 3/8" diameter nozzle as shown in Figure 2. The holding fixture was designed to permit the panels to be tested at various distances and impingement angles. The fixture, with panels attached, were placed in a Vapor Blast Mfg. Co., Model DFH 4836 vapor blast machine and air pressure and sand hoses were connected to the aft end of the 3/8" diameter nozzle. The 3" distance and 50 psia air pressure were selected to obtain a theoretical sand velocity of 750 ft/sec on the test specimens to simulate actual impingement of sand on the outboard end of rotor blade abrasion strips. The silica sand was placed in a hopper alongside the machine and a baffle plate was placed inside the hopper to prevent recycling of



Typical 90° Impingement Angle Panel   Typical 15° Impingement Angle Panel

* Aluminum Plates - Anodized and Primed. Coated Ti 6Al-4V and SAE430SS Specimens - Solvent Cleaned and Primed. Baseline, Uncoated Ti 6Al-4V - Picatinney Etched and Primed. Baseline, Uncoated SAE430SS - Acid Etched and Primed. Specimens Bonded to Aluminum Plates with Metlbond M1113 by Vacuum Bagging and 20-25 PSI Pressure at 250° - 260°F for 115 Minutes in Autoclave.

Figure D-1. SAND EROSION TEST PANELS

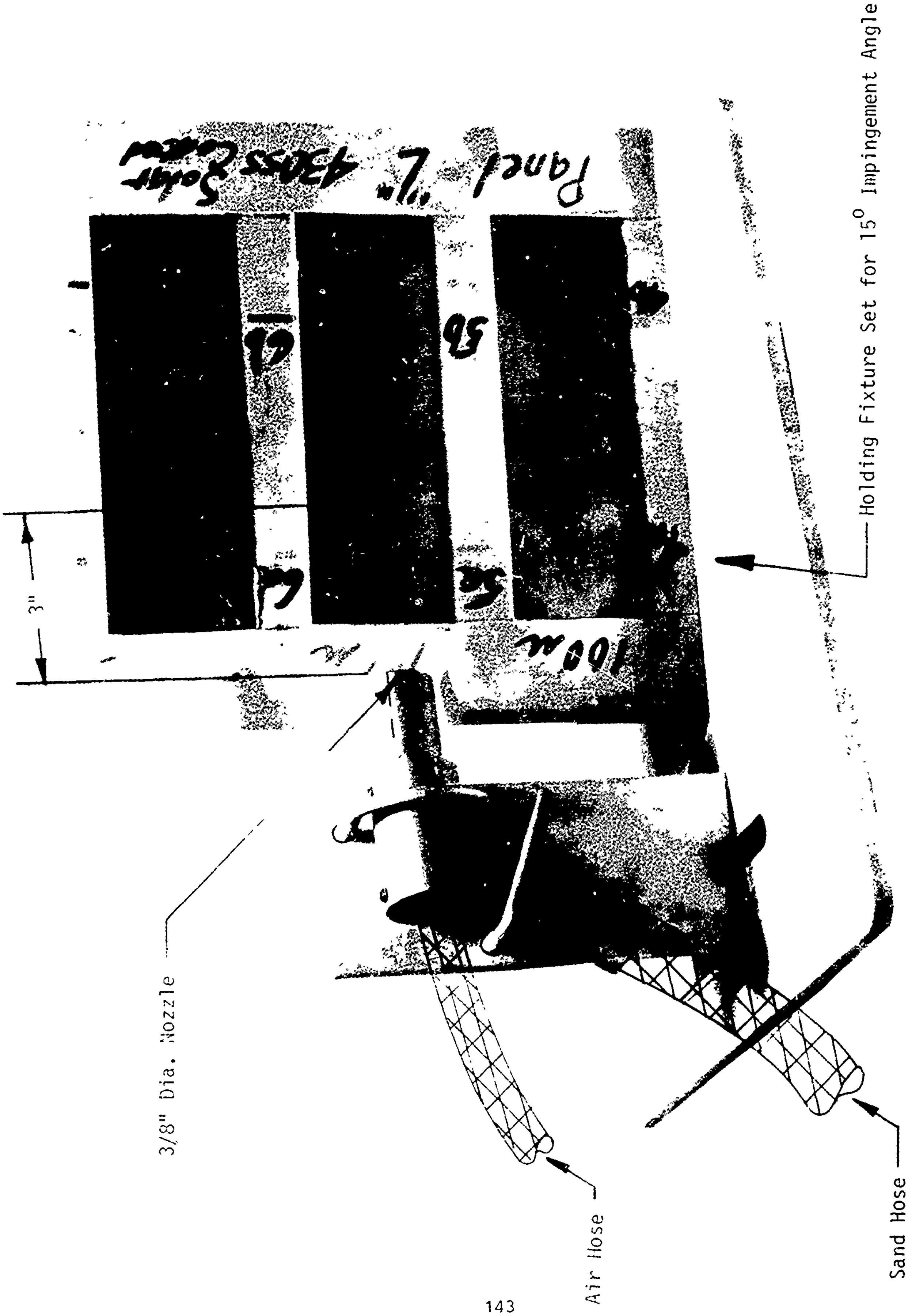


Figure D-2. - SAND EROSION TEST SET-UP

TEST SET-UP (Cont'd)

the sand. New sand was used as required for each test and the amount of sand was weighed and recorded after each test.

TEST CONDUCTED

Tests were conducted at 90° and 15° impingement angles using 100μ, 150μ and 250μ silica sand (.0039", .0059" and .0099" respectively). The 90° impingement angle was utilized to simulate direct sand impingement on the leading nose of rotor blade abrasion strips. The 15° impingement angle simulated an oblique effect from the sand along the sides of a rotor blade tip cap, on the T.E. of leading edge abrasion strip, and on the titanium sheath aft of the abrasion strip.

Preliminary erosion tests were conducted on sample titanium, stainless steel and aluminum plates (panels A, B, C, & D, not shown) prior to the actual tests, to determine the amount of time required to obtain a measurable wear pattern. It was decided from these tests to use up to two (2) minutes at the 90° impingement angle and up to six (6) minutes for the 15° impingement angle. The actual tests at 90° impingement angle were conducted for only one minute since the ceramic coatings wore through within this time. The tests at 15° impingement angle were conducted for the full six minutes to obtain a measurable wear on baseline, uncoated specimens.

TEST RESULTS

Table I summarizes the sand erosion tests. The values shown in the "wear mils/min." column represent an average of 3 tests for each specimen at 90° impingement angle and an average of 2 tests for each specimen at 15° impingement angle.

Solar's ceramic coating at 90° impingement angle wore away in less than one minute on both Ti-6Al-4V and SAE 430SS specimens. Figure 3 and Table I. The time of erosion varied from 5 seconds to 30 seconds depending on the sand grain size. Total wear on the coating and substrate surfaces for Solar coated Ti-6Al-4V and SAE 430SS specimens was better than baseline Ti-6Al-4V and SAE 430SS specimens, up to 100μ sand. It should be noted that the electroformed nickel specimens (Panel M) eroded the least of all materials tested at 90° impingement angle. There appears to be a discrepancy in wear results for 250μ sand testing of the nickel specimen (Panel M) at 90° impingement angle, indicating a possible error in measurement prior to test. However, based on results of 100μ and 150μ sand testing the nickel looks the best at 90° impingement angle.

Table D-1. - SAND EROSION TEST RESULTS

COMPARISON BETWEEN SOLAR CERAMIC COATED AND BASELINE UNCOATED SPECIMENS

Panel	Material		Impinge. Angle	Test Time (min.)	Rate of Sand and Velocity	Wear mils/min			Remarks
						100μ	150μ	250μ	
E	Ti6Al-4V	Uncoated, Baseline	90°	1	37 in.^{3}/min and 750 ft/sec	3.5	4.5	4.6	
F		Solar Coated (.0005" thick)				1.8	4.3	4.8	Coating wore through. See Note 1.
G	SAE 430SS	Uncoated, Baseline				2.2	2.6	3.4	
H		Solar Coated (.002" thick)				Pitted	2.1	5.5	Coating wore through. See Note 2.
M	Electroformed Nickel					1.5	2.0	1.0*	*Discrepancy noted at 250μ testing. See discussion.
I	Ti6Al-4V	Uncoated, Baseline	15°	6		1.0	1.2	1.4	
J		Solar Coated (.0005" thick)				.0	.0	.0	No measurable wear on Solar coating.
K	SAE 430SS	Uncoated, Baseline				.6	.65	.7	
L		Solar Coated (.002" thick)				.0	.0	.0	No measurable wear on Solar Coating.
M	Electroformed Nickel					.5	.6	.7	

NOTE 1: Coating wore through to substrate in 25 sec. using 100μ, in 10 sec. using 150μ, and in 5 sec using 250μ sand.

NOTE 2: Coating wore through to substrate in 30 sec using 150μ and in 5 sec using 250μ sand.

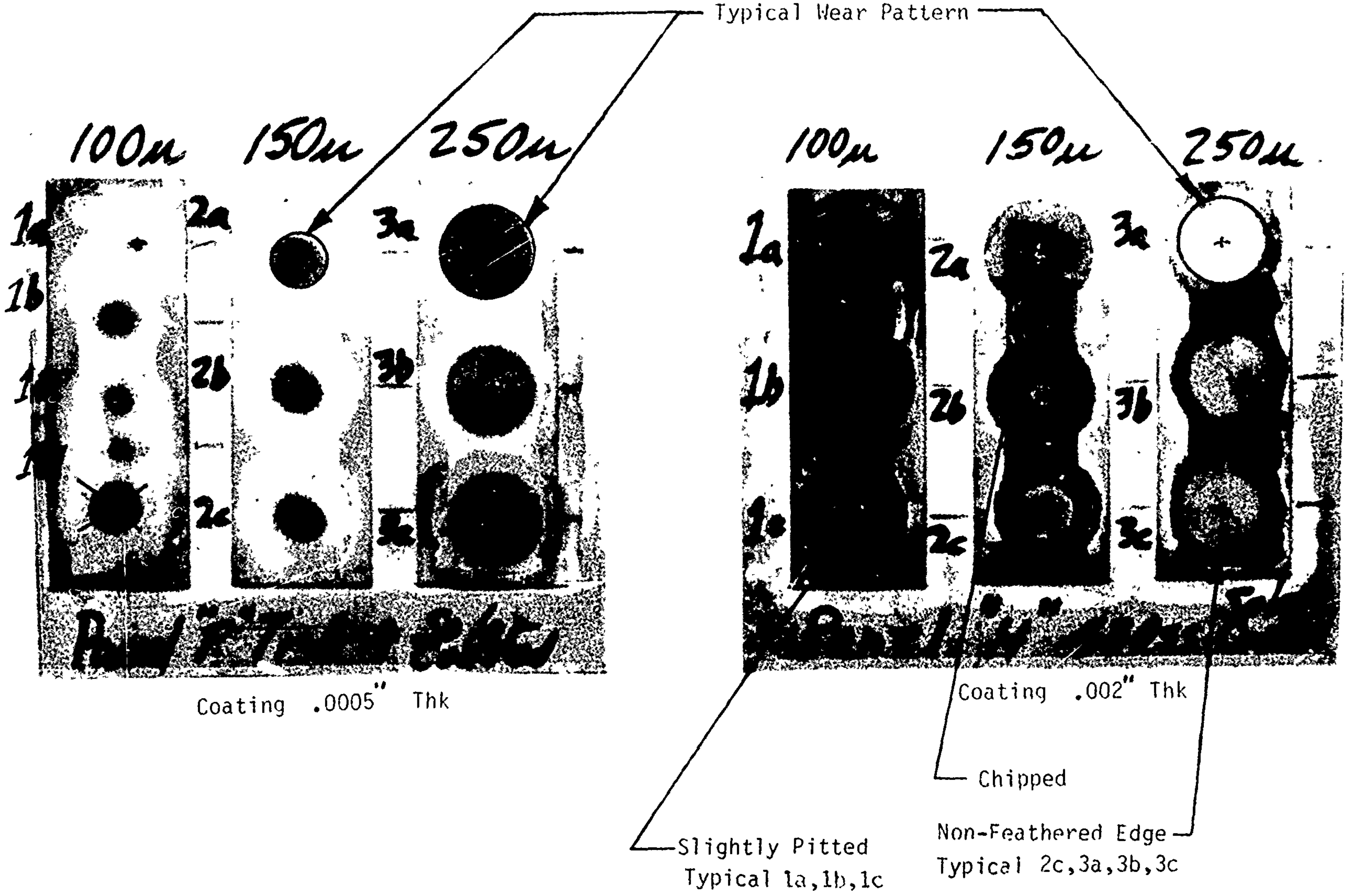


Figure D-3.- SOLAR CERAMIC COATED SAND EROSION PANELS - 90° IMPINGEMENT ANGLE

TEST RESULTS (Cont'd)

It should also be noted that Solar's coating at 90° impingement does not erode, it has a tendency to chip away from the substrate due to the impact of sand particles on the ceramic surface. This was evident on Panel H (SAE 430SS Solar Coated) Figure 3; the surface after 100μ sand testing was pitted (not worn), for the 150μ sand testing, small pieces of the ceramic coating were torn from the substrate surface, and at 250μ sand testing, a non-feather edge existed between the coating wear surface and substrate material. Solar has tested with Arizona Dust (43μ- 70μ) with no evidence of erosion at 90° impingement angle. Reference 1. The present results of total wear on Solar's coating and substrate material at 90° impingement angle indicate the upper limit or threshold is approximately 100μ sand when compared to Ti-6Al-4V and SAE 430SS baseline materials.

After six minutes of test time at 15° impingement angle, Solar's ceramic coatings on Ti-6Al-4V and SAE 430SS specimens remained intact with no evidence of wear. Figure 4 and Table I. The coating on the Ti-6Al-4V was only .0005" thick, as compared to .002" thick for SAE 430SS, however there was no breakdown or wearing away of the coating for either the Ti-6Al-4V or SAE 430SS specimens. The wear patterns on the baseline uncoated specimens were slight but were evident at the end of six minutes of testing.

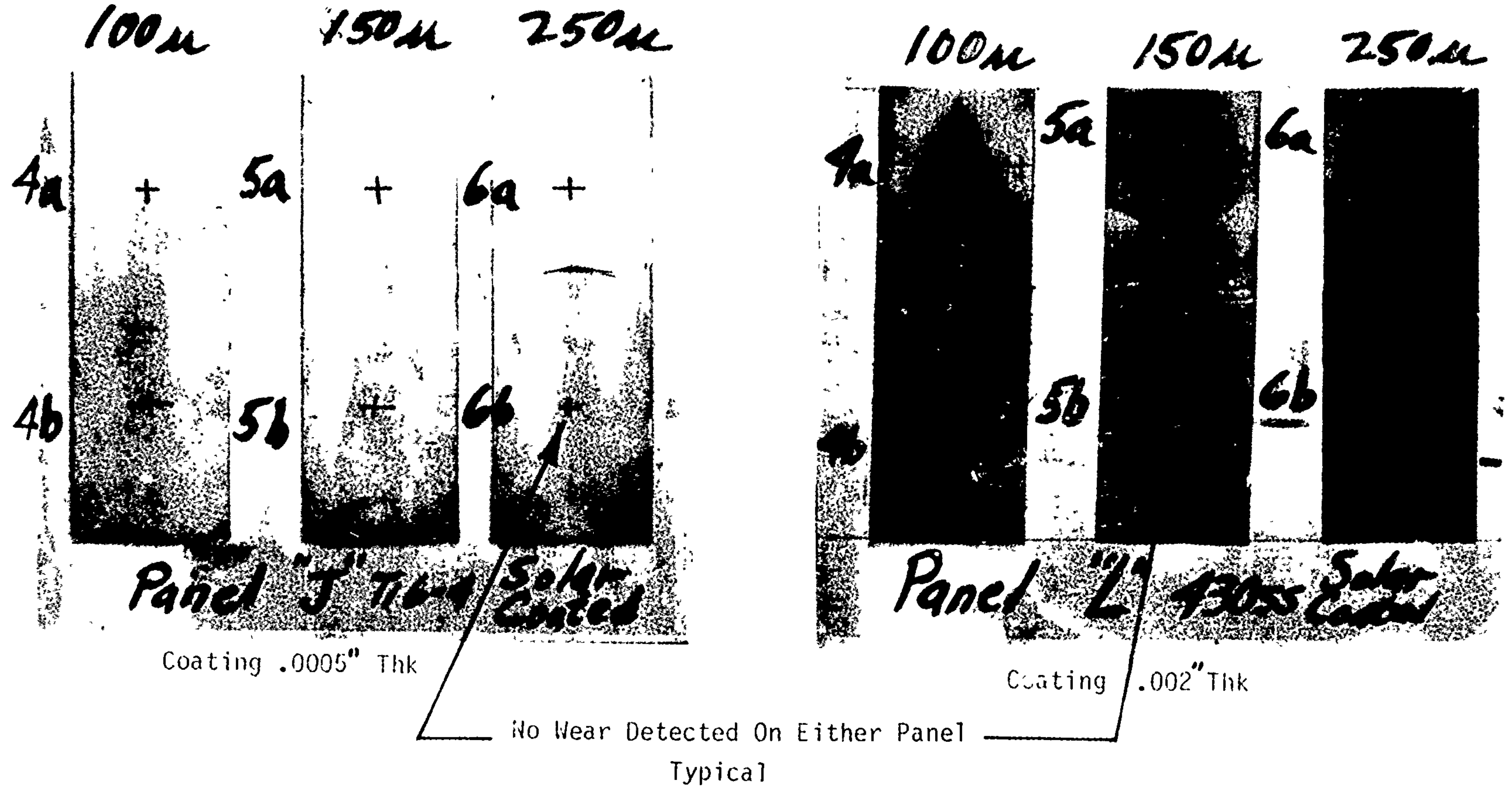


Figure D-4. - SOLAR CERAMIC COATED SAND EROSION PANELS - 15° IMPINGEMENT ANGLE

STRESS DURABILITY, SHEAR AND PEEL TESTS

TEST OBJECTIVE

The objective was to determine the bonding compatibility of Solar's ceramic coating with Sikorsky's Bonding Processes using Metlbond M1113 adhesive system on stress durability, shear and peel specimens.

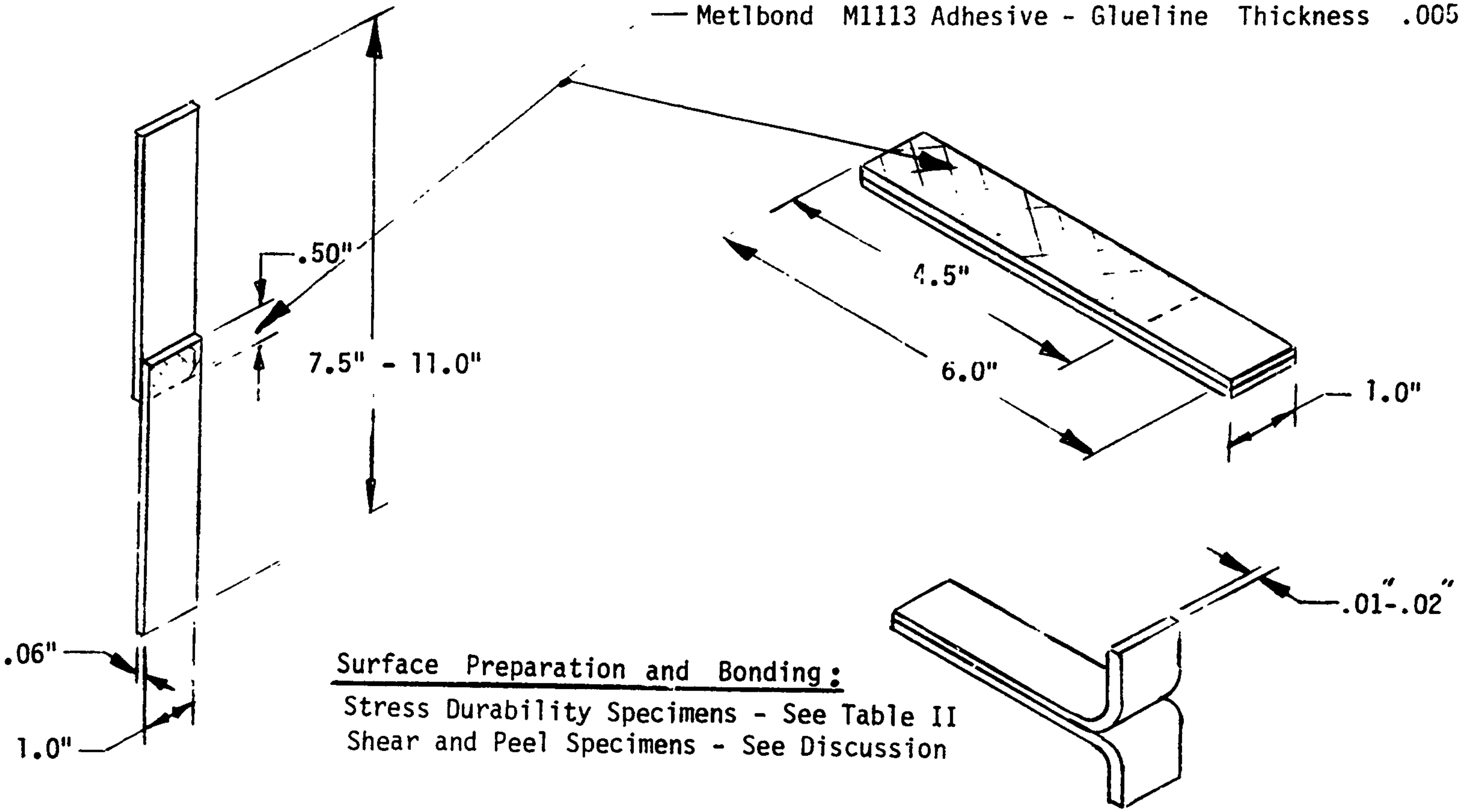
STRESS DURABILITY RESULTS

The stress durability tests consisted of coated and uncoated shear specimens as shown in Figure 5. See Table II for surface preparation and bonding process. The specimens were preloaded in a fixture and prestressed to 2200 psi, 40% of ultimate. The specimens while maintaining their stress condition, were then placed in a Blue M-Humid Environmental Chamber Model AC-7602HA-1 set at 95% humidity and 140°F temperature. To successfully pass the stress durability test, specimens were required to remain intact under shear stress at the prescribed temperature and humidity for a minimum of ten hours. This method of test is in accordance with Reference 2.

The results of these tests are shown in Table II. There were 12 original coated specimens consisting of six SAE 430SS (Nos. 1 through 6) and six Ti-6Al-4V (Nos. 7 thru 12). Specimen Nos. 13 thru 16 were baseline, uncoated Ti-6Al-4V and SAE 430SS. The processing for these specimens prior to test, is noted in Table II.

Due to early failures of the original coated specimens (Nos. 4, 5, 6, 10, and 11), the remaining specimens (Nos. 1, 2, 3, 7, 8, 9 and 12 were never subjected to stress durability tests. They were, however, subsequently tested to determine ultimate shear values. The baseline, uncoated specimens (Nos. 13 thru 16), using standard Sikorsky processing and bonding methods passed the test as shown.

Additional coated Ti-6Al-4V and SAE 430SS specimens (Nos. 17 through 22 were fabricated and processed as noted on Table II. These specimens successfully passed the stress durability test as shown in Table II. The only difference in processing between the original and final coated specimens was that the faying surfaces of the final coated specimens were lightly sanded with 240 grit aluminum oxide paper to clean up residual contamination evident on original coated specimens not removed by solvent cleaning alone. However, it provided the difference between original failures and final successes of coated stress durability specimens.



Surface Preparation and Bonding:
Stress Durability Specimens - See Table II
Shear and Peel Specimens - See Discussion

Typical Stress Durability and Shear Specimens

T-Peel Specimens

Figure D-5. - STRESS DURABILITY, SHEAR AND PEEL TEST SPECIMENS

Table D-2. - STRESS DURABILITY TEST RESULTS

Specimen No.	Surface Preparation and Bonding	Specimens in Environmental Chamber at 95% Humidity and 140°F	Time in Environmental Chamber	Remarks
1	(a)	SAE430SS Solar Coated	-	(d)
2			-	(d)
3			-	(d)
4			10 min.	Failed
5			1 hr.	Failed
6			40 min.	Failed
7		Ti-6Al-4V Solar Coated	-	(d)
8			-	(d)
9			-	(d)
10			2.5 hr.	Failed
11			6 hrs.	Failed
12			-	(d)
13	(b)	Ti-6Al-4V Uncoated	16 hrs.	Passed
14			16 hrs.	Passed
15		SAE 430SS Uncoated	17 hrs.	Passed ruptured @ 17 hrs.
16			15 hrs.	Passed, ruptured @ 15 hrs.
17	(c)	SAE430SS Solar Coated	20 hrs.	Passed
18			33 hrs.	Passed
19			16 hrs.	Passed
20		Ti-6Al-4V Solar Coated	21 hrs.	Passed
21			24 hrs.	Passed
22			22 hrs.	Passed, ruptured @ 22 hrs.

(a) Original Solar coated stress durability specimens processed by solvent cleaning, priming, bonding with Metlbond M1113 by vacuum bagging and 20-25 psi pressure at 250° - 280°F for 115 minutes in Autoclave.

(b) Uncoated baseline stress durability specimens processed by:

1) Ti-6Al-4V-Picatinney etched and primed.
2) SAE430SS-Acid etched, desmutted, water rinsed and primed.

Specimens bonded with Metlbond M1113 as described in (a) above.

(c) Final Solar coated stress durability specimens processed by sanding with 240 grit aluminum oxide paper prior to solvent cleaning. Remainder of processing and bonding with Metlbond M1113 same as described in (a) above.

(d) Original Solar coated specimens, never stress durability tested because of early failures to specimens #4, 5, 6, 10 and 11.

STRESS DURABILITY RESULTS (Cont'd)

Table III shows the results of shear tests on stress durability specimens. These tests were performed in a Baldwin 6401552 Tensile Machine. Table III compares the shear strength of original coated, never tested specimens with successfully tested, uncoated and final coated specimens. The average shear stress of the different specimens is shown in Table III. The lower shear values of the original specimens was the result of the surfaces being contaminated and explains the reason for the early failures in the environmental chamber. This was corrected on final stress durability specimens, resulting in successful stress durability results (Table II) and higher shear values shown in Table III.

PEEL AND SHEAR TEST RESULTS

Peel and shear tests consisted of specimens shown in Figure 5. These specimens were fabricated after successful conclusion of final stress durability tests to utilize results of those tests for optimum processing of shear and peel specimens. The coated shear and peel specimens were processed by slightly vapor blasting the surface with aluminum oxide at approximately a 15° angle. This was followed by solvent cleaning, priming and bonding with Metlbond M1113 as noted for stress durability specimens. The shear specimens were tested in a Baldwin 6401552 Tensile Machine and the peel specimens in a Scott Testers Inc. E2450 Peel Test Machine. The specimens were tested in accordance with References 3 and 9.

The results of the shear tests are shown in Table IV. The coated Ti-6Al-4V shear values are typical of standard uncoated Ti-6Al-4V specimens. The shear values for the coated SAE 430SS specimens are low, however this was the result of using short specimens (?" long) because of limited .062" thick coated SAE 430SS material. The short specimens caused coupling during the pulling operation resulting in bending moment in addition to shear, consequently the lower values. It is estimate the values would be 25% higher utilizing proper length specimens in pure shear.

The peel tests are shown in Table V. The results are typical of standard uncoated Ti-6Al-4V peel values. The specimens exhibited cohesive failure which is the optimum desired.

Table D-3. - STRESS DURABILITY ULTIMATE TEST RESULTS

Specimen No.	Process	Specimens Tested at 70°F Ambient Temperature	Shear Stress (psi)	Shear Stress Average (psi)	Remarks
1 2 3	(a) & (d) ORIGINAL	SAE430SS Solar Coated	4900 5240 4400	4846	Bond Line Contaminated Low Values
7 8 9 12		Ti-6Al-4V Solar Coated	5020 5040 4840 4600	4875	
13 14	(b)	Ti-6Al-4V Uncoated	5560 5920	5740	Acceptable Values
17 18 19	(c) FINAL	SAE430SS Solar Coated	5360 5280 6320	5653	
20 21		Ti-6Al-4V Solar Coated	5600 5020	5310	

See (a), (b), (c) and (d) on Table II

Table D-4.- SHEAR TEST RESULTS

Specimen No.	Specimens Tested at 70°F Ambient Temperature	Failure Mode	Shear Stress Psi	Shear Stress Aver Psi
23 24 25	SAE430SS Solar Coated	Bending and Shear Cleavage 75% Cohesive	4400 4480 4800	4560
26 27 28	Ti-6Al-4V Solar Coated	90% Cohesive	5760 6000 6760	6173
From Previous Tests	Typical Uncoated, Baseline Ti-6Al-4V Specimen at 70°F			6030

Table D-5.- PEEL TEST RESULTS

Specimen No.	Specimens Tested at 70°F Ambient Temperature	Failure Mode	Peel Strength *PIW	Peel Strength *PIW Aver.
29 30 31	SAE430SS Solar Coated	100% Cohesive	26 25.5 27.5	26.3
32 33 34	Ti-6Al-4V Solar Coated	100% Cohesive	25 25.5 26	25.5
From Previous Tests	Typical Uncoated, Baseline Ti-6Al-4V Specimen at 70°F			Range 21-28

* Pounds Per Inch of Width

IMPACT TESTS

The impact resistance of Solar's coating on Ti-6Al-4V and SAE 430SS was evaluated by static drop test. The tests consisted of impact testing coated and uncoated Ti-6Al-4V and SAE 430SS 1" x 6" x .125" specimens by free-fall-dropping a half-pound weight, normal to the specimen surface a distance of 9 feet (4.5 ft-lb energy). The half-pound weight was equipped with 1/4" diameter spherical hardened steel ball. The purpose was to simulate a helicopter hovering with a 1/4" diameter stone impacting the leading edge rotor blade abrasion strip traveling at 750 ft/sec.

Two types of tests were conducted.

a. Dropping the weight with the specimens under simple beam conditions (unsupported).

b. Dropping the weight with the specimens "backed up" to simulate stiffness of an abrasion strip on the leading edge of a rotor blade.

Results of the tests showed that the coatings for both Ti-6Al-4V and SAE 430SS were brittle for the simple beam unsupported specimens. There was identation and flaking of the coating at the impact point due to bending of the specimens. One SAE 430SS coated specimen actually fractured at the impact point. These tests were conservative and the results were not considered realistic of a coating on an abrasion strip attached to a rotor blade.

Results of the supported tests showed that the coatings were impressed into the substrate materials approximately .015" deep. However, the coatings remained intact. Approximately the same amount of impression damage was noted on the uncoated specimens.

FATIGUE AND METALLURGICAL EVALUATION

TEST OBJECTIVE

The objective of these tests was to determine the affect of Solar's boride ceramic coating on the fatigue and metallurgical properties of Ti-6Al-4V and 430SS sheet.

FATIGUE SPECIMENS

Specimen blanks 9-1/4 by 2-1/4 inches were cut longitudinally from 0.125" thick Ti-6Al-4V sheet in accordance with Reference 4 and 0.125" thick 430SS sheet in accordance with Reference 5. Fatigue specimens were machined to the elliptical specimen configuration illustrated in Figure 6. The specimen edges were broken and polished longitudinally to a 400 grit finish. A total of (6) Ti-6Al-4V and (12) 430SS specimens were fabricated. A greater number of 430SS specimens were fabricated because control (non-coated) data in this alloy was lacking for comparison purposes. Six specimen blanks of each material were supplied to Solar to be coated with their M9-13 boride coating. After coating, the specimens were shot peened in the grip area to reduce the risk of a fracture occurring in that area. After having tested (4) of the (6) coated Ti-6Al-4V fatigue specimens and all fatigue origins were at the specimen corner, the coating was removed from the corner and edges on the last two specimens to determine if the stress concentration and/or coating cracking at the corner may be an overly severe test condition which contributed to the low fatigue properties obtained.

STATIC SPECIMENS

Since 430SS tensile data was also lacking, 7 specimen blanks were cut in both the longitudinal and transverse direction and tensile specimens were fabricated in accordance with Reference 6 to the configuration shown in Figure 7. These specimens were not coated prior to testing, since control data was desired.

TEST PROCEDURE

Fatigue tests were conducted on a Sonntag model SF-1-U fatigue machine with a 5:1 load amplifier at 1800 cpm. The tests were performed in accordance with References 7 and 8. The tests were performed in axial tension-tension at a stress ratio, R = +.10 until fracture or 10^7 cycles. Specimens not failing at 10^7 cycles were rerun at higher stress levels.

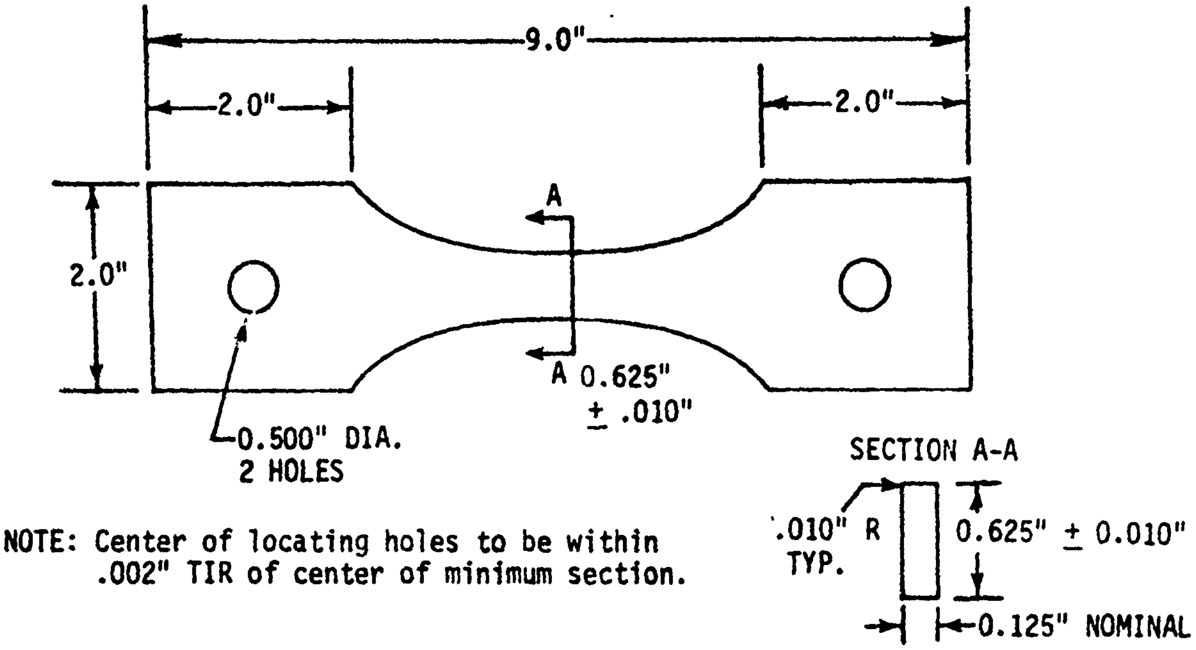


Figure D-6. FATIGUE SPECIMEN

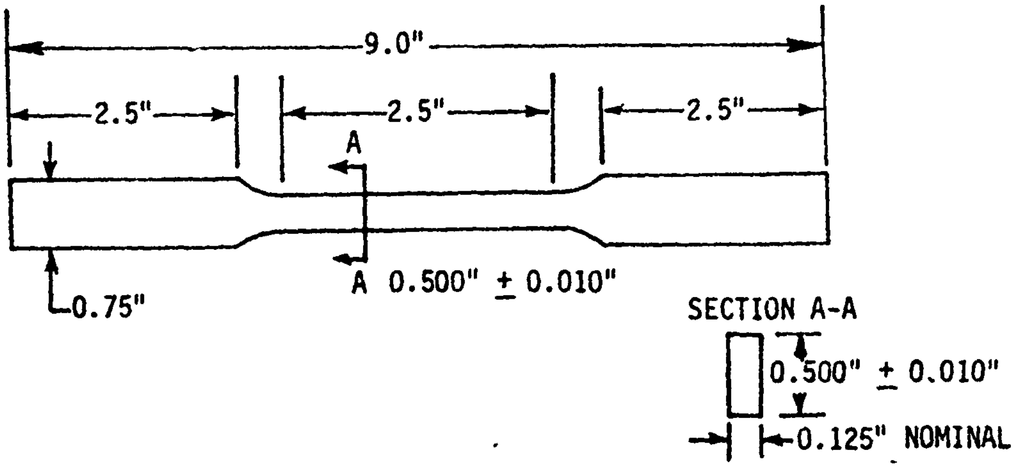


Figure D-7. TENSILE SPECIMEN

TEST PROCEDURE (Cont'd)

Tensile tests were conducted on a Riehle PS-60 Universal Test Machine in accordance with Reference 6.

FATIGUE TEST RESULTS

a. Boride Coated Ti-6Al-4V Sheet

The results of the fatigue test are compiled in Table VI. The mean S/N curve is plotted in Figure 8 along with the S/N curve for typical Ti-6Al-4V alloy sheet previously tested at Sikorsky Aircraft. The fatigue strength of boride coated Ti-6Al-4V sheet is 50% of the fatigue strength of uncoated Ti-6Al-4V. Since the fatigue origins were at the corner in the first (4) specimens tested, the coating was removed from the specimen corners and edges in the last two specimens as previously indicated under specimen preparation. The fatigue strength, however, was not improved as illustrated in Figure 8, but the fatigue origins moved from the specimen corner to the flat surface where the coating began. Minor cracking of the boride coating was noted on all specimens along with very minor flaking.

b. Boride Coated 430SS Sheet

Six boride coated 430SS specimens and six control (non-coated) samples were fatigue tested. The results are tabulated in Table VI and plotted in Figure 8 with mean S/N curves indicated. The fatigue strength for the boride coated specimens is 50% of the fatigue strength of the uncoated 430SS at 10^8 cycles. Fatigue cracking of the coated 430SS specimens initiated at the specimen corner similar to the coated Ti-6Al-4V specimens, whereas fatigue cracking in the uncoated 430SS specimens initiated along the flat surfaces. Substantial cracking of the coating was noted on all specimens along with flaking in the region of the fracture.

STATIC TEST RESULTS

Results of the 430 stainless steel tensile tests from the longitudinal and transverse directions are tabulated in Table VII with the minimum required mechanical properties of Reference 5. The mean transverse tensile strength is approximately 10% higher than the longitudinal tensile strength. However, the longitudinal tensile strength was approximately 8.0% below the minimum required by Reference 5. The remainder of the properties substantially exceeds the minimum requirement of Reference 5.

Table D-6. - FATIGUE TEST RESULTS

MATERIAL	SPEC. NO.	MAX. STRESS R=+.10 (KSI)	CYCLES X 10^6	COMMENTS
SAE 430 Stainless Steel Boride Coated	S-1	20	10	Runout
	S-1	25	10	Runout
	S-1	30	1.25	Failed
	S-2	35	0.81	Failed
	S-3	40	0.36	Failed
	S-4	30	1.14	Failed
	S-5	35	0.44	Failed
	S-6	35	0.50	Failed
SAE 430 Stainless Steel Control	SS-1	35	10	Runout
	SS-1	40	10	Runout
	SS-1	45	10	Runout
	SS-1	50	10	Runout
	SS-1	55	10	Runout
	SS-1	60	10	Runout
	SS-1	65	2.91	Failed
	SS-2	60	2.82	Failed
	SS-3	60	1.07	Failed
	SS-4	65	2.33	Failed
	SS-5	60	1.61	Failed
	SS-6	65	1.31	Failed
Ti-6Al-4V Boride Coated	T-1	60	0.06	Failed
	T-2	35	10	Runout
	T-2	45	10	Runout
	T-2	60	1.04	Failed
	T-3	45	10	Runout
	T-3	55	0.14	Failed
	T-4	50	10	Runout
	T-4	55	10	Runout
	T-4	60	0.09	Failed
	T-5	60	0.05	Failed
	T-6	55	10	Runout
	T-6	60	10	Runout
	T-6	70	0.03	Failed

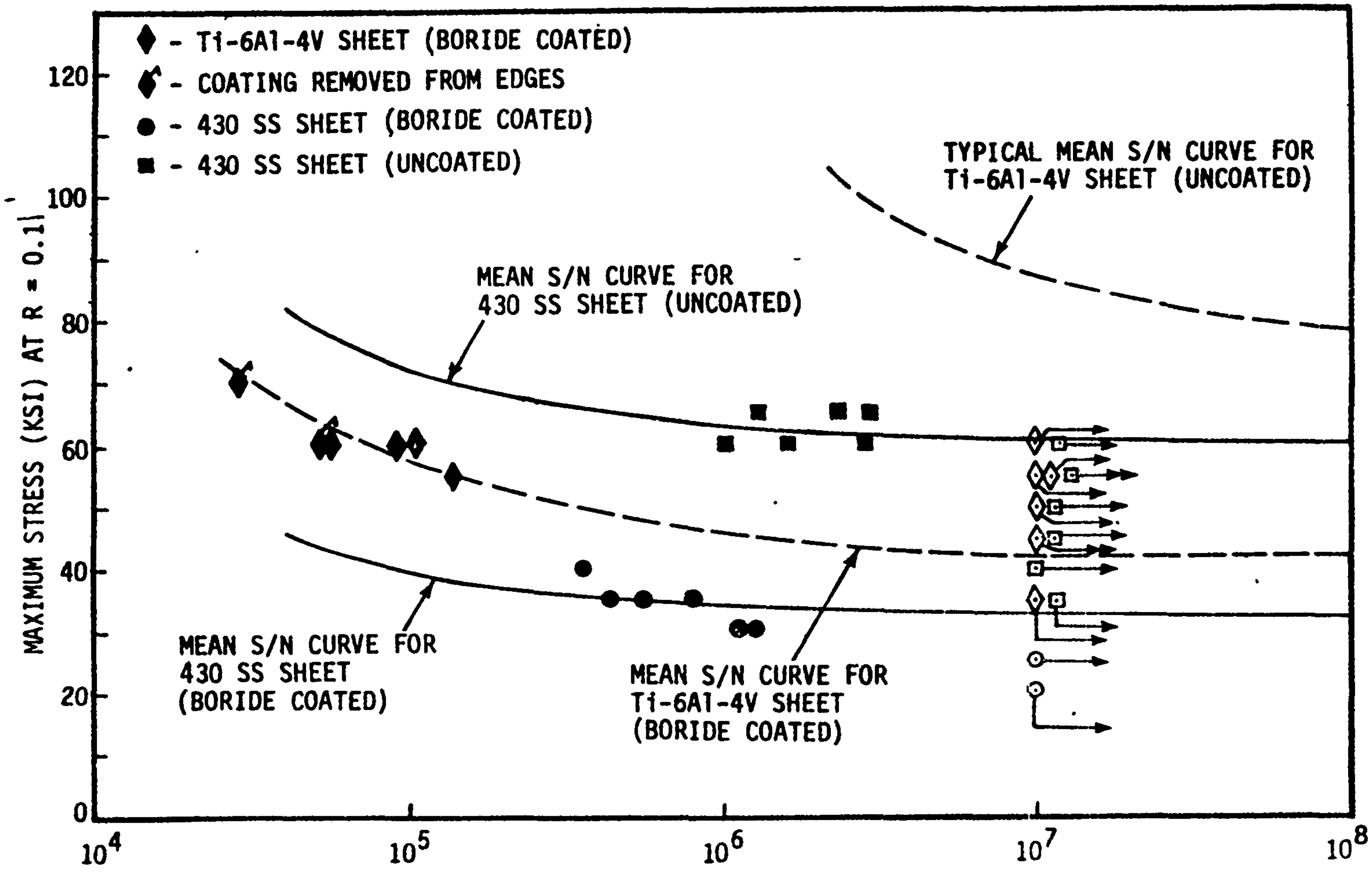


Figure D-8. FATIGUE TEST RESULTS - S/N CURVE

Table D-7. - TENSILE PROPERTIES - SAE 430SS

CONTROL SPECIMENS	F_{tu} (PSI)	F_{ty} (PSI)	%e
Transverse			
T-1	71010	50160	28
T-2	70820	50820	28
T-3	70990	50240	29
Average	70900	50400	28
Longitudinal			
L-1	63550	45810	33
L-2	64250	46700	32
L-3	64410	46380	33
L-4	64540	47010	32
Average	64200	46500	33
Reference 5			
QQ-S-766C			
Minimum	70000	35000	22

METALLURGICAL EVALUATIONS

Metallographic mounts were prepared from the boride coated fatigue and erosion test specimens for both the Ti-6Al-4V and 430SS base material to evaluate coating appearance, thickness transition zone and base metal.

Examination of the coated Ti-6Al-4V specimen mounts revealed a continuous coating approximately .0005--.0006 inches in thickness for both the fatigue and erosion samples as illustrated in Figure 9. This measured thickness is in good agreement with the .0005 inch thickness quoted by Solar to have been applied. The transition zone for the Ti-6Al-4V samples basically consisted of spike like fingers, Figure 9, extending from the coating into the base material. These fingers may act as stress raisers and be a factor in the large fatigue strength reduction previously reported. The Ti-6Al-4V base material exhibits a transformed beta structure after the coating process which is indicative of heating above the beta transus (1800--1850°F). This is consistent with the reported coating baking temperature of 2100°F, Reference 1.

Examination of the coated 430SS specimen mounts revealed a continuous coating approximately .0015 inches thick for both the fatigue and erosion samples as illustrated in Figure 10. This coating thickness was the same as that quoted to have been applied by Solar. A well defined transition zone .0008 to .001 inches thick was present on the 430SS samples, Figure 10, with fewer and finer spike like fingers penetrating the base material than was apparent for the Ti-6Al-4V.

A hardness traverse was performed om both the Ti-6Al-4V and 430SS boride coated specimens. The Ti-6Al-4V boride coating resulted in a Knoop Hardness Number of approximately 3700 KHN with the base metal about 345 KNH, Figure 11. The 430SS boride coating resulted in a Knoop Hardness Number of approximately 1950 KHN with a transition zone reading of 330 KNH as compared to the base metal hardness of 200 KHN, Figure 12. The coating hardness values were consistent with those recorded by Solar, Reference 1.

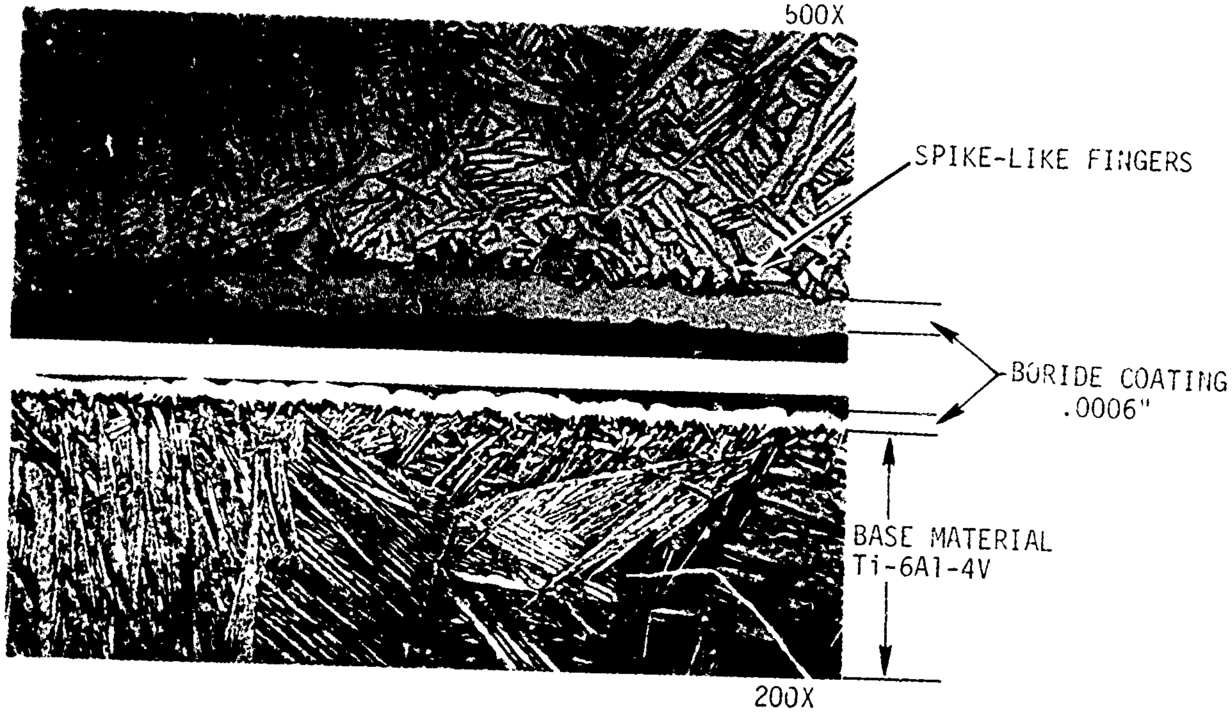


Figure D-9. MICROSTRUCTURE OF M9-13 BORIDE COATING ON TI-6Al-4V

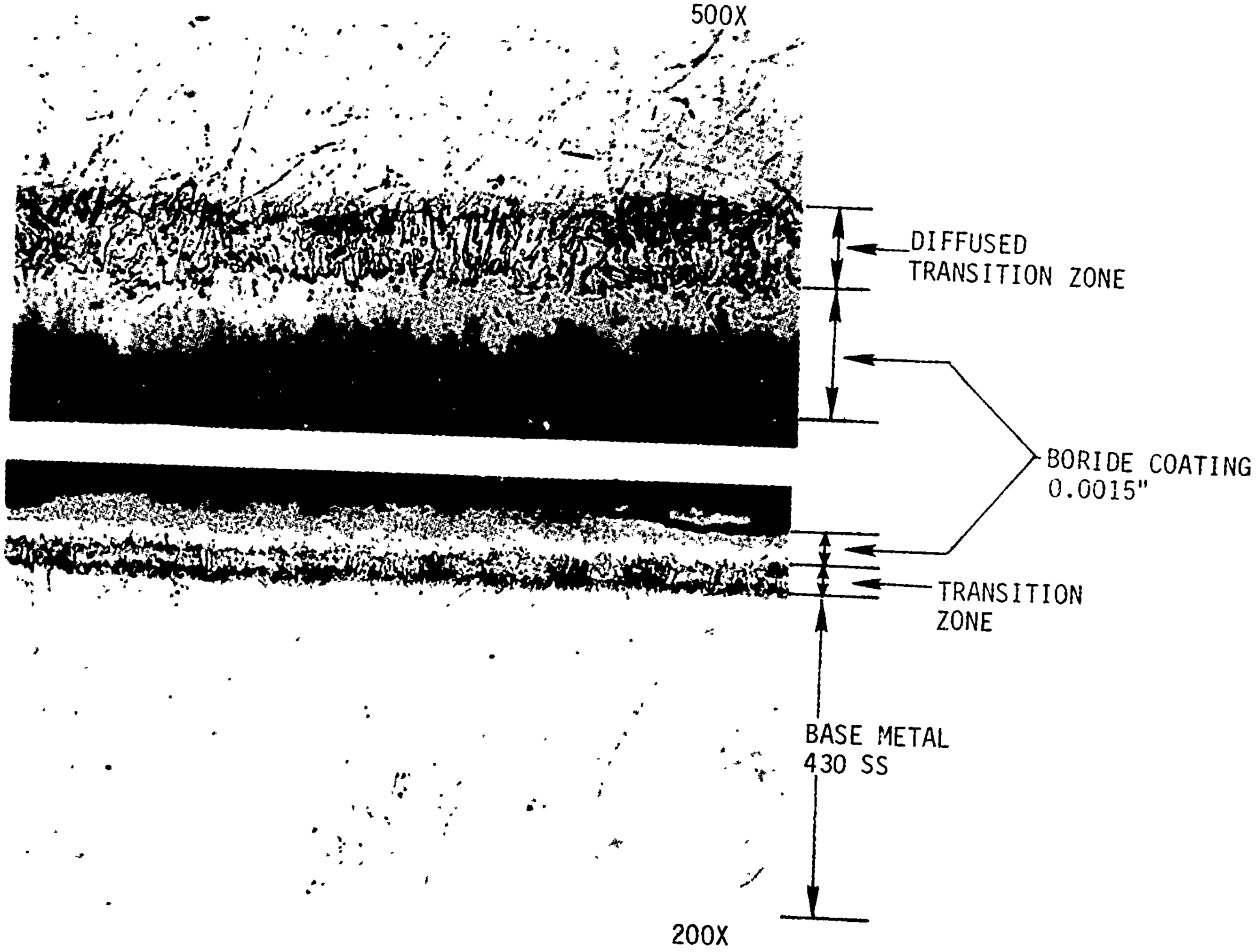


Figure D-10. MICROSTRUCTURE OF M9-13 BORIDE COATING ON SAE 430SS

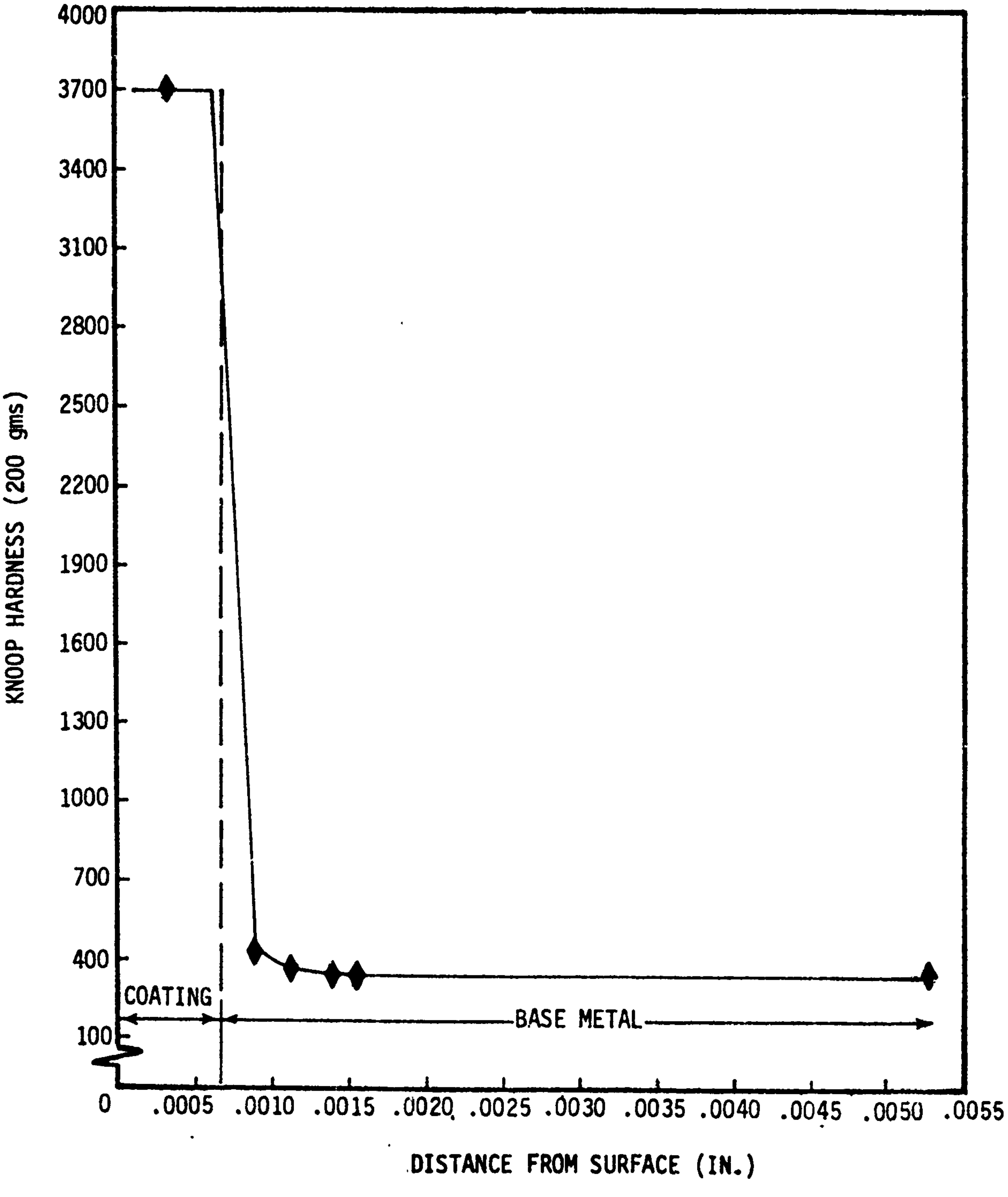


Figure D-11. **KNOOP HARDNESS OF M9-13 BORIDE COATING ON Ti-6Al-4V**

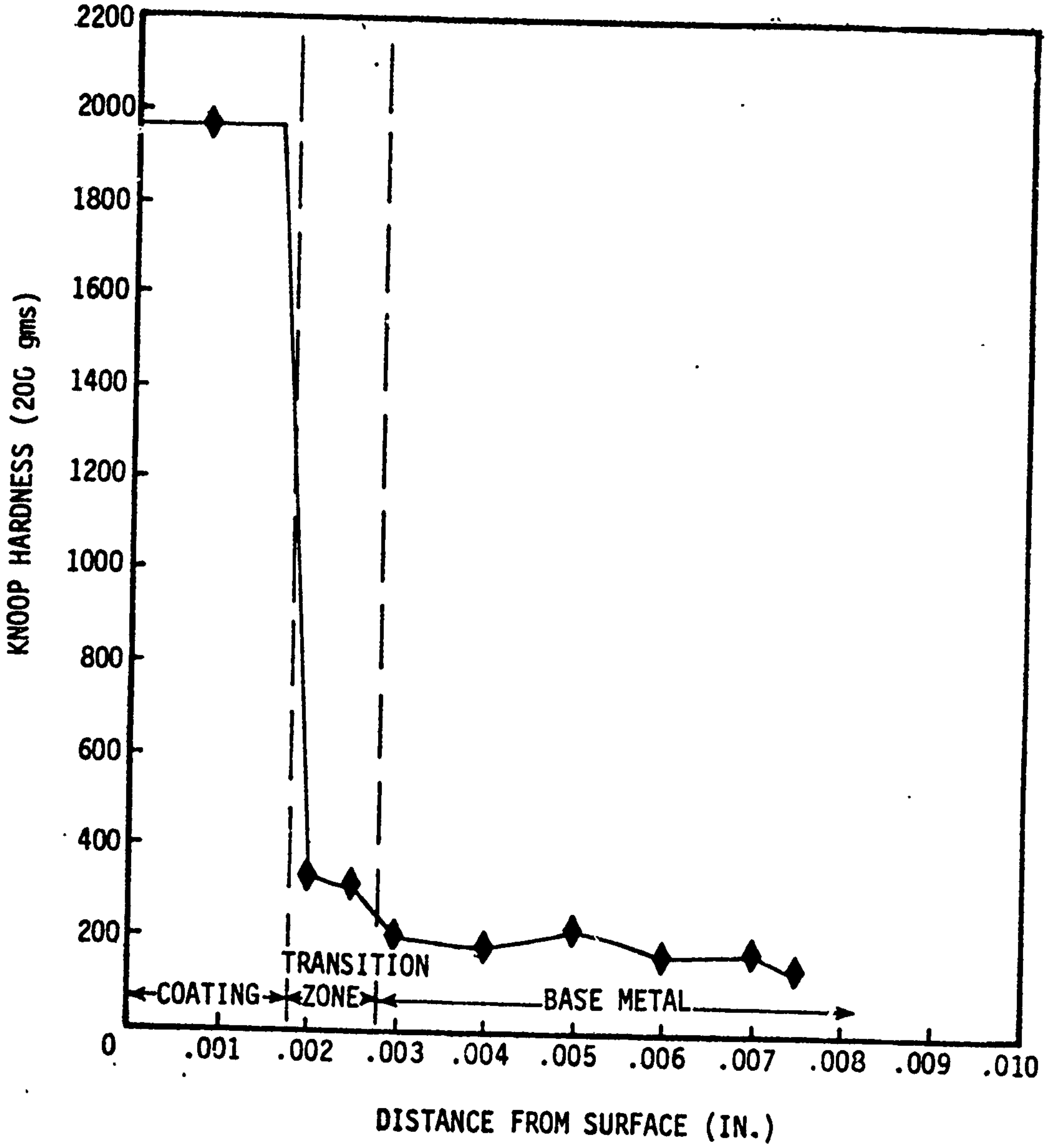


Figure D-12. KNOOP HARDNESS OF M9-13 BORIDE COATING ON SAE 430SS

CONCLUSIONS

1. Sand Erosion Tests Using 100, 150, and 250 Sand at 750 FT/SEC

a) At 90° Impingement Angle

The coatings on Ti-6Al-4V and SAE 430SS specimens wore through (or pitted) to the substrate in less than one minute. Total wear on the coating and substrate surfaces for Solar coated Ti-6Al-4V and SAE 430SS, specimens was better than baseline Ti-6Al-4V and SAE 430SS specimens, up to 100μ sand. Solar coated materials however were inferior to electroformed nickel for all sand grain sizes (100μ, 150μ and 250μ).

b) At 15° Impingement Angle

Solar's ceramic coated Ti-6Al-4V and 430SS test specimens exhibited no wear from 100μ, 150 μ, or 250μ sand after six (6) minutes of test time. These panels were superior to baseline, uncoated Ti-6Al-4V and 430SS and electroformed nickel panels which showed definite wear patterns.

The rapid erosion of Solar's coated Ti-6Al-4V and 430SS specimens at 90° impingement angle indicates it is unsuitable for designs subjected to erosion from sand over 100μ normal to the wear surface. Conversely the absence of wear on Solar's coated Ti-6Al-4V and 430SS specimens at 15° impingement angle, using up to 250μ sand, indicates it may be practical on surfaces obliguely positioned to the erosion direction.

2. Stress Durability, Shear and Peel Tests

a) Solar's ceramic coated Ti-6Al-4V and 430SS final stress durability specimens passed the stress durability tests and were equivalent to baseline, uncoated Ti-6Al-4V and 430SS specimens.

b) Solar's ceramic coated Ti-6Al-4V and 430SS peel specimens produced values comparable to baseline, uncoated Ti-6Al-4V peel specimens.

c) Solar's ceramic coated Ti-6Al-4V shear specimens had values comparable to baseline, uncoated Ti-6Al-4V shear specimens.

d) Solar's ceramic coated 430SS shear specimens had values approximately 25% lower than baseline uncoated specimens. (See below).

2. (Cont'd)

All ceramic coated final stress durability and peel and shear tests for both Ti-6Al-4V and 430SS (except for 430SS shear tests) show that Solar's coating is compatible with Metlbond M1113 Adhesive System. The coated 430SS shear specimens had values slightly lower than production requirements, however, by use of proper specimens and more testing would meet production requirements.

3. <u>Impact Tests</u>

Solar's ceramic coated Ti-6Al-4V and 430SS and uncoated Ti-6Al-4V and 430SS specimens exhibited same amount of impression damage on supported, normal-to-surface, impact tests. For the same tests, unsupported (simple beam), the coated specimens showed signs of brittleness. Flaking of the coated surface for both the Ti-6Al-4V and 430SS was noted and one 430SS specimen broke at the impact point.

4. <u>Fatigue Tests</u>

The fatigue strength of Ti-6Al-4V and 430SS sheet is reduced to 50% by the boride erosion resistant coating (M9-13) applied by Solar. Minor cracking and very minor flaking of the coating was noted in the region of the fatigue fracture for the Ti-6Al-4V coated specimens. Gross cracking and substantial flaking of the coating was noted in the region of the fatigue fracture on the 430SS coated specimens.

RECOMMENDATIONS

1. Based on results of erosion tests at 90° impingement angle, Solar's ceramic coating is not recommended on wear surfaces subjected to direct impingement from sand over 100μ at a velocity of 750 ft/sec (or more). It would not be recommended for use on outboard, leading edge nose area of rotor blade abrasion strips.

2. Based on satisfactory results of erosion tests at 15° impingement angle and successful rain erosion conclusions on coated Ti-6Al-4V (Reference 10), the following recommendations are made:

   a) Perform more sand erosion tests on coated Ti-641-4V specimens at 15° impingement angle and other oblique angles to determine greatest impingement angle free of erosion.

   b) Perform cost study analysis to determine cost effectiveness of utilizing coated titanium material for abrasion resistance on outboard side of rotor blade tip cap. (This area is subjected to impingement angle of approximately 15° or less).

   c) Perform additional adhesive tests (peel, shear, etc.) to substantiate bonding qualities of Solar coated titanium for abrasion strips for item (b) above.

   d) Based on favorable results from above, outline program to experimentally install Solar's coated titanium on sides of BLACK HAWK rotor blade tip caps.

REFERENCES

1 - D.P. Huey, A.R. Stetson, "Claddings for Upgrading Helicopter Rotor Erosion Resistance", May 1977.

2 - ASTM-D2919-71 "Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading".

3 - D1876, "Standard Method of Test for Peel Resistance of Adhesive (T - Peel Test).

4 - MIL-T-9046H, "Titanium and Titanium Alloy, Sheet, Strip and Plate".

5 - QQ-S-766C, "Steel Plates, Sheets and Strip Corrosion Resisting-Class 430A".

6 - ASTM E-8-77a, "Tension Testing of Metallic Materials".

7 - ASTM-E466, "Constant Aplitude Axial Fatigue Tests of Metallic Materials".

8 - ESM-K-7016 "Standard Method of Test for Conducting Room Temperature Fatigue Tests on Sonntag SF-1-U Fatigue Machines".

9 - D1002, "Standard Method of Test for Strength Properties of Adhesives in Shear by Tension Loading (Metal to Metal)".

10- HH78-160 "Final Report for Solar Ceramic Coating Tests at Hughes Helicopters", June 1978.

APPENDIX E

BELL HELICOPTER TEXTRON FINAL REPORT
ON
EROSION TESTS OF BORIDED TITANIUM AND STAINLESS STEEL

Bell Helicopter TEXTRON
Division of Textron Inc

Engineering Laboratories

Report No. 0079M-253
October 30, 1979
Page 1 of 5

To: Mr. R. Zeites

Copy: P. Baumgardner, G. Rodriguez

Subject: EROSION TESTS OF BORIDED TITANIUM AND STAINLESS STEEL

References: (a) Engineering Laboratories Notebook N77-17

INTRODUCTION

As a portion of a BHT/Solar Turbine International program to investigate borided abrasion strips, erosion tests were performed at BHT using sand and water environments. Four specimens of borided 6Al-4V titanium and four specimens of borided Type 430 stainless steel were exposed to sand erosion. Similarly four specimens of each borided material were exposed to simulated rain erosion. Specimen weight loss data are compared with weight loss from Type 301 stainless steel standards.

All testing was conducted from September 25 to 27, 1979, in the Erosion Test Stand of the Mechanical Laboratory, Bell Helicopter Textron, Fort Worth, Texas. All test data are retained in Ref. a).

RESULTS

Results for eight erosion tests are discussed below. Each test involves two specimens and two stainless steel reference standards as discussed in Apparatus and Method. All weight loss data are tabulated in Table I.

Sand Erosion

Borided 6Al-4V Titanium. Tests 1 and 2 exposed borided titanium specimens to sand erosion. Test 1 was run for 5 minutes and resulted in erosion through the coating. Test 2 was run for only 0.5 minutes and still exhibited erosion through the coating.

Borided Type 430 Stainless Steel. Tests 3 and 4 exposed borided stainless steel specimens to sand erosion. Test 3 was run for 0.5 minutes and resulted in erosion through the coating. Test 4 was run for 5 minutes, for reference purposes, and exhibited erosion through the coating.

Rain Erosion

Borided 6Al-4V Titanium. Tests 5 and 7 exposed borided titanium to simulated rain erosion for 2 hours and 1 hour, respectively. Each of these tests resulted in coating failure caused by residual sand in the Erosion Test Stand.

Borided Type 430 Stainless Steel. Tests 6 and 8 exposed borided Type 430 stainless steel to simulated rain erosion for 1 hour and 2 hours, respectively. Each of these tests resulted in coating failure caused by residual sand in the Erosion Test Stand.

CONCLUSIONS

The solar boride coatings on both 6Al-4V titanium alloy and Type 430 stainless steel failed to meet sand erosion requirements and, in fact, failed within 30 seconds in the test. Although the rain erosion results were inconclusive because of sand contamination in the test stand, even had the coating withstood rain erosion it would not have been acceptable because of its sand erosion behavior.

APPARATUS AND METHOD

Both the sand and the water erosion tests were conducted in the BHT Erosion Test Stand. This stand consists of a 48 inch symmetrical dummy blade rotating about a horizontal axis at 3600 rpm. Test specimens and reference standards are bolted at the outboard ends on the leading edge. The two ends are referred to as "red" and "white". The test specimens are placed at the red outboard position and at the white inboard position. Reference standards are located at adjacent locations at the red inboard position and the white outboard position. Further details of the sand and water erosion setups are described in the following paragraphs.

Sand Erosion

Sand for the erosion test is Clemtex #4 sand. A sieve analysis for the sand was requested and is provided as Table II. The sand is contained in a fertilizer spreader hopper above and in the plane of the blade so that when the sand is released it falls at a mass flow rate of 3.0 lbs/min and falls directly on the outboard portion of the leading edge when the blade is positioned horizontally in the stand. Based upon tests made in 1966 at Ft. Rucker, a 20 minute exposure in the test stand at these "standard" conditions corresponds to approximately 27 hours of helicopter hovering over a sand pit. As used at BHT this is a screening test for candidate erosion protection systems. For each test a weight loss ratio is calculated which compares the test specimen weight loss ($\Delta W(Spec)$) to the weight loss of Type 301 stainless steel reference standards run with the specimens ($\Delta W(Std)$). The weight loss ratio (WLR) is calculated as

$$WLR = \Delta W(Spec)/\Delta W(Std)$$

The specimens and standards are weighed on an analytical balance both before and after erosion testing and from these measurements the WLR is calculated.

Rain Erosion

Rain erosion testing is conducted in the Test Stand utilizing #22 hypodermic needles in a water manifold to provide the water to the plane of the blade at the proper rate to simulate 1 inch per hour rainfall. In the current tests, in spite of repeated washing of the stand, the rain erosion test conditions were contaminated with residual sand. The last test run, however, did exhibit less sand damage, but was not free from sand. The WLR was not calculated for rain erosion test samples.

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Table E-1

TEST DATA - EROSION TESTS OF BORIDED MATERIALS

Test No.	Coated Base Material	Erosion Medium	Exposure Time	Weight Loss Ratio (WLR)	Remarks
1	6Al-4V Titanium	Sand	5.0 min.	0.56	Eroded through boride.
2	6Al-4V Titanium	Sand	0.5 min.	0.66	↓
3	Type 430 Stainless Steel	Sand	0.5 min.	1.21	
4	Type 430 Stainless Steel	Sand	5.0 min.	0.63	
5	6Al-4V Titanium	Rain	2.0 hr.	NA	Local erosion through boride due to sand.
6	Type 430 Stainless Steel	Rain	1.0 hr.	NA	↓
7	Type 430 Stainless Steel	Rain	1.0 hr.	NA	
8	Type 430 Stainless Steel	Rain	2.0 hr.	NA	

Table E-2

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Division of Textron Inc.
POST OFFICE BOX 482 • FORT WORTH, TEXAS 76101

PART No. ______

P.O. No. ______

R.R. No. ______

REPORT No. CPL-79-2040

DATE 9-25-79

TESTED BY J. D. Moore

APPROVED JDMoore
J. D. Moore

APPROVED KW Porter
K. W. Porter

COPIES TO:
R. Schiltz
R. Zeits (2)
Lab File

LABORATORY REPORT

TITLE Sieve Analysis

ITEM Sand, Submitted by R. Schiltz

SPEC. No. ______

VENDOR ______

Results of Sieve Test

Sieve Size ASTM, E-11	Sieve Opening in Inches	Sieve Opening in Microns	% of Submitted Sample Retained on Sieve
20	.0331	841	.07
30	.0234	594	.25
45	.0139	353	43.60
60	.0098	249	44.02
80	.0070	178	10.20
100	.0059	150	1.02
120	.0049	125	.35
140	.0041	104	.25
170	.0035	89	.12
200	.0029	74	.07
230	.0025	64	.02
270	.0021	53	.02
325	.0017	43	.01
325+	-	-	.001

GENERAL DESCRIPTION OF THE
BELL HELICOPTER COMPANY
EROSION TEST FACILITY

The Bell Helicopter Company erosion stand consists of an electric motor driven, flat pitch propeller, four foot in diameter. The propeller is whirled in a vertical plane.

The propeller is basically an aluminum spar with an airfoil contour formed by a bonded and riveted aluminum skin. The finished assembly has about a six inch chord. The center portion of the blade has a two inch square hole which adapts to a steel driving sleeve, which in turn adapts to the driveshaft.

The outboard portions (the two ends) of the blade are specially machined to hold two test specimen holders. The specimens are each 2.225 inches long, therefore this area is 4.450 inches long. It is contoured for a close fit with the inside contour of the specimen. Four 5/16 inch threaded Rosan inserts are installed at each holder position, two on either side of the blade, approximately one-inch from the leading edge. These provide for attachment of the specimens.

The leading edge area inboard of the specimen area is provided with a replaceable protector strip of 0.040 inch stainless steel. The protectors and blade are drilled through (1/4 inch bolts at two places) for attachment. The protectors are contour formed to the blade shape.

The drive system consists of a 50 horsepower variable speed motor with associated electric speed change and generator tach. The motor to blade attachment is through a three foot long, 1.5 inch diameter driveshaft mounted on pillow block bearings. This allows displacement of the motor from the sand or water environment of the test stand.

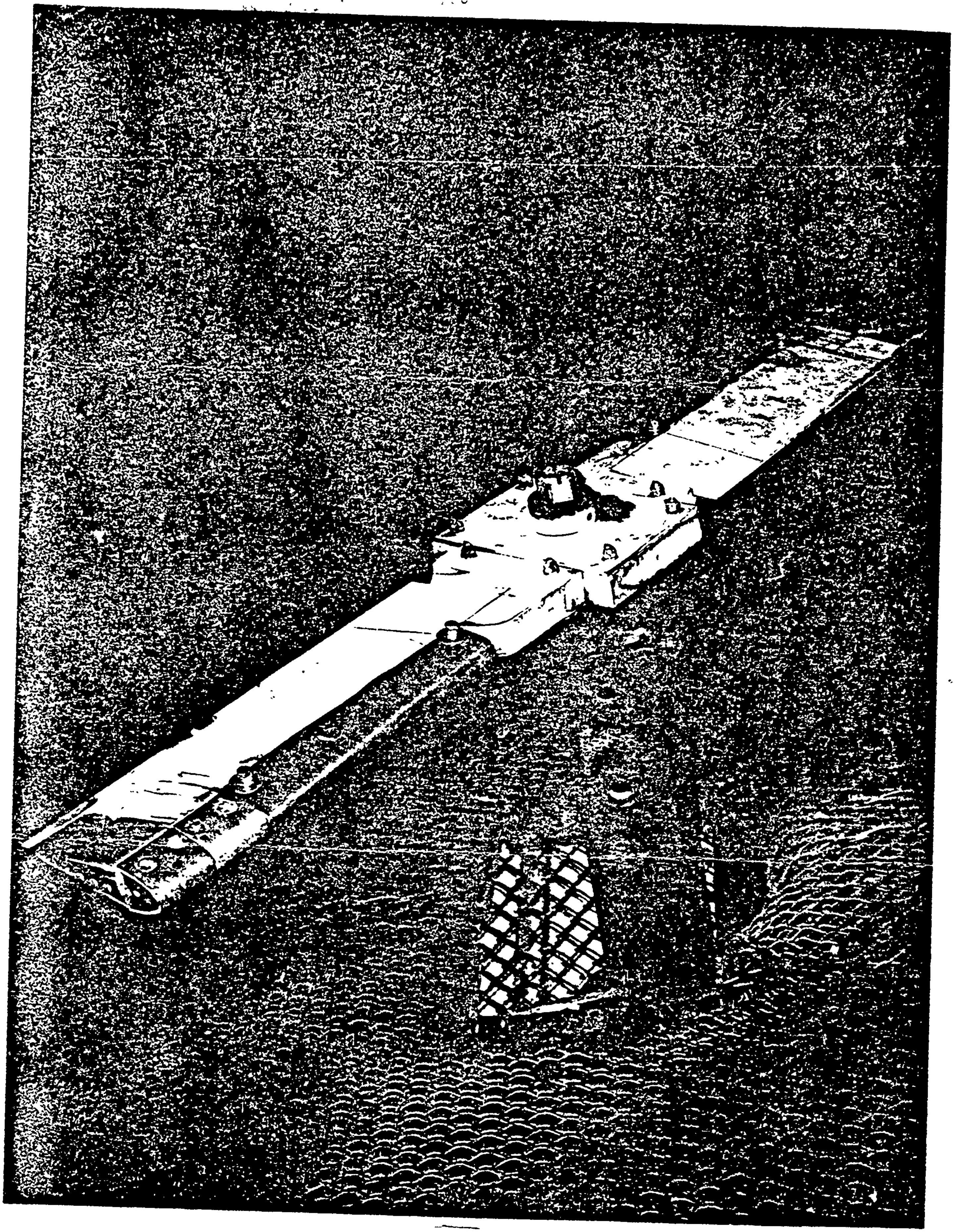
The test stand is an eight foot long by three foot wide by nine foot tall steel framework. The eight foot sides are covered with expanded steel and marine plywood, while the three foot ends are 1/4 inch steel. The top of the stand is open.

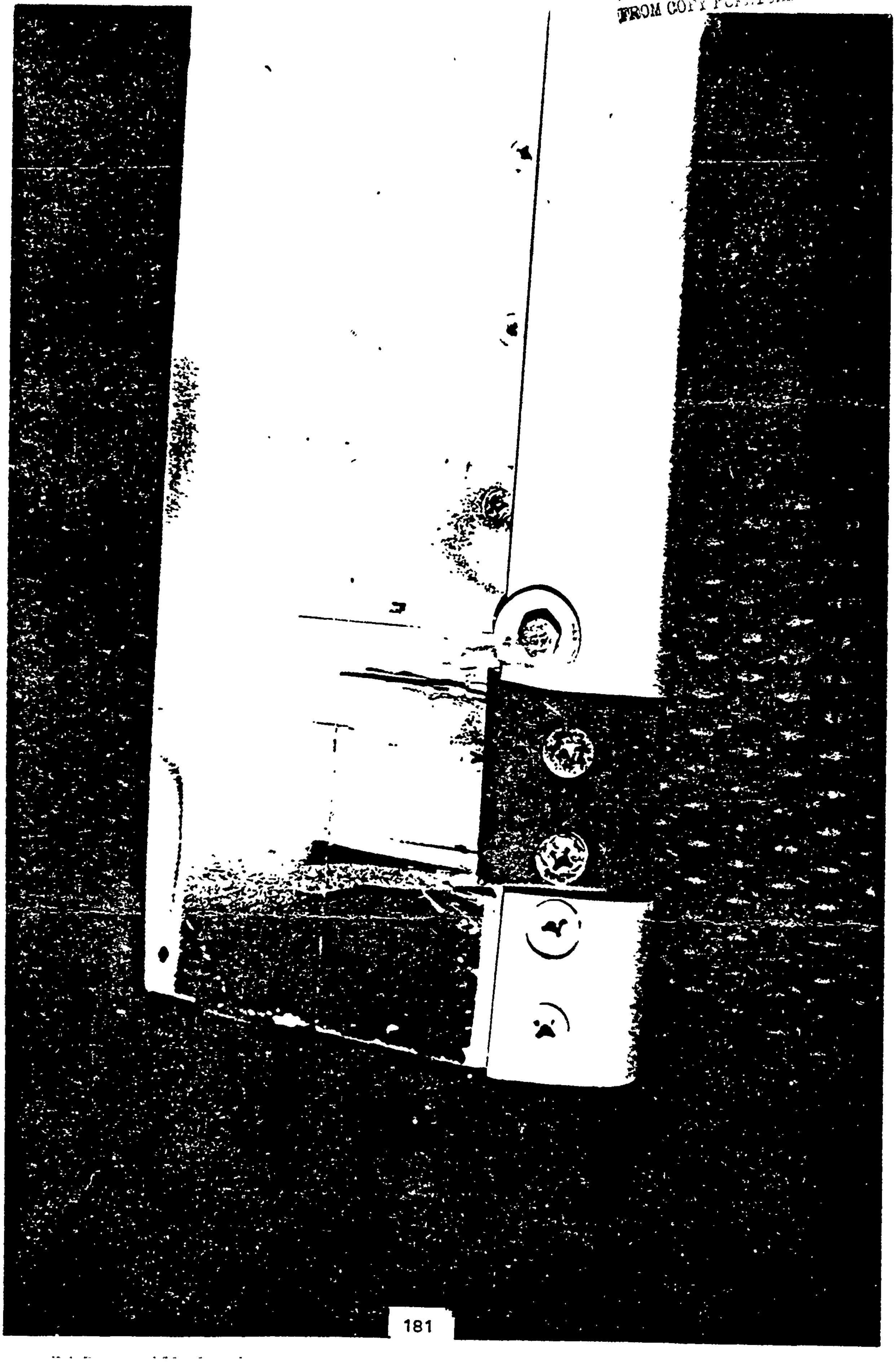
Two systems are used to provide the erosive media. For sand application, a stainless steel fertilizer spreader base (Sears Model 452.19250) is fitted to the bottom of a 55-gallon drum. The spreader agitator is included. For operation, a 5 horsepower electric (low speed) motor is connected to the agitator. The shut-off and rate control mechanism of the spreader is used to control these functions during test. The rate control is blocked off at an opening which produces the desired rate of sand. The shut-off mechanism is controlled using cables and linkages running to a remote control area. The drum with spreader base is positioned in the top of the test stand directly over the oncoming blade. A standard sand (commercially available cleaned and dried silica) is used for tests. The sand rate is normally set at 3-4 pounds per minute.

For rain erosion, two aluminum tubing manifolds are mounted on the eight foot wall in front of the blade. The manifolds are bent in a 21.5 inch radius, covering a 90 degree segment. (Two manifolds run 180 degrees around.) Each manifold contains adapters, evenly spaced, to mount standard medical hypodermic needles. The needles point at the blade, and the manifolds are offset slightly from the circumferential path of the specimens so that water from each needle hits a different spot along the specimens length.

Number 22 gage needles are used for rain erosion. The manifolds are fed using a low pressure 28 volt DC pump, regulator and filter. The number of needles used in tests are varied to produce proper rainfall rates. (Normally 1"/hr)

The specimens are all configured similar to standards. A 0.100 inch thick 2024-0 aluminum sheet is contoured, using form blocks, to the shape of the propeller leading edge. A 0.032 301 x 1/2 hard sheet of stainless steel is formed to the outside surface of the aluminum. The two are bonded together, and a jig is used to drill four 0.313 inch diameter countersunk holes through the sides of the assembly in the same pattern as in the test propeller. This assembly is a "standard." All specimen materials are similarly configured. The normal procedure is to form the candidate materials and bond them directly to standards, forming specimens.





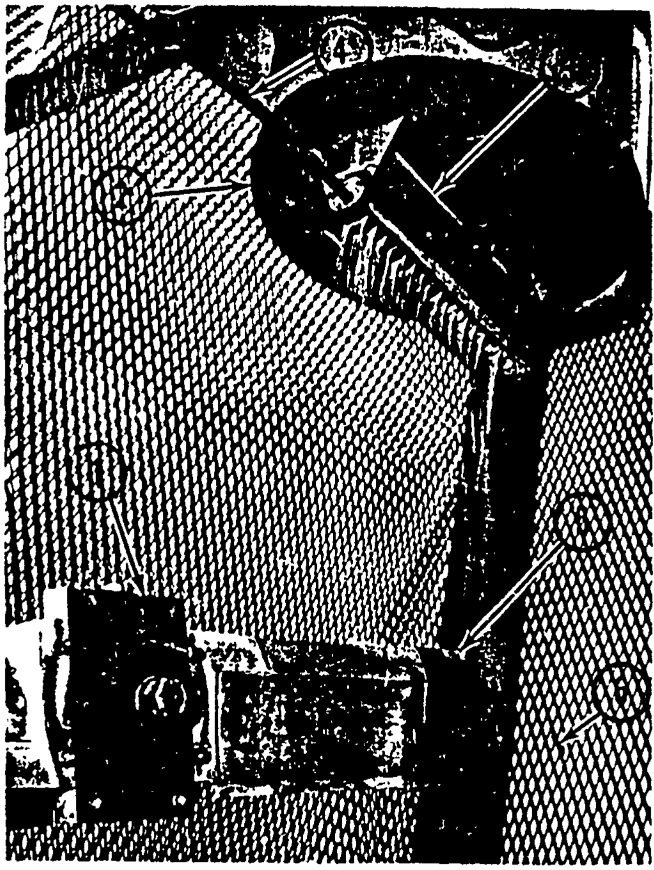


Photo No.
MET 7022

FIG. 1

SAND EROSION TEST SETUP

Arrows indicate:
- (1) Propeller
- (2) Sand hopper
- (3) Spreader with adjustable slots
- (4) Flexible drive shaft to drive agitator
- (5) Sample and standard
- (6) Expanded metal safety screen

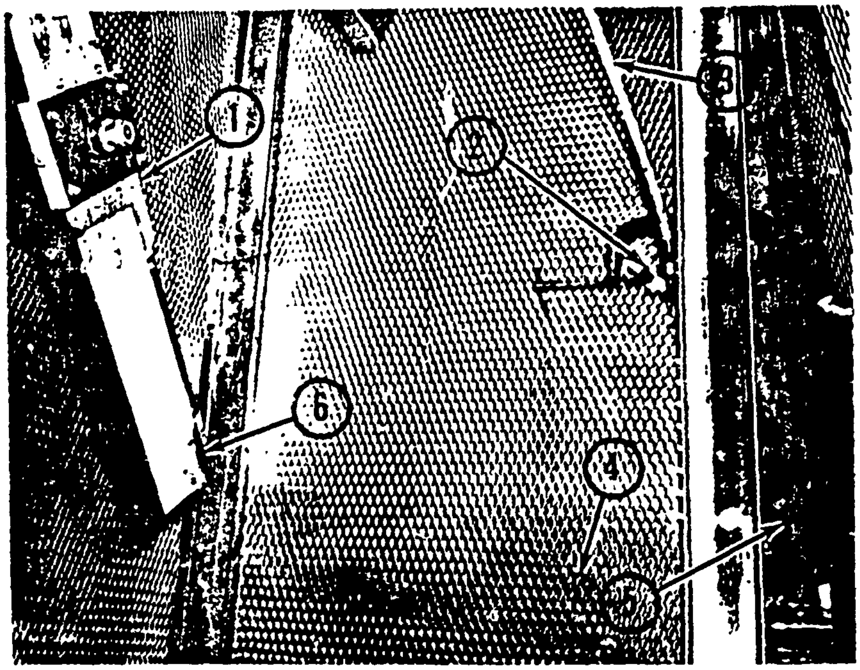


Photo No.
MET 5810

FIG. 2

WATER EROSION TEST SETUP

Arrows indicate:
- (1) Propeller
- (2) Showerhead
- (3) Supply hose
- (4) Expanded metal safety screen
- (5) Tarpaulin used for windbreak on outside of screen
- (6) Specimen and standard

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MANUFACTURING PROCESS DEVELOPMENT FOR
DUST AND RAIN EROSION RESISTANT COATED
METALLIC CLADS FOR HELICOPTER ROTORS
David P. Huey and Alvin R. Stetson,
Solar Turbines International, An Operating
Group of International Harvester, P. O. Box
80966, San Diego, California 92138.
Technical Report AMMRC TR 80-F-13, May 1980,
illus - tables, Contract DAAG46-76-C-0033
AMCMS Code 1497-94.S87017 (GX5)
Final Report, 5 April - 30 June, 1980

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Key Words

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Rotor Blades	Erosion
Leading Edge	Resistance
Rain	Dust
	Clads

Manufacturing processes for creating erosion resistant coatings on metallic rotor blade leading edges were optimized as a follow-on to a coating development program sponsored by AMMRC (Contract DAAG74-C-0054). Solide coated, titanium rotor nose caps were produced in sections up to 30 inches long. Commercially pure (A75) and alloyed (Ti-6Al-4V) titanium was used. Newly developed graphite coating mandrels made possible simultaneous coating and creep forming of titanium sheet material to accurate airfoil contours. Sand and rain erosion tests were performed along with tensile, impact, salt spray and adhesive bonding tests. Costs per part for production quantities were estimated.

Solide coated test specimens of tianium and SAE 430 stainless steel were provided to three major helicopter manufacturers for test and evaluation: Hughes, Sikorsky and Bell. Their conclusions were that Solide coatings are excellent in rain erosion resistance and low angle sand erosion resistance but do not meet minimum survival requirements when subjected to sand erosion by large particles (>100μm) impinging at high angles (>45°).

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