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EROSION AND FATIGUE BEHAVIOR OF COATED TITANIUM ALLOYS FOR GAS TURBINE ENGINE COMPRESSOR APPLICATIONS

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Army Materials and Mechanics Research Center
Watertown, Massachusetts

February 1976

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METALS RESEARCH DIVISION

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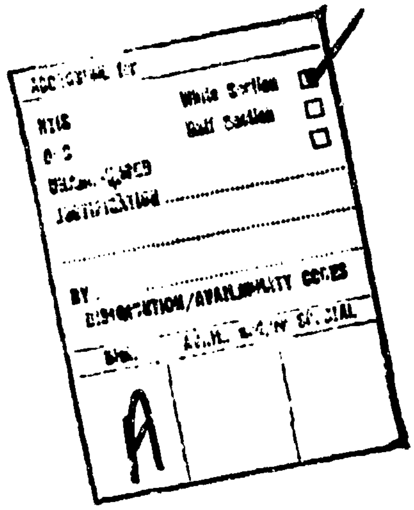

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ABSTRACT

The erosion and fatigue behavior of several potentially protective coatings for reducing the severity of sand erosion degradation of titanium alloys was studied. The coatings can be ranked in the following order of decreasing merit incorporating erosion indices at 30, 60, and 90° impingement: titanium carbonitride (nickel interlayer); titanium diboride (nickel interlayer); boron carbide; diffusion-bonded electroless nickel plus overlay of chromium; diffusion-bonded electroless nickel; and plasma-sprayed boron. All coatings caused fatigue strength reductions of between 22% and 80%. Shot peening reduced fatigue degradation in some cases.

CONTENTS

INTRODUCTION

The high airflow per horsepower requirement for gas turbine engines is responsible for the degradation of compressor components by erosive particle contamination in the air.[1] In fact, erosion of compressor components by sand and dust ingestion has been responsible in part for the very low time-between-overhaul (TBO) for gas turbine engines which have operated in Southeast Asia. In spite of the utilization of inlet particle separators, compressor erosion damage continues to occur in helicopters operating from unimproved landing sites. Figure 1 shows the eroded wide-chord titanium compressor blades from a growth version of the T55-L11 gas turbine engine. Thus, there is a critical need to develop erosion-resistant coatings for titanium alloys.

Since the components of specific interest, i.e., centrifugal impeller and axial blades, are subject to high rotational speeds, the coating processing must not produce appreciable degradation in the fatigue strength of the titanium alloy. It has been proposed by some gas turbine engine manufacturers that a 10 to 15% reduction is acceptable for axial blades while larger reductions can be tolerated for the centrifugal impeller.

The objective of this study was to determine the erosion and fatigue behavior of several potentially protective coatings for reducing the severity of the problem.

Reported herein are the quantitative comparative data obtained on the erosion and fatigue behavior of boron, nickel, nickel and chromium, boron carbide (B_4C), titanium diboride (TiB_2), and titanium carbonitride (Ti_2CN) coatings on several titanium alloys which can be used as design criteria.

MATERIALS

Substrate Alloys

The titanium alloys utilized were the near-alpha 8Al-1Mo-1V in the single annealed condition, the advanced alpha-beta composition 6Al-6V-2Sn which was heat treated to the 160 ksi yield strength level, and the alpha-beta 6Al-4V in the annealed condition.

Coatings

Six coatings were initially selected for evaluation:

1. Diffusion-Bonded Electroless Nickel

Prior work[2,3] demonstrated that the adhesion of electroless nickel plate to several titanium alloys, including 6Al-6V-2Sn and 8Al-1Mo-1V, was significantly improved by diffusion-bonding treatments. Also, the interdiffusion between the

1. McANALLY, W. J., III. *Erosion-Resistant Coating for Titanium.* Pratt and Whitney Aircraft, Contract DAAG46-71-C-0173, Final Report, AMMRC CTR 73-6, January 1973.
2. LEVY, M., and ROMOLO, J. B. *Improved Adhesion of Electroless Nickel Plate on Titanium Alloys.* American Electroplaters Society 48th Annual Technical Proceedings, 1961, p. 135-141.
3. LEVY, M., and MORROSSI, J. L. *Wear- and Erosion-Resistant Coatings for Titanium Alloys in Army Aircraft.* Army Materials and Mechanics Research Center, AMMRC TR 70-36; also in Titanium Science Technology, Plenum Publishing Co., New York, 1972.

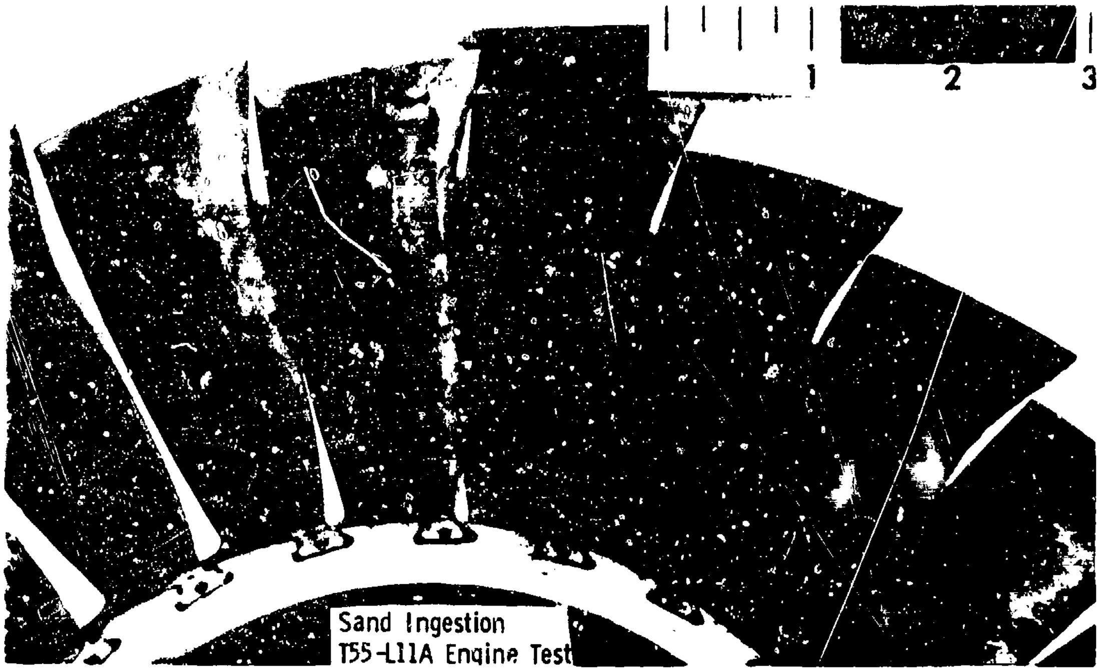

Figure 1. Severe erosion of first stage titanium compressor blades.

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nickel and titanium produced a wear-resistant surface which, under conditions of sliding and rubbing wear, was comparable to steel (case hardened to R_c 60). Little or no effect on the mechanical properties (tensile strength, impact energy, elongation, and reduction of area) of the titanium alloy substrates was observed.

2. Diffusion-Bonded Electroless Nickel plus Overlay of Chromium

One of the major problems associated with coatings for titanium alloys is the relatively poor adhesion of coating to substrate. This has been attributed to the ever-present oxide film on titanium. Since the diffusion-bonding treatments have provided a metallurgically bonded nickel-rich surface on titanium, the feasibility of depositing adherent electroplated chromium over titanium has been greatly enhanced. Indeed, initial experimentation demonstrated that adherent chromium plate can be deposited over titanium alloys which have been electroless nickel plated and diffusion bonded. It was expected that the chromium would provide additional erosion and corrosion resistance.

3. Plasma-Sprayed Boron

This coating material was selected because of the very dense (1.95 g/cc) and hard (R_c 57 to 63) coatings that can be produced by the arc plasma spray process. To obtain optimum adhesion, the titanium alloy specimens were preheated to 300 C prior to deposition. Maximum temperatures attained during deposition did not exceed 500 C.

4. Boron Carbide

National Research Corporation has developed a vacuum evaporation process (PVD) to deposit a hard, impervious layer of B_4C on titanium and other alloys. The coating possesses an extremely fine equiaxed microstructure with an average boron content varying from 74 to 77 weight percent. The substrate temperature for deposition is maintained in the range 370 to 565 C. The material reportedly has a hardness of 3300 Knoop and a density of 2.33 to 2.35 g/cc.

5. Titanium Diboride

United Aircraft Research Laboratories has been able to plate titanium diboride from a fused salt bath at 1200 F. For deposition on titanium alloys, an intermediate layer of nickel is utilized to prevent attack of the substrate alloy. Vickers hardness values as high as 4060 ± 200 have been reported for the coating.

6. Titanium Carbonitride

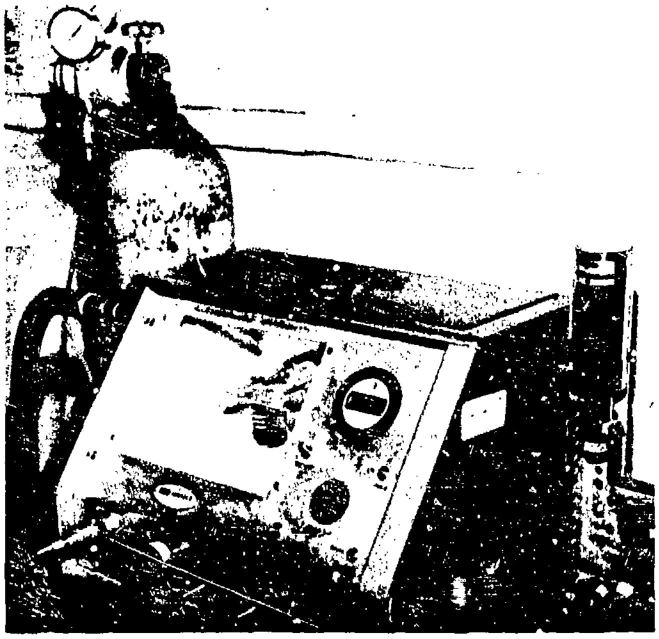
Texas Instruments has developed a titanium carbonitride overlay coating (TIKOTE-C), applied by a chemical vapor deposition process that is basically a reduction of titanium tetrachloride in an atmosphere containing hydrogen, nitrogen, and nitrogen containing hydrocarbon gas. In developing the coating, nitrogen was added to titanium carbide to increase the strain capability of the coating and to reduce the modulus of elasticity from 58 to 50 million psi. In 1968 Pratt and Whitney Aircraft (P&WA) carried out erosion tests on TIKOTE-C coated Ti-6Al-4V specimens and found that the coating could provide 100 times more erosion resistance than bare Ti-6Al-4V. However, a separate investigation[4] reported a severe loss in fatigue strength when the coating was applied to Ti-6Al-4V. Pratt and Whitney Aircraft, in conjunction with Texas Instruments and under contract to Army Materials and Mechanics Research Center, undertook the task of improving the coating system by applying an intermediate layer of nickel between the titanium substrate and the Ti_2CN overlay.[5]

EXPERIMENTAL PROCEDURE

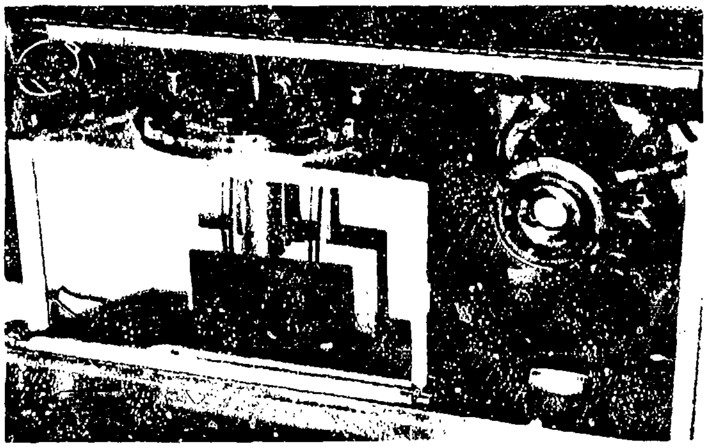
Room Temperature Erosion Test

The laboratory erosion test uses a jet abrader to measure the erosion resistance of materials. Pressurized gas propels dry abrasive powder through a tungsten carbide nozzle onto the test specimen placed inside a work chamber with transparent viewing window (see Figure 2). The spent powder is removed by vacuum exhaust. Abrasive flow, pressure, nozzle distance, and angle are closely controlled to provide good reproducibility of test data. The end point is signalled by the first show of bare substrate and for titanium alloys this is clearly manifested by sparking. The abrasive employed is 27 micron aluminum oxide which is propelled at a velocity of 800 ft/sec at the nozzle and has an impact velocity of 250 to 300 ft/sec at a distance 0.6 inch from the nozzle. Approximately 1 g/min of abrasive is utilized

4. GREEN, H. M. *Manufacturing Techniques for Application of Erosion-Resistant Coatings to Turbine Engine Compressor Components.* General Electric Co., Technical Report AFML-TR 70-14, May 1970.
5. McCOMAS, C. C., and SAKAL, L. S. *Research for Engine Demonstration of Erosion-Resistant Coating Effectiveness.* Pratt and Whitney Florida Research, Contract DAAG46-73-C-0249, Final Report, AMMRC CTR 74-9, January 1974.



a. front view



b. top view

Figure 2. Erosion tester.

at a compressed air pressure of 45 psi. Tests are conducted at 30, 60, and 90° impingement angles in order to determine the effect of both impact and abrasion erosion. The 90° impingement is essentially impact erosion, whereas the 30° impingement is considered to be abrasion erosion which is representative of much of the erosion condition in an engine. The erosion index, which is the number of seconds required to erode or remove 1 mil of material, is used to rank the various candidate coatings in order of merit. The titanium alloy test panels were 2" x 3" x 1/4"; a minimum of five tests were conducted to establish an erosion index. To avoid the variable surge of Al_2O_3 particles on initiation of flow and to insure stability and uniformity of the stream, the test specimen was shielded from the stream for 30 seconds prior to exposure.

Fatigue Test

Stress versus cycles-to-failure tests of smooth fatigue specimens were carried out using a Krouse rotating bending fatigue machine. The fatigue apparatus was operated at 3000 rpm, which is equivalent to a cycle stress reversal frequency of 50 Hertz and a stress ratio R = -1. Rotating bending fatigue specimens measured 1/2" diameter by 5" long, with a 2" radius reduced section giving a minimum cross section of 1/4" diameter at the specimen center. Stressing of the specimen was accomplished using a sliding weight to apply a bending moment. A counter kept track of the number of stress cycles, and a limit-switch shut off the machine at specimen failure.

Additional mechanical tests were conducted to determine the effect of the coatings on the tensile strength, elongation, and reduction of area of the titanium alloy substrates, and the coatings were characterized by microscopic examination. Shot peening, when utilized to reduce the extent of fatigue damage caused by the plating processes, was achieved with 110 glass shot at a peening intensity of 0.004 to 0.006 A.

RESULTS AND DISCUSSION

Room Temperature Erosion Test

The results of the erosion tests are shown in Table 1. Boron carbide, titanium diboride, and titanium carbonitride were superior to all the other coatings tested at all impingement angles. Titanium diboride and titanium carbonitride were clearly the outstanding coatings evaluated, i.e., both coatings exhibited a 100 to 112X improvement over bare titanium at 30° impingement, and a 17 to 23X improvement at 90° impingement, the Ti_2CN giving the better results. The boron carbide coating exhibited improvements of 12X at 30° impingement and 3X at 90° impingement. Slightly better results were achieved when the B_4C coating thickness was increased from 0.8 mil to 1.7 mils. The degradation of erosion behavior of these hard coatings at the high impingement angle (90°) is probably due to fracture and spallation. Softer coatings, on the other hand, would be able to absorb the energy of the impacting particles.[6]

Diffusion-bonded electroless nickel, with and without an overlay of chromium, improved the erosion resistance of titanium by only a factor of 2 at 30° impingement. These results were obtained when the electroless nickel was diffusion bonded at the higher temperatures (1150 to 1550 F). The overlay of chromium provides only a marginal improvement in erosion resistance.

The plasma-sprayed boron coating gave the poorest results. Erosion resistance was clearly inferior to even the titanium substrate. The poor showing of this coating may be due to the surface roughness and porosity which are inherent in plasma spray processing. Erosion data obtained for all coatings tested at 60° and 90° impingement were quite comparable and more severe than the 30° impingement. However, the greatest emphasis should be placed on the data obtained at 30°; it is the most representative of engine conditions.

6. BERGMAN, P. A., and BARTOCCI, R. S. *Erosion-Tests of Compressor Alloys and Coatings for Aircraft Gas Turbines.* Proc. of 8th Annual Conference on Aircraft and Propulsion Systems, 1968.

Table 1. EROSION RESISTANCE INDICES*

Material	Impingement Angles 30°	60°	90°
Ti-8Al-1Mo-1V	88	-	80
Ti-6Al-4V	80	-	80
Ti-6Al-6V-2Sn	78	63	79
Electroless Nickel, as-plated, Diffusion Temperature (deg F)			
80	58	32	35
750	58	36	39
950	80	52	54
1150	80	50	50
1350	73	-	49
1450	81	-	47
1550	161	-	78
Chromium and Nickel			
750	97	79	78
950	108	84	81
1150	134	83	81
Arc-Plasma Boron on Ti-6Al-6V-2Sn	2.0	1.0	0.8
Boron Carbide B_4C			
0.8 mil thick	991	313	258
1.7 mils thick	996	478	346
Titanium Diboride (TiB_2)	7793	1393	1326
Titanium Carbonitride (Ti_2CN)	8753	-	1807

*Time in seconds required to erode 1 mil of material with the Roberts Jet Abrader.

Fatigue Test

Figure 3 shows the effect of electroless nickel, both as-plated and diffused, on the fatigue life of Ti-6Al-6V-2Sn. The fatigue life of the as-plated specimen remained the same as the uncoated specimen, namely, 97 ksi. Diffusion at 750, 950, and 1150 F reduced the value to 28, 24, and 19 ksi, respectively. (Diffusion bonding was achieved by vacuum heat treatment (1.5×10^{-5} Torr) at temperature for 4 hours.) Fatigue life decreased with increasing diffusion temperature and in each case the reduction represented severe degradation of the titanium alloy (70 to 80%). Figure 4 shows the effect of diffusion temperature on the diffusion zone depth and structure of the coating/substrate system. As the diffusion temperature increased, the diffusion zone depth increases with increasing amounts of brittle intermetallics[2] along with greater degradation of fatigue life. The effect of electroplated chromium on the fatigue behavior of the diffusion-bonded electroless nickel Ti-6Al-6V-2Sn system is shown in Figure 5. The fatigue life of this duplex coating system was 42 ksi (750 F nickel diffusion), 33 ksi (950 F nickel diffusion), and 32 ksi (1150 F nickel diffusion). The chromium plate improved the fatigue life of the diffusion-bonded nickel-coated specimens; however, the fatigue degradation of the base titanium alloy was still greater than 50%.

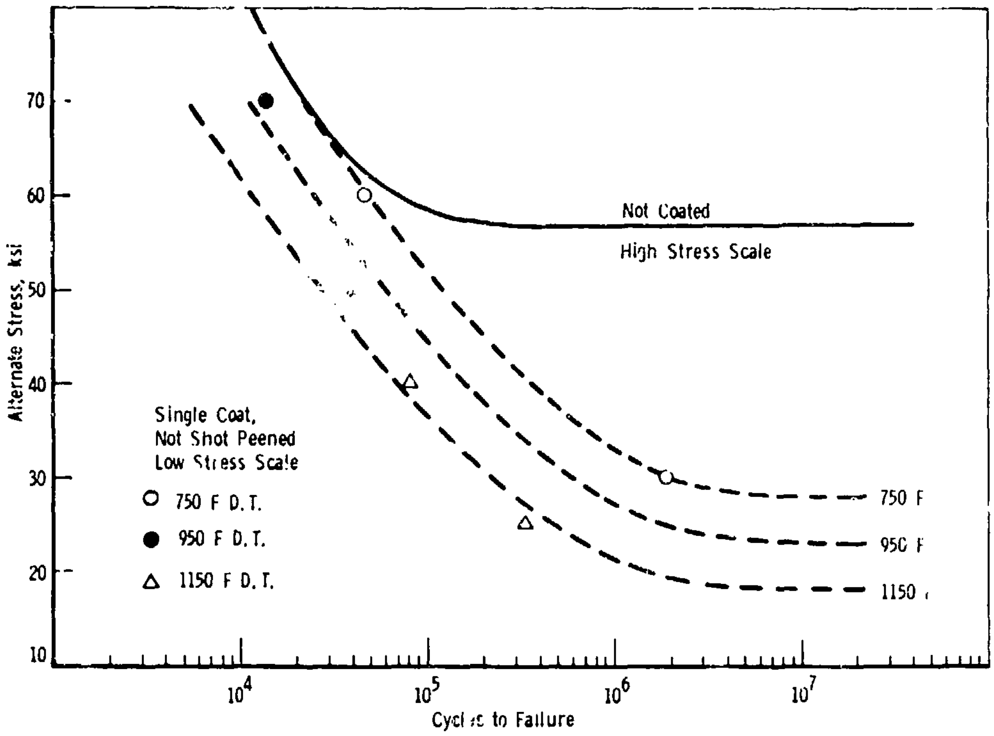


Figure 3. Effect of electroless nickel plate on the fatigue life of Ti-6Al-6V-2Sn.

The reduction of the fatigue properties of the titanium alloy by the nickel and chromium plate may be attributed to (a) deleterious residual stresses in the plating, (b) notch effects of the minute cracks in the plating, and (c) the poorer fatigue properties of the plating itself which causes fatigue cracks to initiate prematurely in the weaker plating and propagate into the titanium quicker than if the fatigue cracks developed in the bare titanium surface.

The effect of shot peening (0.004 to 0.006 intensity) on the fatigue life of the diffusion-bonded electroless nickel-plated specimens (750 to 1150 F) is shown in Figure 6a. The shot peening treatment, which was applied after diffusion bonding, restored fatigue life to within 10% of the unplated Ti-6Al-6V-2Sn alloy (87 ksi) regardless of the diffusion temperature. Figure 6b shows the effect of shot peening on duplex-coated Ti-6Al-6V-2Sn (diffusion-bonded electroless nickel plus chromium, shot peened after chromium plating.) In this case, the diffusion temperature did affect fatigue life, i.e., the higher the diffusion temperature, the lower the fatigue life. The reduction in fatigue life varied between 15% at a diffusion temperature of 750 F and 25% at 1150 F. Viglione et al.[7] have reported the deleterious effects of electroless nickel and chromium plate on the fatigue strength of high-strength steels, and also the effectiveness of shot peening in restoring most of the fatigue strength of the steel. Figure 7 summarizes all the fatigue results for Ti-6Al-6V-2Sn coated with both the single and duplex coating systems as a function of diffusion temperature. Figure 8 contains photomicrographs of the

7. VIGLIONE, J., JANKOWSKY, E. J., and KETCHAM, S. J. *Effects of Metallic Coatings on the Fatigue Properties of High Strength Steels.* Materials Protection and Performance, v. 11, no. 3, March 1972, p. 31-36.

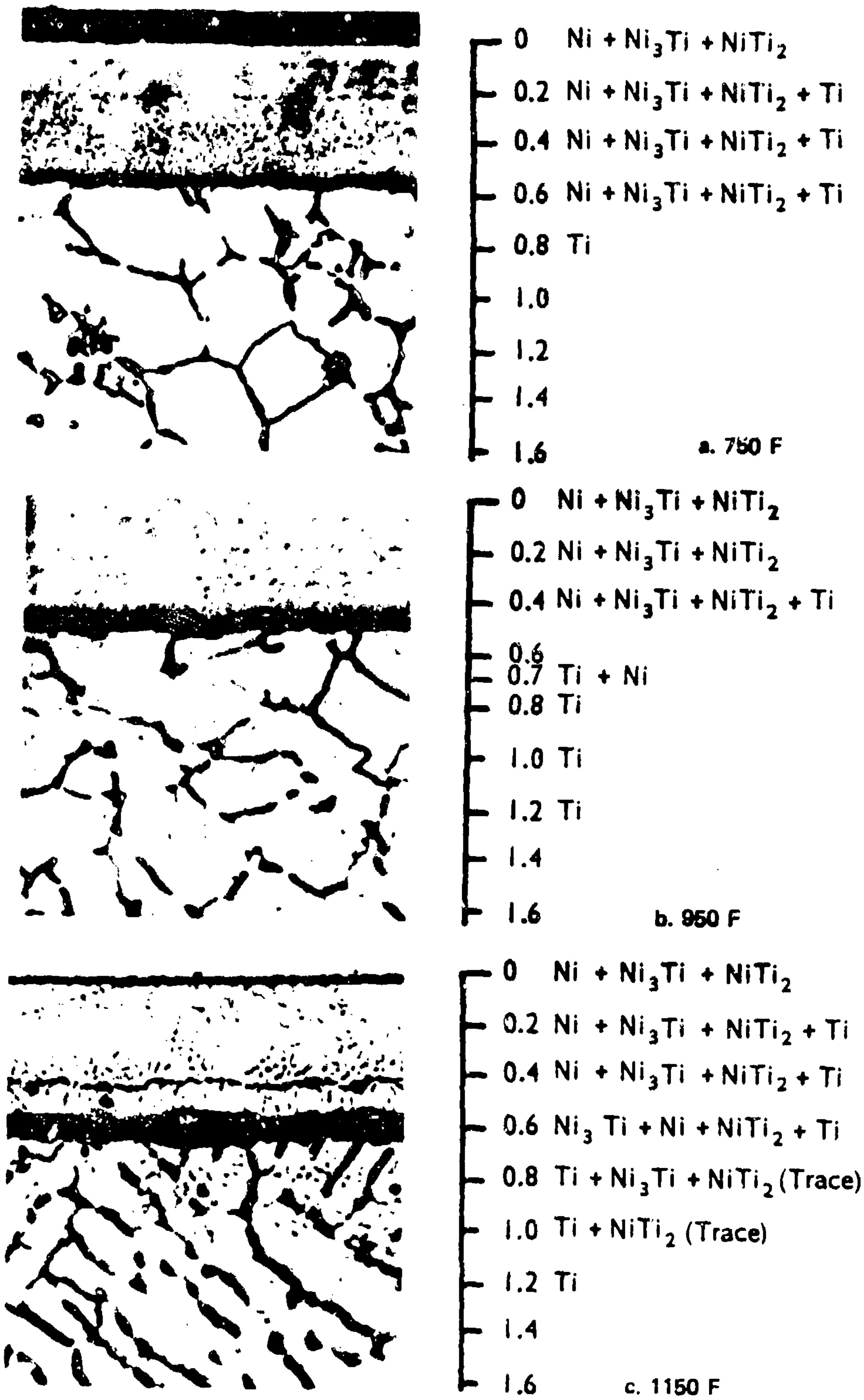


Figure 4. Effect of diffusion temperature on the diffusion zone depth and structure of the electroless nickel substrate system. Mag. 1500X
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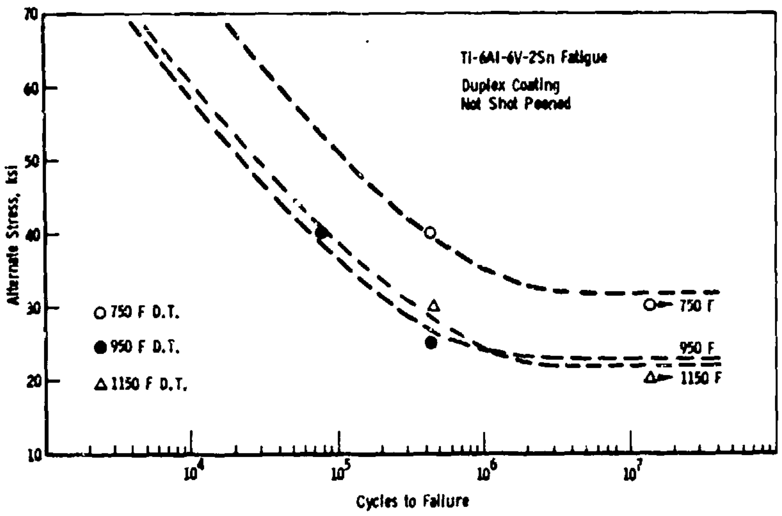


Figure 5. Effect of electroplated chromium on the fatigue behavior of the diffusion bonded electroless nickel Ti-6Al-6V-2Sn system.

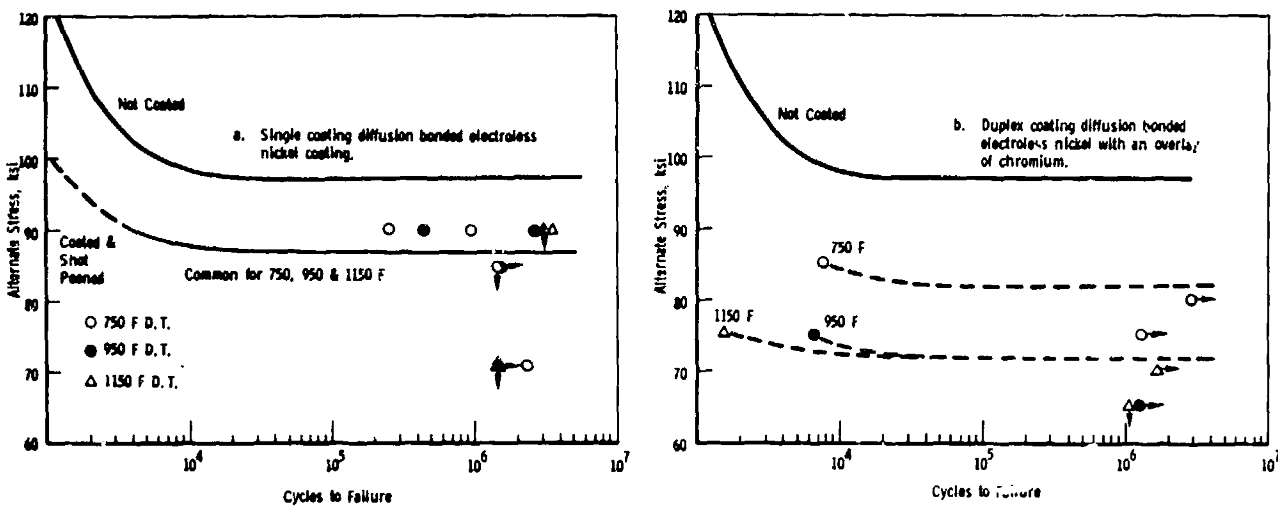


Figure 6. The effect of shot peening on the fatigue life of coated Ti-6Al-6V-2Sn.

cross-sectional areas of electroless nickel-coated Ti-6Al-6V-2Sn specimens which had been diffusion bonded at 750 F and 950 F, shot peened, and fatigue tested. Only a few cracks have initiated in the nickel coating and none have propagated into the substrate. A photomicrograph of the cross-sectional area of the duplex-coated Ti-6Al-6V-2Sn specimen which had been diffusion bonded at 950 F, shot peened, and fatigue tested is shown in Figure 9a. Note that there are many cracks in the chromium plate but only one has propagated through the electroless nickel and into the substrate alloy. In the main, the crack appears to follow along the alpha (white) grain boundaries. Figure 9b shows another area of the same specimen where none of the cracks formed in the coating have propagated into the substrate.

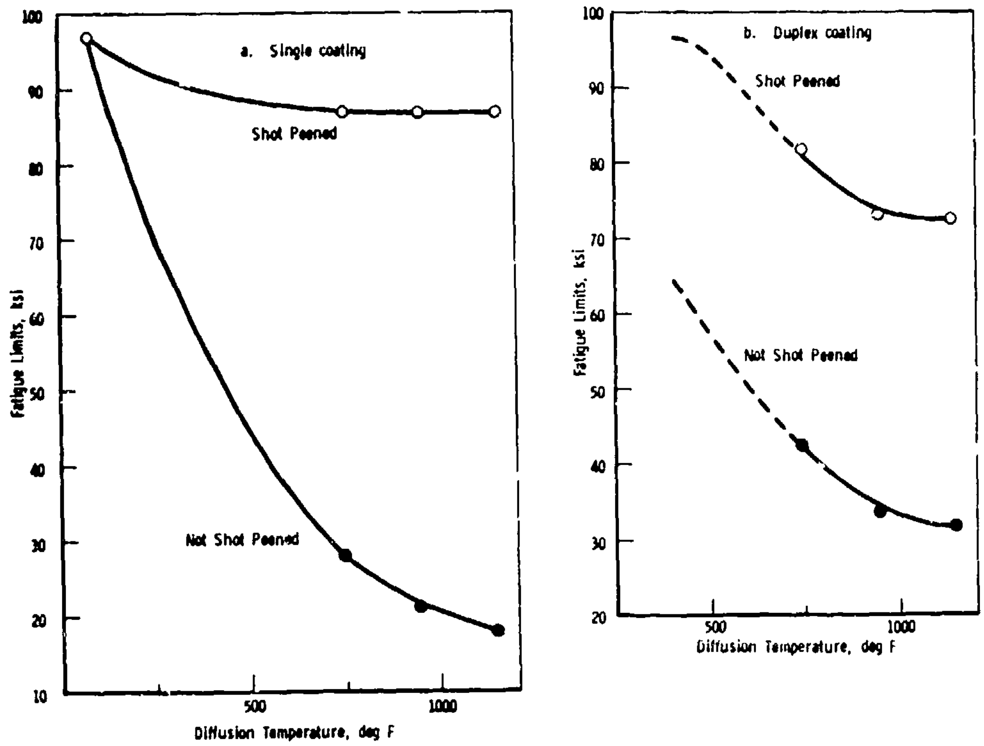
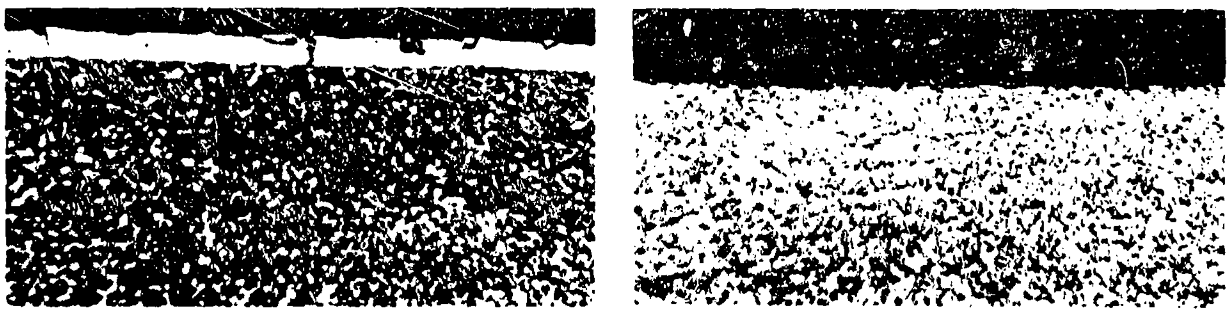


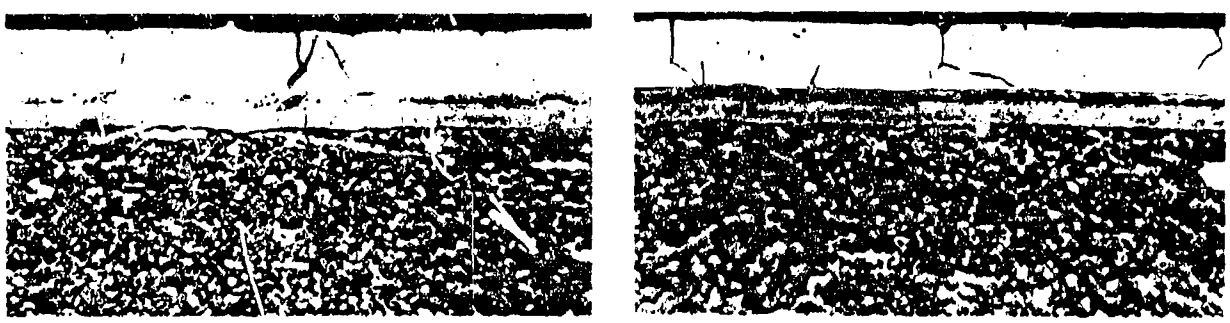
Figure 7. Summary of fatigue results for coated Ti-6Al-6V-2Sn as a function of diffusion temperature.



a. diffusion bonded at 750 F

b. diffusion bonded at 950 F

Figure 8. Photomicrographs of cross-sectional areas of electroless nickel coated Ti-6Al-6V-2Sn specimens which were diffusion bonded, shot peened, and fatigue tested. Mag. 250X



a. area where a crack has propagated into the substrate

b. another area where none of the cracks have propagated into the substrate

Figure 9. Photomicrographs of cross-sectional areas of the duplex coated Ti-6Al-6V-2Sn specimens which had been diffusion bonded at 950 F, shot peened, and fatigue tested. Mag. 250X

Shot peening improves fatigue properties as a result of the introduction of compressive residual stresses on the surface by cold working. The surface compressive stresses negate any applied tensile stresses of equal magnitude. Thus, initiation of a fatigue crack is delayed and sites for crack nucleation are shifted to some point or points below the surface (tensile stresses have a greater tendency to initiate fatigue cracks than compressive stresses).

Fatigue data was also obtained for the aforementioned coatings applied to Ti-8Al-1Mo-1V. For the diffusion-bonded electroless nickel-plated shot-peened specimens fatigue degradation was 15% (from 97 ksi to 82 ksi, Figure 10a). The shot-peened duplex-coated specimens exhibited 22 to 33% fatigue degradation depending on the diffusion temperature (97 to 75 and 65 ksi, see Figure 10b). These data for the coated Ti-8Al-1Mo-1V are summarized in Figure 11 as a function of diffusion temperature.

Fatigue data for the remaining coatings, namely B_4C, TiB_2, and Ti_2CN, are contained in Table 2. The plasma-sprayed boron reduced the fatigue life of Ti-6Al-6V-2Sn from 97 ksi to 50 ksi, or a reduction of 48%. Figure 12 is a photomicrograph of the coating/substrate interface, which shows that the substrate has

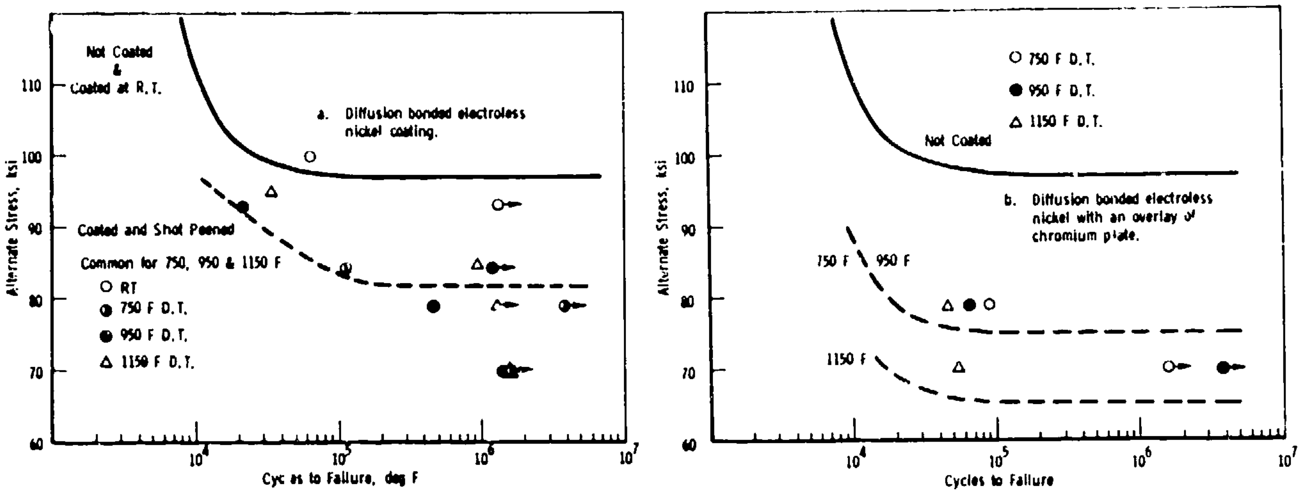


Figure 10. Effect of shot peening on the fatigue behavior of coated Ti-8Al-1Mo-1V.

Table 2. FATIGUE DATA FOR COATING/SUBSTRATE SYSTEMS

Coating/Substrate	Fatigue Strength Substrate (ksi)	Fatigue Strength Coated Substrate (ksi)	Fatigue Strength Reduction Due to Coating (%)
Boron/Ti-6Al-6V-2Sn	97	50	48
B_4C/Ti-8Al-1Mo-1V	90	70	22
Ni+TiB_2/Ti-6Al-4V*	67.5	25	63
Ni+Ti_2CN/Ti-6Al-4V*	67.5	37.5	45
Ni+Ti_2CN/Ti-8Al-1Mo-1V*	67.5	45	32

*These data were supplied by Pratt & Whitney Aircraft, Florida R&D Center, where fatigue testing was carried out at a cyclic stress reversal frequency of 100 Hz. Note that AMMRC testing was conducted at 50 Hz.

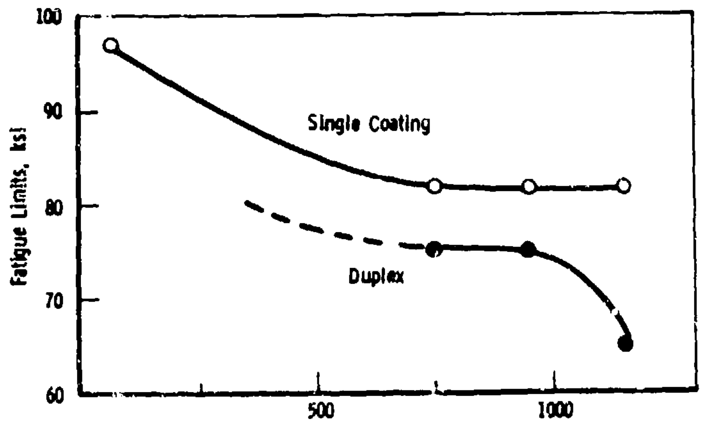


Figure 11. Summary of fatigue results for coated Ti 8Al-1Mo-1V as a function of diffusion temperature.

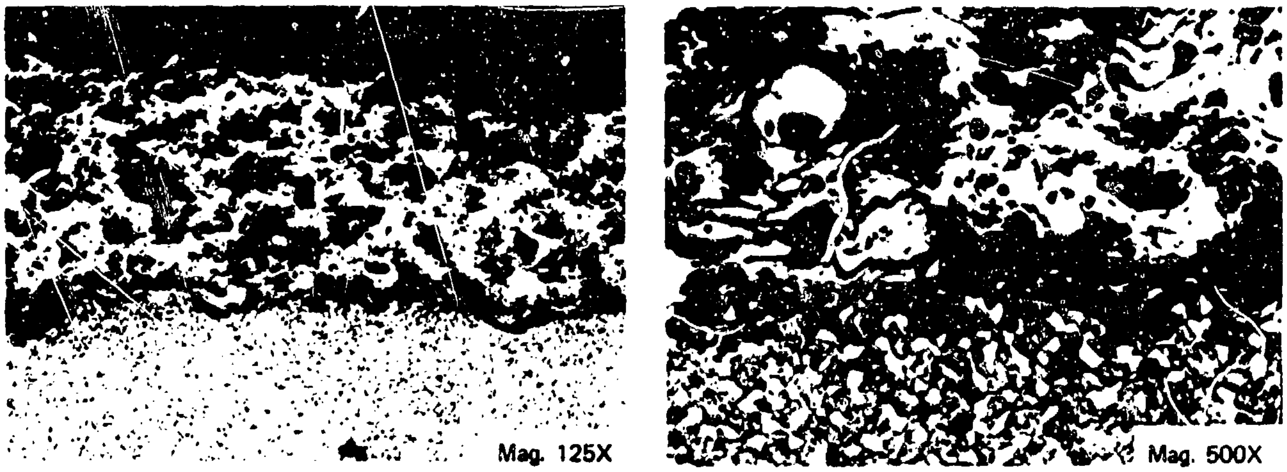


Figure 12. Photomicrographs of plasma sprayed boron/Ti-6Al-6V-2Sn substrate interface.

been mechanically abraded (grit blasted) to promote coating adhesion (surface roughness) and that the coating has porosity. During fatigue testing, some of the coating flaked off from the substrate (as early as 20,000 to 35,000 cycles). The roughened substrate surface, which produces stress raisers, in conjunction with the relatively poor adhesion and porosity of the coating contributed to the early failure of the system.

The PVD applied B_4C reduced the fatigue strength of Ti-8Al-1Mo-1V from 90 ksi to 70 ksi, a fatigue degradation of 22%. This coating produced the least amount of degradation in the fatigue strength of the titanium alloy. Figure 13 illustrates the columnar structure of the coating and shows that the microstructure of the substrate titanium alloy has not been affected by the temperature of the vacuum deposition (700 to 1050 F). There is good bonding between coating and substrate.

Reverse bending fatigue results at 10^7 cycles indicated that Ti-6Al-4V coated with nickel plus Ti_2CN suffered a fatigue strength reduction of 45% (from 67.5 ksi to 37.5 ksi). Ti-8Al-1Mo-1V coated with the same system experienced a fatigue strength reduction of 32% (from 67.5 ksi to 45.0 ksi). Figure 14 is a photomicrograph of the cross section of Ti-6Al-4V coated with nickel plus titanium

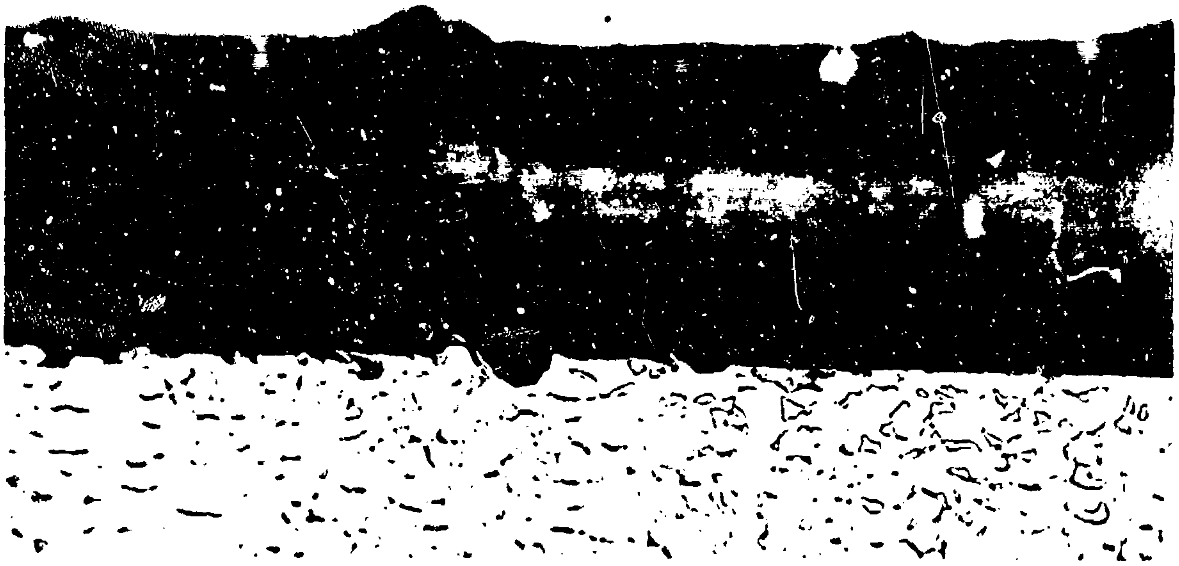


Figure 13. Photomicrograph of PVD of plied B_4C/Ti-8Al-1Mo-1V substrate interface Mag. 1000X

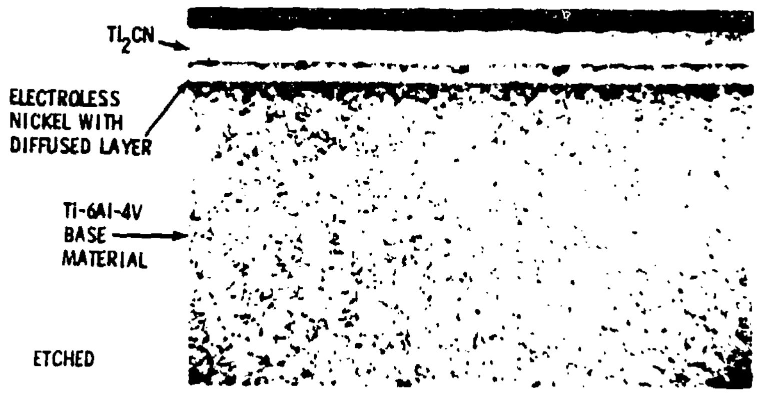


Figure 14. Photomicrograph of the cross-section of Ti-6Al-4V coated with nickel plus titanium carbonitride. Mag. 125X
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carbonitride after fatigue evaluation. Note the excellent bonding and uniformity of the coatings. The application of nickel plus TiB_2 coatings to Ti-6Al-4V reduced the fatigue life of the substrate alloy 63% (from 67.5 ksi to 25.0 ksi).

Benson[8] has reported that a coating such as an oxide or a plating can alter the dislocation interactions at a surface. If the elastic modulus of the coating is greater than that of the substrate metal, then dislocations may be repelled from the coating and the surface made more resistant to fatigue crack initiation. The Ti_2CN, TiB_2, and B_4C coatings all have an elastic modulus approximately four times the modulus of titanium (60×16^6 versus 15×10^6), yet they all cause appreciable fatigue degradation. Apparently the elastic modulus differential is an oversimplification and other factors are overriding here.

8. BENSON, D. K. *Surface Treatments for Fatigue Strengthening.* ASTM STP 467, 1970, p. 188-208.

Effect of Coatings on the Mechanical Properties of the Substrate Titanium Alloys

Table 3 shows the effects of the electroless nickel and diffusion bonding on the ultimate tensile strength, yield strength, elongation, and reduction of area of the alloys. The nickel plating had little or no effect on the mechanical properties of both Ti-8Al-1Mo-1V and Ti-6Al-6V-2Sn. For Ti-8Al-1Mo-1V, the diffusion-bonding treatments (between 750 and 1150 F) had no degradation effects on room temperature tensile and yield strengths but there was an approximate 10% reduction in elongation and reduction of area. For the Ti-6Al-6V-2Sn alloy, heat treatments between 750 and 1150 F did not affect tensile and yield strengths. However, heat treatments at 750 and 950 F caused approximately 10% reduction in elongation and about 30% decrease in reduction of area while the 1150 F treatment did not affect those properties. Mechanical property data for the duplex coating (diffusion-bonded electroless nickel with an overlay of chromium electroplate) was not obtained since the chromium did not significantly enhance the erosion and/or fatigue resistance of the diffusion-bonded nickel plate.

Table 4 contains mechanical property data for the remaining coatings: plasma-sprayed boron, nickel plus titanium diboride, and nickel plus titanium carbonitride. These coatings had little or no effect on the mechanical properties of the corre-

Table 3. MECHANICAL PROPERTIES OF TITANIUM ALLOYS ELECTROLESS NICKEL PLATED AND DIFFUSION BONDED

Diffusion Temperature (deg F)	Ti-8Al-1Mo-1V Plated	Ti-8Al-1Mo-1V Not Plated	Ti-6Al-6V-2Sn Plated	Ti-6Al-6V-2Sn Not Plated
a. Tensile Strength (ksi)				
80		137.0	166.8	169.6
750	137.4	136.9	171.5	170.0
950	137.1	137.1	169.4	170.0
1150	138.8	135.3	168.6	167.1
b. 0.2% Yield Strength (ksi)				
80		127.5	162.3	160.9
750	124.8	127.3	165.5	161.8
950	129.8	137.1	165.0	163.2
1150	131.3	128.3	164.5	161.0
c. Impact Energy (ft-lb)				
80	18.9	17.8	10.2	11.1
750	17.0	18.3	10.3	10.1
950	17.7	20.0	8.7	10.0
1150	19.1	20.0	9.3	12.9
d. Elongation (%)				
80		17.9	12.5	12.2
750	14.7	17.2	10.4	11.8
950	15.7	19.3	7.1	9.3
1150	17.1	17.5	14.3	14.3
e. Reduction of Area (%)				
80		40.5	29.5	27.6
750	33.8	34.7	18.9	30.5
950	34.3	37.4	10.3	16.9
1150	35.2	33.8	35.3	36.5

Table 4. EFFECT OF COATINGS ON MECHANICAL PROPERTIES OF SUBSTRATE TITANIUM ALLOYS

	U.T.S. (ksi)		Y.S., 0.2% (ksi)		Elon. (%)		R.A. (%)	
Alloy Coating	Substrate	Coating	Substrate	Coating	Substrate	Coating	Substrate	Coating
Ti-6Al-6V-2Sn, plasma-sprayed boron	167	168	159	159	15	†	42.2	37.8
Ti-6Al-4V, Ni + TiB_2	164	158	154	151	15	12.4	36.8	42.1
Ti-6Al-4V, Ni + Ti_2CN*	150	150	150	150	16.8	17.0	53.8	51.0

*Data supplied by P&WA, Florida R&D Center (Ref. 4).
†Coating delaminated

sponding substrate titanium alloy. National Research Corp., the supplier of the B_4C coated specimens, has reported that B_4C does not degrade the mechanical properties of the substrate titanium alloy.

CONCLUSIONS

1. The coatings can be ranked in the following order of decreasing merit incorporating erosion resistance indices at 30, 60, 90° impingement: titanium carbonitride (nickel interlayer), titanium diboride (nickel interlayer), boron carbide, diffusion-bonded electroless nickel plus overlay of chromium, diffusion-bonded electroless nickel, and plasma-sprayed boron. Titanium diboride and titanium carbonitride were clearly the outstanding coatings evaluated.

2. All coatings caused fatigue strength reductions of between 22% and 80%. The fatigue life of the diffusion-bonded nickel plate, which represented the most severe degradation of the titanium alloy, was restored to within 10% of that of the unplated alloy by a shot peening treatment.

3. Boron carbide, which provided a moderate improvement in erosion resistance over bare titanium alloy, produced the least fatigue degradation (22%) of all the coatings evaluated. Of the most erosion-resistant coatings, Ti_2CN and TiB_2, the fatigue life was reduced less by the Ti_2CN.

4. Comparing the three most erosion-resistant coatings; Ti_2CN, TiB_2, and B_4C, the B_4C coating, which caused the least fatigue degradation, was applied at the lowest temperature (<1000 F versus 1200 F). This suggests that efforts to reduce the deposition temperature of Ti_2CN and TiB_2 to 1000 F or less might be beneficial in reducing fatigue degradation, however, erosion resistance might be compromised.

5. None of the coatings studied caused significant reductions in mechanical properties of the titanium alloys (ultimate tensile strength, yield strength, elongation, reduction of area). In marked contrast, coating effects under conditions of alternating stress (fatigue) wer appreciabl deleterious.