# Ion Beam Enhanced Deposited (IBED) Tribological Coatings for Non-Ferrous Alloys

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## Abstract

Non-ferrous alloys such as aluminum and titanium, when used as base materials for precision mechanical components, usually require protective coatings to improve their wear-resistance. The tribological coatings usually employed are hard oxide layers grown by various anodizing processes. Hard metallic nitride coatings (TiN, $Cr_2N$) are more resistant to abrasive wear but cannot be deposited easily on these non-ferrous alloys with conventional chemical or PVD-type processes. These hardcoatings can however be deposited on most non-ferrous alloy substrates by ion beam enhanced deposition (IBED). The abrasive wear-resistance of IBED hardcoated aluminum, and titanium alloy substrates is measured by the Taber Abraser Test and compared to the wear performance of anodized aluminum and titanium per MIL-A-8625F and AMS 2488 respectively. Metallic nitride hardcoatings deposited by IBED techniques are shown to be viable alternatives to hard anodizing treatments for aluminum and titanium alloys.

**Keywords:** IBED hardcoatings, aluminum, titanium, nickel

## Introduction

For many engineered components including gears, bearings, cylinders, pistons and other wear parts it is desirable to substitute either aluminum or titanium alloys for ferrous alloys because of their lighter weight and ease of machining. Unfortunately, both aluminum and titanium alloys have very poor abrasive wear resistance which limits the applications where substitution of these materials for ferrous alloys can be made and still meet component performance specifications. Application of wear-resistant coatings such as hard chromium (plating) to both aluminum and titanium alloys is very difficult because they both form tight stable oxide coatings[1], and design engineers usually discount the use of these lightweight alloys because the necessary wear-resistance cannot be achieved.

Since both aluminum and titanium alloys do form stable oxide films their surfaces they can be electrochemically anodized to grow hard, corrosion-resistant, abrasion-resistant surface coatings[2]. These surface oxides do provide enhanced corrosion and wear resistance and may in some cases provide sufficient enough performance to meet operating design specifications.

There are however many limitations of electrochemical anodizing, and anodized layers, that prevent more widespread substitution of anodized aluminum and titanium alloy components for ferrous alloy components. The major limitations include the following[3].

Oxide Layer Properties and Durability

The oxide layers that form on aluminum (and titanium) alloys are not nearly as hard as metallic layers such as chromium, and much softer than metallic nitride hardcoatings such as titanium nitride and chromium nitride. In most cases the slight increase in wear-resistance obtained by anodizing is not sufficient to meet component design specifications.

Surface Sensitivity

The quality of anodized oxide coatings is a strong function of both the composition and mechanical quality of the surface on which they are grown. Denser and harder oxide coatings are developed on pure unalloyed aluminum. Milled and turned surfaces provide the best surfaces for coating growth. Surfaces that are ground or lapped inhibit coating growth and often yield coatings with degraded properties.

Process is Difficult to Control

The anodizing process requires very tight monitoring and control of a number of interdependent parameters including electrolyte concentrations, temperature, and current density. Throughout the coating cycle the electrolyte concentrations can easily become imbalanced resulting in a significant change in the oxide composition and morphology and thus mechanical properties of the anodized coating.

Dimensional Tolerances

The anodizing process converts aluminum to an oxide at the surface to a depth of approximately 0.025 mm (0.001 inch) and then grows it out an additional 0.025 mm (0.001 inch). This dimensional change must be accounted for in the component design and then controlled accurately during anodizing. Post-anodizing machining (grinding, lapping, or honing) operations are required to reproduce original dimensions and tolerances.

Sharp corners and edges on components must also be avoided. Outside edges do not support the oxide coating and it can easily be chipped. On inside corners sharp edges result in voids or thin coatings.

Final Finish Roughened

Hardcoat anodizing usually produces a roughening effect on the anodized surface. The increase in surface roughening is not predictable and is affected by many factors including the base alloy, the mechanical condition of the machined surface, and the thickness in the grown coating. Again refinishing is required post-anodizing to regenerate the original surface finish.

IBED coating technology and IBED-deposited hardcoats can circumvent may of these limitations[4] and if it can be proven that IBED coatings can be successfully deposited on aluminum and titanium alloys it would enable substitution of these lightweight alloys for many components in a variety of applications.

## Abrasive Wear Measurements

Sets of sample disks were prepared for anodizing and IBED coating and subsequent wear testing. The alloys chosen for the experiment included; aluminum (5056), commercially pure titanium (CP), titanium alloy (Ti6Al-4V), and nickel (200). All disks were approximately 9.5 cm (3.75 inches) in diameter and 0.16 cm (0.0625 inches) thick. The surfaces to be anodized and IBED coated were polished to the same finish by running the uncoated disks on a Taber Abraser[5] for 2,000 cycles with a CS-10 resilient abrasive wheel. The wheel was loaded with a 1 kg (2.2 pound) weight. The CS-10 wheel contains 50 micron ($1x10^{-6}$ meter) diameter aluminum oxide grits which produce a surface finish equivalent to that generated by polishing with 600 grit abrasive. All of the sample disks therefore had a uniform, equivalent surface finish in the wear track area.

### Taber Wear – Uncoated Base Alloys

Prior to testing coated samples, the abrasive wear rates of uncoated alloy samples were measured with the Taber Abraser (according to the AMS 2438A test standard[6]) to establish a baseline of the abrasive wear rates of the various alloys. A CS-10 resilient wheel, loaded with a 1 kg (2.2 pound) weight was used for the measurement. The wear rate measured in units of microns per 10,000 cycles is tabulated in Table 1 and plotted in Fig. 1. The wear rate of industrial hard chrome is listed as a reference point. The aluminum is the least resistant to abrasive wear, followed by the titanium alloys, then nickel, with the industrial hard chrome the most resistant to abrasive wear.

***Table 1 Wear Rates of Uncoated Substrates (CS-10 Wheel)***

| **Uncoated Substrate Material** | |
|---|---|
| **Material** | **Wear (μ/10,000 Cycles)** |
| Al (5056) | 20.7 |
| Ti (CP) | 18.5 |
| Ti-6Al-4V | 12.1 |
| Ni (200) | 6.5 |
| Hard Cr | 0.4 |

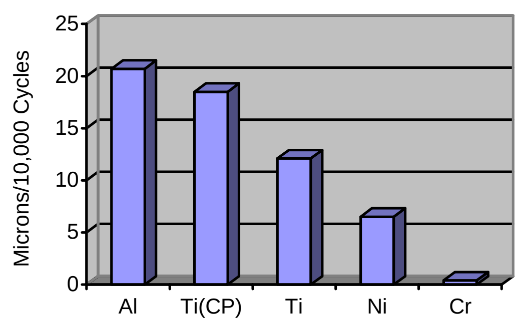


***Figure 1: Abrasive wear rate comparison for untreated alloys (CS-10 wheel).***

### Sample Disk Treatments

Sets of sample disks were treated by anodizing and IBED coating and submitted to wear testing using the Taber Abraser according to the AMS-2438A test standard to compare the relative wear resistances. The anodizing treatments and IBED coatings applied to the sample disks are summarized in Table 2. The aluminum anodizing[7] was done according to the standard defined in MIL-A-8625F. Titanium anodizing[8] was done according to the standard defined in AMS-2488D[9].

*Table 2 Treatment Specifications*

| Treatment | Standard | Thickness |
|---|---|---|
| Anodized (Aluminum) | MIL-A-8625F (Type III) | 50 microns |
| Anodized (Titanium) | AMS-2488D (Type 2) | < 2.5 microns |
| IBED TiN | | 4 microns |
| IBED $Cr_2N$ | | 4 microns |

The abrasive wear resistant performance of the coated samples was then measured with the Taber Abraser Test.

### Taber Wear of Anodized Aluminum

An aluminum alloy (5056) disk was Type III anodized per MIL-A-8625. The anodized layer was 0.025 mm (0.001 inch) deep and thick. The surface in the wear track area was polished to a 50 micron finish prior to anodizing. The abrasive wear resistance of the anodized aluminum disk expressed in units of microns per 10,000 cycles is tabulated in Table 3.

*Table 3 Wear of Type III Anodized Aluminum*

| Type III Hard Coat Anodized | | |
|---|---|---|
| **Material** | **Taber Wheel** | **Wear (µ/10,000 Cycles** |
| Al (5056) | CS-10 | 1.7 |
| Al (5056) | CS-17 | 3.5 |

The anodized layer met specifications of MIL-A-8625 that requires the total mass loss of the anodized layer when abraded with a CS-17 wheel (abrasive grit size of 150 microns) be less than 35 mg. In this case the mass loss was 27 mg. The Type III hard coat anodize treatment improves the wear resistance of the aluminum by a factor of 12X.

### Taber Wear of Anodized Titanium

Pure titanium (CP) and titanium alloy (Ti-6Al-4V) disks were anodized per AMS-2488D. Prior to anodizing the surfaces in the wear track area were polished to a 50 micron finish. The abrasive wear resistances of the anodized titanium disks expressed in units of microns per 10,000 cycles are tabulated in Table 4.

*Table 4 Wear of Type 2 Anodized Titanium*

| Type 2 Anodic Treatment | |
|---|---|
| **Material** | **Wear (µ/10,000 Cycles)** |
| Ti (CP) | 20.0 |
| Ti-6Al-4V | 11.9 |

The Type 2 anodic treatment of both the CP titanium and the Ti-6Al-4V alloy did not improve the abrasive wear resistance of either alloy by any significant amount.

### Taber Wear of IBED Hardcoated Alloy

Sets of aluminum, titanium, and nickel disks were prepared by polishing the wear track areas to a 50 micron finish and then IBED coated with TiN and $Cr_2N$. The abrasive wear resistances of the IBED coated disks expressed in units of microns per 10,000 cycles are tabulated in Table 5.

*Table 5 Wear of Hardcoated Aluminum, Titanium, and Nickel Alloys*

| IBED Hardcoated Substrates | | |
|---|---|---|
| **Material** | **Wear (µ/10,000 Cycles)** | |
| | **TiN** | **$Cr_2N$** |
| Al (5056) | - | 0.47 |
| Ti (CP) | 0.04 | 0.24 |
| Ti-6Al-4V | 0.06 | 0.06 |
| Ni (200) | 0.02 | 0.13 |

The wear rates of IBED TiN coatings deposited on Ti (CP), Ti-6Al-4V, and Ni are all of the same order of magnitude. (An IBED TiN coating was not deposited on the Al alloy because of time constraints.) The wear rates of IBED $Cr_2N$ coatings deposited on Al, Ti(CP), Ti-6Al-4V, and Ni showed wider variations than did the IBED TiN coatings.

### Wear Rate Comparisons - Aluminum

The abrasive wear rates of untreated, Type III hard coat anodized, and IBED coated ($Cr_2N$) aluminum are plotted for comparison in Fig. 2. Type III hard coat anodizing provides a significant improvement in the wear performance of untreated aluminum (12X). The IBED $Cr_2N$ coating provided an even more significant increase (44X) in the wear performance of untreated aluminum.

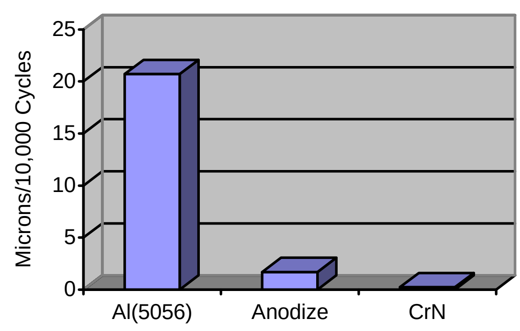


***Figure 2: Abrasive wear rate comparison for untreated and treated Al (5056).***

### Wear Rate Comparisons – Titanium (CP)

The abrasive wear rates of untreated, Type 2 anodized, and IBED coated (TiN and $Cr_2N$) titanium

(CP) are plotted for comparison in Fig. 3. Type 2 anodizing did not provide any improvement in the wear performance of untreated titanium (CP). The IBED TiN and $Cr_2N$ coatings provided an increase of 462X and 77X respectively in the wear performance of untreated titanium (CP).

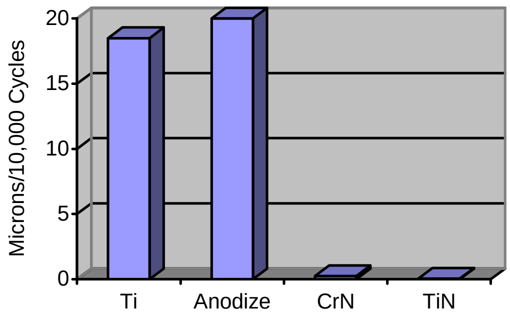


***Figure 3: Abrasive wear rate comparison for untreated and treated Ti (CP)***

### Wear Rate Comparisons – Ti-6Al-4V

The abrasive wear rates of untreated, Type 2 anodized, and IBED coated (TiN and $Cr_2N$) Ti-6Al-4V are plotted for comparison in Fig. 4. Type 2 anodizing did not provide any improvement in the wear performance of untreated Ti-6Al-4V. The IBED TiN and $Cr_2N$ coatings both provided an increase of 200X in the wear performance of untreated Ti-6Al-4V.

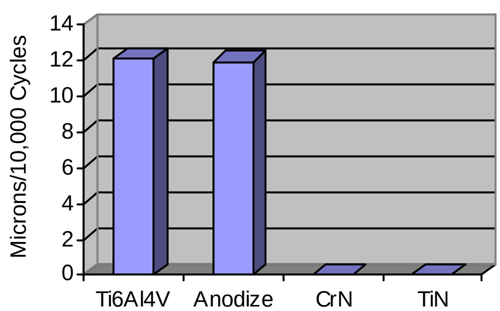


***Figure 4: Abrasive wear rate comparison for untreated and treated Ti-6Al-4V.***

### Wear Rate Comparisons – Nickel

The abrasive wear rates of untreated, and IBED coated (TiN and $Cr_2N$) nickel-200 are plotted for comparison in Fig. 5. The IBED TiN and $Cr_2N$ coatings provided an increase of 325X and 50X respectively in the wear performance of untreated nickel-200.

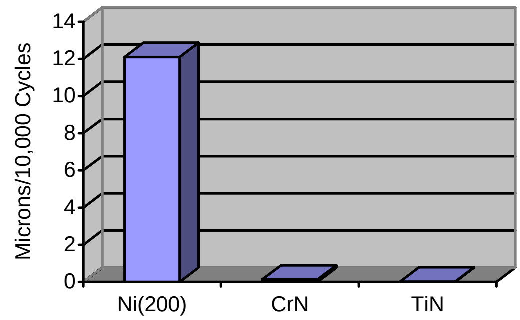


***Figure 5: Abrasive wear rate comparison for untreated and treated Ni-200.***

### Results and Conclusions

The increase in abrasive wear-resistance provided by the anodizing and IBED hardcoating treatments is summarized in Table 6. The data in this table is expressed as a wear-resistance increase factor that is calculated by dividing the wear rate measured for the coated disk by the wear rate measured for the corresponding uncoated disk.

***Table 6 Summary of Increases in Wear Resistance***

| Wear Resistance Increase Factors | | | | |
|---|---|---|---|---|
| **Base Material** | **Anodizing** | | **IBED Coating** | |
| | **Type III** | **Type 2** | **TiN** | **$Cr_2N$** |
| Al (5056) | 12X | na | - | 44X |
| Ti (CP) | na | 0.9X | 462X | 77X |
| Ti6Al4V | na | 1X | 200X | 200X |
| Ni-200 | na | na | 325X | 50X |

Type III hardcoat anodizing provided the expected increase in abrasive wear-resistance on the aluminum (5056) alloy. IBED $Cr_2N$ provided an additional 4X increase in abrasive wear-resistance compared to the Type III hard coat anodizing. IBED TiN coatings were not deposited or tested on aluminum because of time constraints.

The Type 2 anodizing specified for titanium and titanium alloys did not provide any significant increase in abrasive wear-resistance. This was as expected since the Type 2 anodizing is most often specified to be used in conjunction with lubricants to reduce galling wear. Significant increases in abrasive wear-resistance were however provided by both the IBED coatings on pure titanium and titanium alloy.

Both of the IBED coatings deposited on nickel also showed significant increases in abrasive wear-resistance. The TiN performed better by a factor of 6X compared to $Cr_2N$.

Significant increases in the abrasive wear-resistant performance of aluminum, titanium, and nickel alloys can be achieved through the application of IBED hardcoatings. The results of the Taber Abraser tests confirm that TiN and $Cr_2N$ hardcoatings can be deposited on these non-ferrous alloys and these coatings will exceed the wear resistance provided by conventional hard anodizing treatments for aluminum and titanium alloys.


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Hard coat anodizing of the aluminum samples was done by the Luke Engineering & Manufacturing Co., 456 South Boulevard, Wadsworth, Ohio, 44282.

Anodizing of titanium and titanium alloy samples was done by the Tiodize Company, Inc. 455 Bryant Street, Wadsworth, California, 14120.


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