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FRETTING WEAR-RESISTANT, MICRO-ARC OXIDATION COATINGS FOR ALUMINUM AND TITANIUM ALLOY BEARINGS (PREPRINT)

K.J. Choppy, R.F. Kovar, and B.M. Cushman

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14. ABSTRACT
This report was developed under a SBIR contract, and has been released to the public by Infoscitex. Aluminum and titanium alloys are used as replacements for steel in gear boxes of aircraft and helicopters in both military and commercial air vehicles, due to their low density, mechanical strength and thermal conductivity. However, these alloys are susceptible to fretting wear when matched to harder steel surfaces under high loads at elevated temperatures. Anodized coatings are too thin and porous to protect these metals. Infoscitex applied a proprietary micro-arc oxidation process to produce hard, thick, and adherent oxide coatings on aluminum and titanium alloys that rendered the coated metal components resistant to fretting type wear. Selected aluminum and titanium alloy test specimens were micro-arc treated then measured for surface hardness, roughness, and adhesion to metal substrate. Block-on-Ring fretting wear tests on polished test specimens against M-50 steel were conducted in the presence of lubricant, under high loading, at ambient and 400 °F temperatures. Coefficient of friction and wear volume were measured versus number of test cycles. The results of efforts to improve the fretting wear resistance of aluminum and titanium alloy bearings for use in aircraft gear box applications will be discussed.

15. SUBJECT TERMS
SBIR Report, Microarc coating, fretting wear, aluminum and titanium alloy

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Fretting Wear-Resistant, Micro-Arc Oxidation Coatings for Aluminum and Titanium Alloy Bearings

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Aluminum and titanium alloys are used as replacements for steel in gear boxes of aircraft and helicopters in both military and commercial air vehicles, due to their low density, mechanical strength and thermal conductivity. However, these alloys are susceptible to fretting wear when matched to harder steel surfaces under high loads at elevated temperatures. Anodized coatings are too thin and porous to protect these metals. Infoscitex applied a proprietary micro-arc oxidation process to produce hard, thick, and adherent oxide coatings on aluminum and titanium alloys that rendered the coated metal components resistant to fretting type wear. Selected aluminum and titanium alloy test specimens were micro-arc treated then measured for surface hardness, roughness, and adhesion to metal substrate. Block-on-Ring fretting wear tests on polished test specimens against M-50 steel were conducted in the presence of lubricant, under high loading, at ambient and 400^{o}F temperatures. Coefficient of friction and wear volume were measured versus number of test cycles. The results of efforts to improve the fretting wear resistance of aluminum and titanium alloy bearings for use in aircraft gear box applications will be discussed.

Introduction

Infoscitex Corporation developed a surface modification process using microarc oxidation that will reduce wear on aluminum and titanium alloy gear boxes and other structures on military and civilian aircraft and helicoptors. Our long term solution for this process would be to replace steel inserts currently used in gear boxes with a coated aluminum or titanium alloy that will provide greatly improved wear resistance, increased hardness, and decreased weight and complexity of the entire rotating mechanism.

The overall objective of this department of defense funded program was to demonstrate the feasibility of using microarcing techniques to provide a wear resistant coating for aluminum and titanium alloys. The objectives discussed in this manuscript focused on establishing the feasibility of using microarcing on aluminum and titanium alloy surfaces to reduce wear and increase hardness, thereby reducing the amount of steel required in aircraft gear boxes.

Traditional anodizing is not strong enough to support high fretting wear environments. It produces coatings that are quite porous, and it does not increase thickness efficiently [1]. Therefore, many aerospace and automotive parts cannot be satisfactorily anodized, if at all [2].

Experimental

Infoscitex Corporation evaluated two microarc oxidation vendors and chose Whyco Finishing Technologies (Thomaston, CT). Founded in 1946, Whyco operates out of a 120,000 sq. ft. facility and is one of the largest high volume specialized surface finishing companies in the country. They perform both traditional anodizing and offer their CeraFuse Process, a typical microarc ceramic deposit. The outer layer is generally removed by polishing, tumbling or other method before parts are put into service. The hard, dense ceramic is formed by the conversion of the substrate surface into a predominately alpha phase ceramic. In order to get a secure electrical contact, the coating process requires a 10-32 screw hole for processing. Infoscitex held an initial meeting with Whyco and determined to work with Whyco to develop an optimal wear-resistant coating process for the materials under examination in our program due to their ability to support larger parts and long-term scale-up during additional program funding.

Infoscitex obtained 10 microarc coated samples of each of the Aluminum 2219 and Titanium 6Al-4V from Whyco Finishing Technologies. The average measured dimensions of the coated and uncoated blocks are shown in Table I below. Simultaneously, we had Aluminum 2219 traditionally anodized from Metalast (Minden, Nevada) for evaluation in fretting / reciprocating wear testing as well for comparison against the microarc coated samples.

The first tests were completed following ASTM G77 for block on ring wear testing (see Figure 1) to assess the susceptibility of selected substrates to wear. Initial testing utilized M50 steel rings as the counter surface to uncoated aluminum and titanium alloys. The geometry of the M50 ring is 0.321" wide by 1.3775" diameter, and for the test blocks is 0.25" wide x 0.620" long. These tests served as a baseline for assessing the ability of candidate coating processes to impart a wear-resistant nature to the targeted alloys. Falex Testing Corporation (Sugar Grove, IL) provided the ring on block testing service. The Block-on-Ring Test Conditions were as follows:

- 75 RPM
- Ambient Temperature

- 10 lb (44.4 N) load
- 4500 cycles
- No lubrication
- Repeated 3 times

The second tests were ball on flat fretting wear tests. The Infoscitex team decided to use the testing conditions shown in Table II. The test loading conditions on the samples are shown in Figure 8. The load used for the initial tests was 10 Newtons, in a TE77 Plint fretting/reciprocating wear system utilizing a Ball on Flat configuration. The displacement selection was chosen based on which amplitude would show reciprocating wear, just above 400 μm [3]. Weight loss was measured after each test.

Results

Block on Ring Wear Testing

The wear scar produced by the loading conditions in the block on ring tests are shown in Figure 2. Representative wear test data are shown below for each test sample. The block scare image and information are shown on the left and the friction forces were recorded and plotted over the 4500 cycles, as shown in the right of Figure 3, depicting results of the best performing test substrate, M50 Steel vs Microarc Coated Aluminum. Figure 4 shows a coefficient of friction summary of all test sample results.

SEM Micrographs, as well as EDS for elemental composition analysis of the surface were taken of each test sample at Analytical Answers (Woburn, MA). The images of the sample which performed the best, the microarc coated Aluminum are shown below in Figures 5 through 7. The EDS images compare the worn area to the unworn area and the presence of Si is much higher in the unworn area, a factor of the coating itself. The worn area shows presence of Fe, contributed to the fact that M50 steel was the counter surface. The composition of Aluminum increased, showing exposure to the base material, but the presence of Si indicates that the coating was still intact.

Ball on Flat Fretting Wear Testing

During fretting wear tests there was very little mass lost during testing of the microarc coated samples. Negative weight loss on the Ti 6-4 at 70°F indicates transfer of M50 steel material on to the test sample. The anodized aluminum and steel samples did not hold up as well against the M50 as the microarc coated samples did. Full results are shown in Table III. SEM images were taken of each of the samples. Images of the best performing sample, the microarc coated Aluminum 2219 are shown in Figures 9 through 12 in the following order:

- Microarc Coated Al2219 at 10N load, 77°F
- Microarc Coated Al2219 at 10N load, 400°F
- Microarc Coated Al2219 at 50N load, 77°F

Discussion

Ring on Block Wear Testing

The wear scar images show that the microarc coated Aluminum 2219 was much more resistant to wear against the M50 steel than the microarc coated Titanium 6Al-4V. These samples were run dry (no lubrication) to allow us to observe actual wear scars. The coating treatment did reduce the wear scar for the Titanium as compared to untreated Titanium, and the friction force dropped off after the outer layer of coated material was worn away, revealing the harder inner layer. The wear scar on the microarc coated

Aluminum was drastically smaller than the untreated aluminum sample, showing the effectiveness of the coating.

The SEM images of the titanium treated block show the porous outer layer of the unpolished coated sample as well as the uncoated sample against the wear track. The EDS displays that Titanium is mostly dominant on the worn area of the coated sample, indicating that the wear test broke through the coated outer layer; where the EDS of the unworn area shows a high amount of Silicon, the major element present in the coating. The EDS of the uncoated titanium shows that there may be some elements from the M50 that were deposited on the worn area during testing.

The SEM images of the untreated aluminum clearly shows the wear area edge, where the SEM images of the treated aluminum show much less of a scar in the worn area. This is one indication that the coating was wear resistant to the M50 ring. The SEM of the M50 test ring used against the coated aluminum showed some damage, indicating that the coated block was stronger than the M50 test ring. Finally, the EDS of the coated aluminum block worn area still displayed some amounts of Silicon, showing that the coating was still present. The EDS of the aluminum block's worn area showed some amounts of Iron, indicating some deposit of the M50 on the uncoated test block that was not present in the unworn area.

Ball on Flat Fretting Test

The one million cycles, 500 µm, 50 Hz. fretting tests conducted showed very minimal damage in both microarc treated Aluminum 2219 and Titanium 6Al-4V samples. Similar wear scars were observed at 10N and ambient temperature (77°F) for both metals.

The fretting test of microarc treated Aluminum 2219 at 400°F indicated greater wear, as was to be expected because the lubrication breaks down at such a high temperature, and the part was subject to some fretting wear damage, but some of the coating looks to have remained intact and we did not completely wear through the hard microarc coating.

Weight loss on the microarc coated samples was nearly immeasurable, with the test configuration at the Pennsylvania State University Tribology Lab. The anodized aluminum did not hold up as well during the fretting testing, with average mass loss of 3mg on each sample tested at 400°F. The 4340 steel baseline samples also did not hold up as well as the microarc coated Aluminum, with mass loss of 2mg and 3mg respectively, at 400°F and 77°F.

Microarc treated Aluminum 2219 at 50N and ambient temperature (77°F) showed more significant results, including oxidation and M50 transfer. The transfer of M50 onto the Aluminum 2219, however, indicates that the aluminum sample withstood the harsher test conditions, and the M50 failed. Additionally, small weight gains were observed on the microarc coated Ti6-4 at 400°F and 4340 steel at 77°F, indicating possible steel transfer onto the fretted surface. After transfer, self-mating M50 on M50 would then accelerate fretting and damage. Rust was also observed on some surfaces. Iron oxide buildup is harder than aluminum oxide, and could do damage in long term applications.

Finally, lubrication has minimized the wear on these samples, but complete influence of the lubricant can not be determined without un-lubricated baseline tests.

Conclusions

In conclusion, anodized coatings are too thin and porous to protect aluminum and titanium alloys used in air craft gear boxes and other high fretting environments. Infoscitex applied a proprietary micro-arc oxidation process to produce hard, thick, and adherent oxide coatings on aluminum and titanium alloys that rendered the coated metal components resistant to fretting type wear. Selected aluminum and titanium alloy test specimens were micro-arc treated, other samples were anodized, and then all samples measured for fretting wear as compared to baseline steel. Block-on-ring and Ball-on-flat fretting wear tests on polished test specimens against M-50 steel were conducted in the presence of lubricant, under high loading, at ambient and 400°F temperatures. Coefficient of friction and wear volume were measured versus number of test cycles and the micro-arc coated samples were able to withstand the high fretting environments better than the baseline steel and traditional anodized coatings. The next step would be to modify the microarc coating process for other substrates such as Titanium to maximize fretting wear protection. Variables such as concentration of the electrolyte, treatment time, and current density can be altered to affect the coating thickness which, consequently, also affects coating hardness [4].

References

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Tables

Table I. Test block dimensions

	Length	Width	Height
Aluminum Uncoated	0.6215”	0.4035”	0.249”
Aluminum Coated	0.6325”	0.4095”	0.257”
Titanium Uncoated	0.6205”	0.4005”	0.251”
Titanium Coated	0.6280”	0.4110”	0.2545”

Table II. Test Parameters

Parameter	Test Condition
Displacement (amplitude)	500µm
Cycles	10^6
Frequency	50 Hz
Load	10N and 50N
Temperature	77°F (25°C) and 400°F (204°C)
Oil Lubrication	Thin film of Shell Turboil (MIL-L-23699)

Table III. Fretting Test Results

Fretting Tests at ~50Hz					
Reciprocating distance:	.5mm=500 microns		**Test Duration:**	5.6 Hours	
Material	**Original Mass (g)**	**Final Mass (g)**	**Mass Loss (g)**	**Final Temp (C)**	**Load (N)**
Microarc 2219 Al	NA	NA	NA	23	10
Microarc 2219 Al	2.833	2.833	0	30	50
Microarc 2219 Al	2.838	2.838	0	208	10
Microarc TiAl6:V4	2.273	4.272	-1.999	23	10
Microarc TiAl6:V4	4.276	4.276	0	204	10
2219 Al (Anodized I)	2.451	2.448	0.003	204	10
2219 Al (Anodized II)	2.454	2.451	0.003	204	10
2219 Al (Anodized III)	2.444	2.441	0.003	204	10
2219 Al (Anodized)	2.45	2.451	-0.001	23	10
4430 Steel	8.344	8.341	0.003	23	10
4430 Steel	8.324	8.322	0.002	204	10

Figure Captions

1. Block on Ring Wear Test Conditions
2. Wear Scars on Coated and Uncoated Samples
3. Friction Force and Temperature of Coated Aluminum
4. Coefficient of Friction Data for All Wear Tested Samples
5. SEM image of Coated Aluminum after Wear Test
6. EDS of Coated Aluminum Worn Area
7. EDS of Coated Aluminum Unworn Area
8. Ball on Flat Fretting Test Loading Configuration
9. SEM of Coated Aluminum at 10N, 77°F
10. SEM of Microarc coated Al 2219 fretting sample tested at 10N, 400°F
11. .SEM of Microarc coated Al 2219 fretting sample tested at 50N, 77°F
12. Further magnified SEM of Microarc coated Al 2219 fretting edge tested at 50N, 77°F

Figures

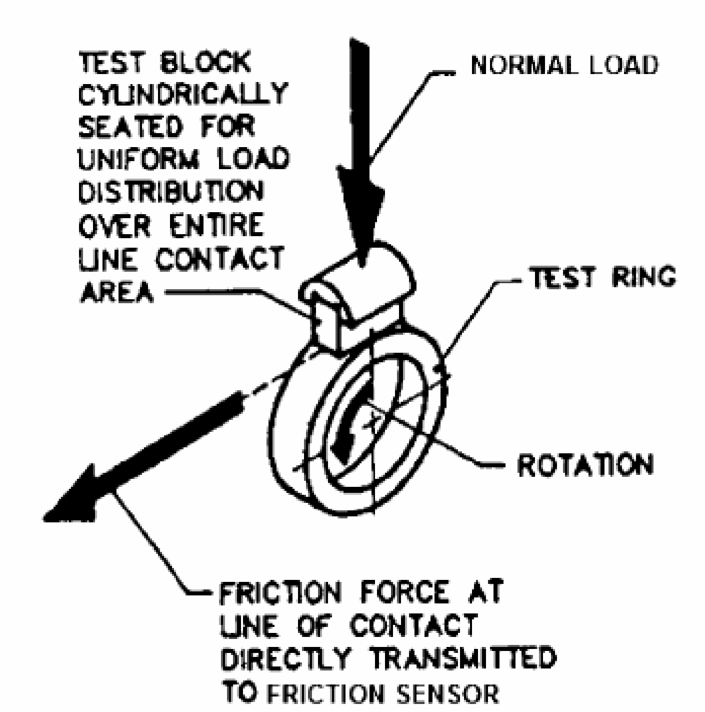


Figure 1.

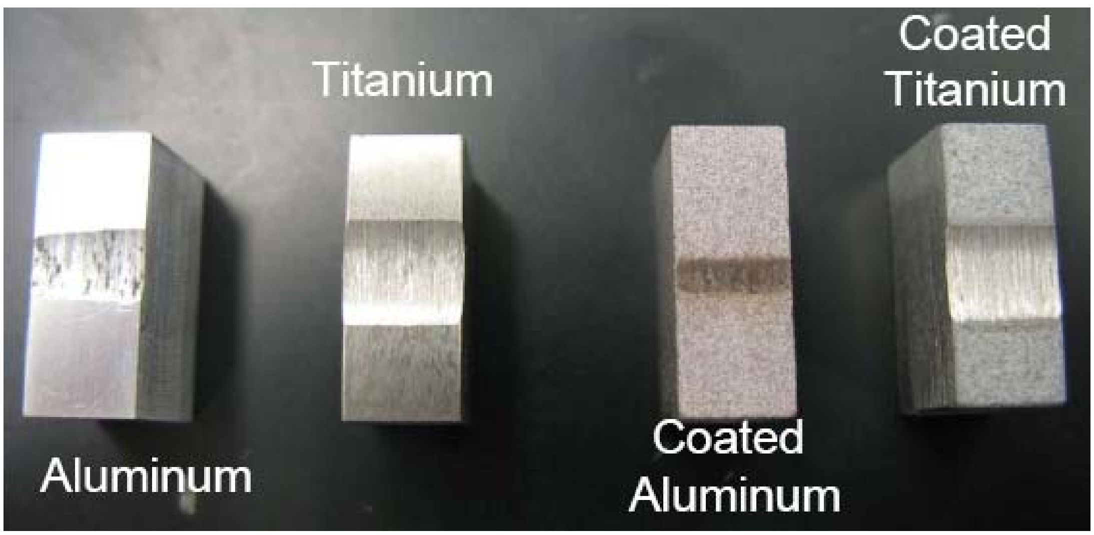


Figure 2

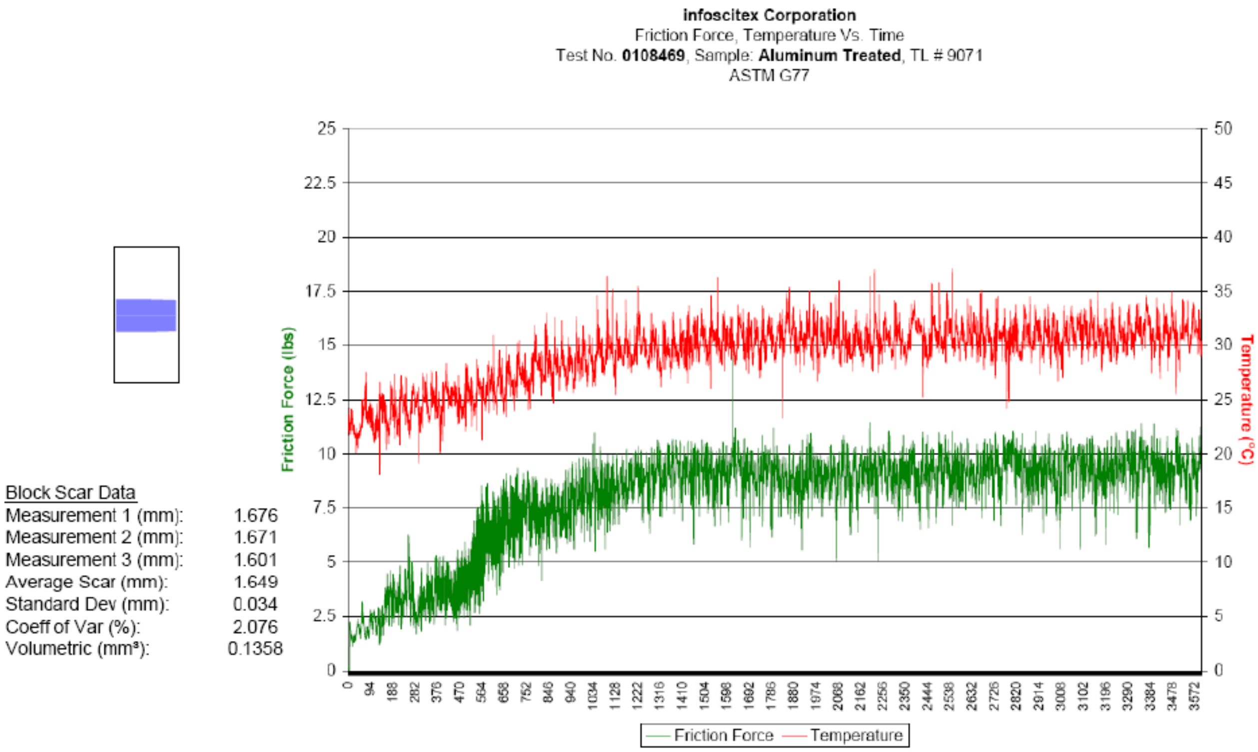

infoscitex Corporation
Friction Force, Temperature Vs. Time
Test No. 0108469, Sample: Aluminum Treated, TL # 9071
ASTM G77
Friction Force (lbs)
Temperature (°C)
Friction Force
Temperature
Block Scar Data
Measurement 1 (mm): 1.676
Measurement 2 (mm): 1.671
Measurement 3 (mm): 1.601
Average Scar (mm): 1.649
Standard Dev (mm): 0.034
Coeff of Var (%): 2.076
Volumetric (mm³): 0.1358

Figure 3

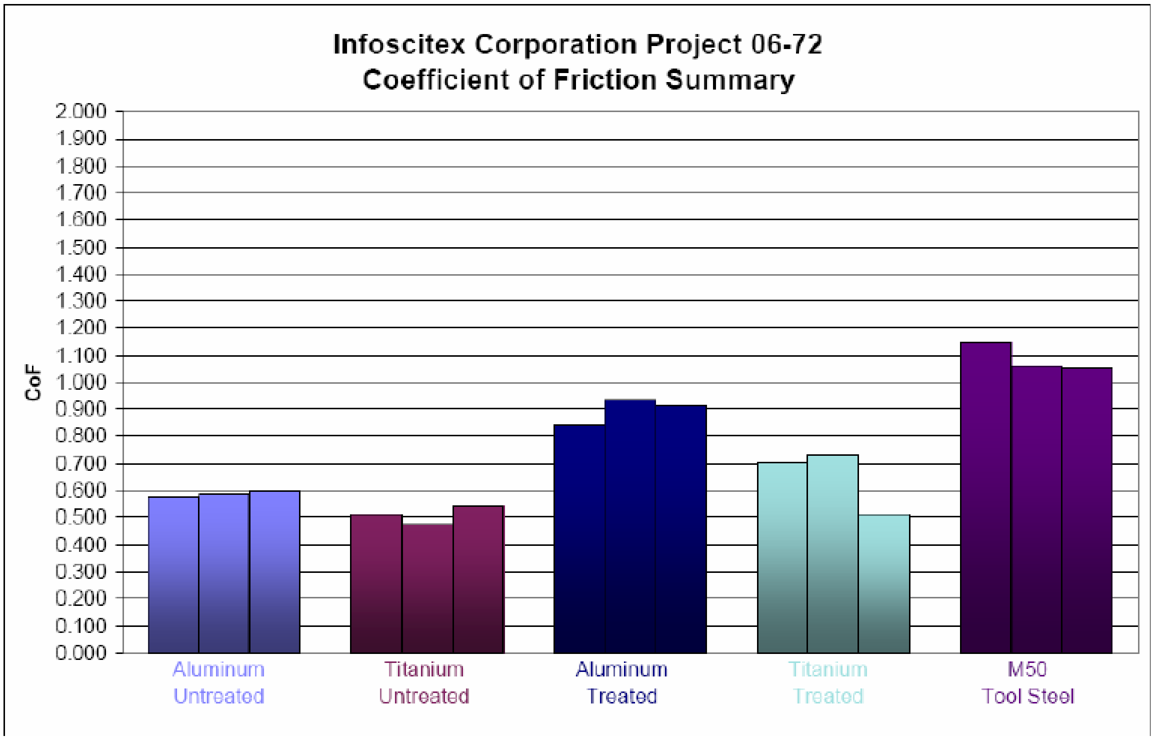
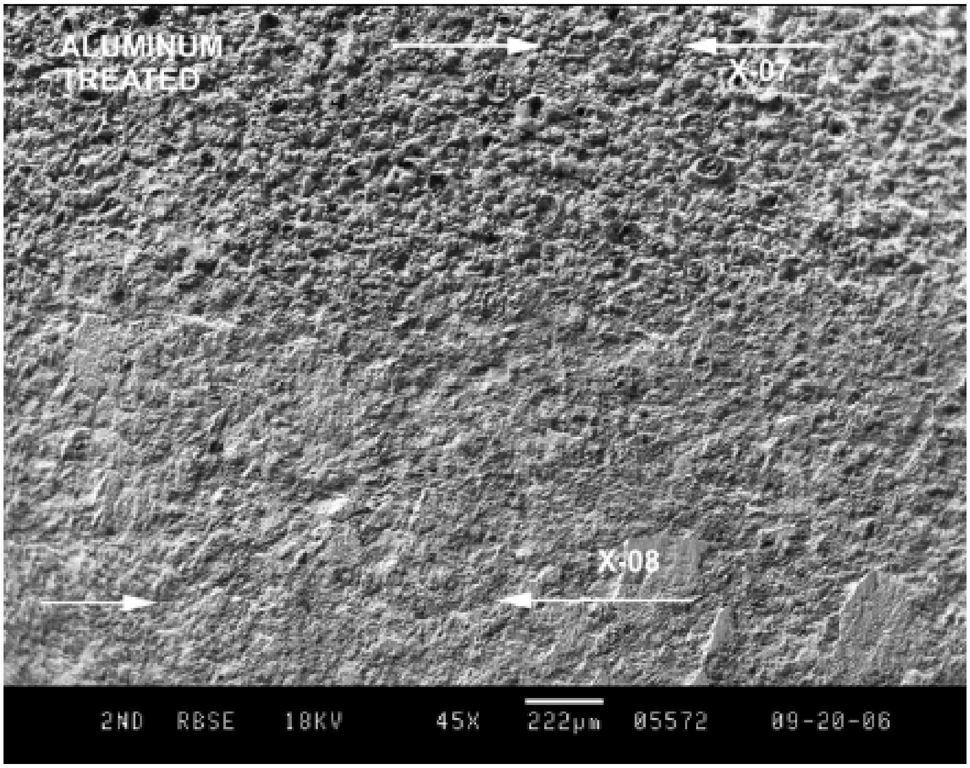

Infoscitex Corporation Project 06-72
Coefficient of Friction Summary
CoF
2.000
1.900
1.800
1.700
1.600
1.500
1.400
1.300
1.200
1.100
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Aluminum Untreated
Titanium Untreated
Aluminum Treated
Titanium Treated
M50 Tool Steel

Figure 4



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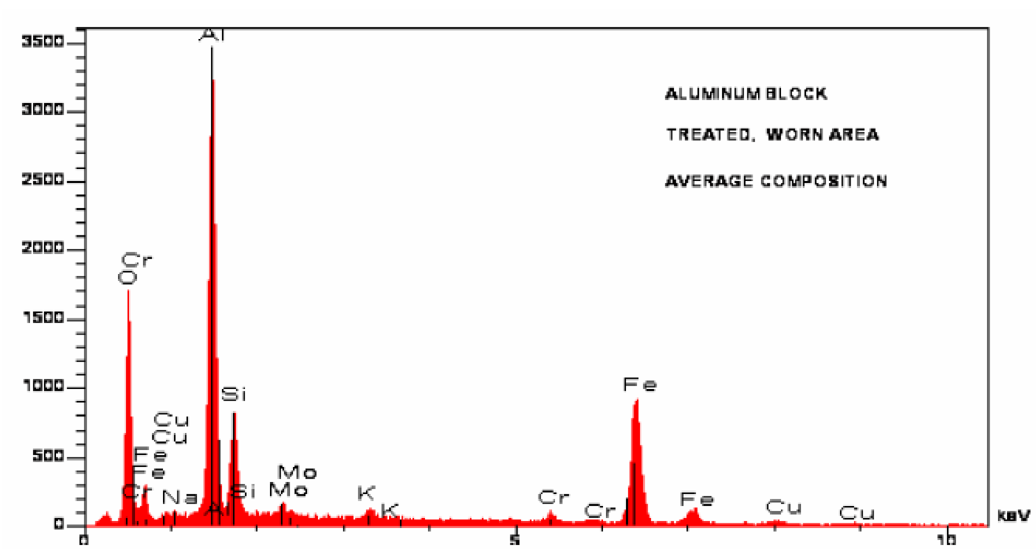

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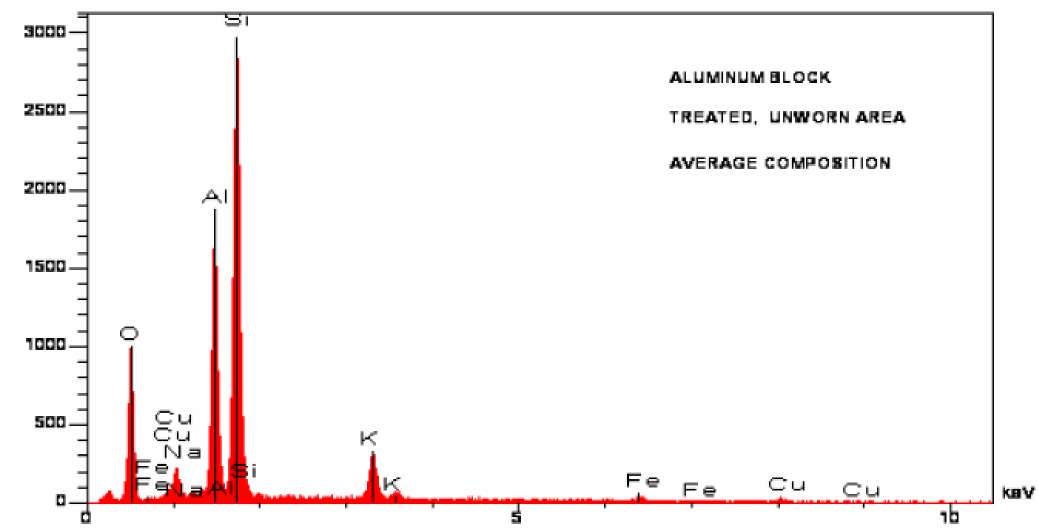

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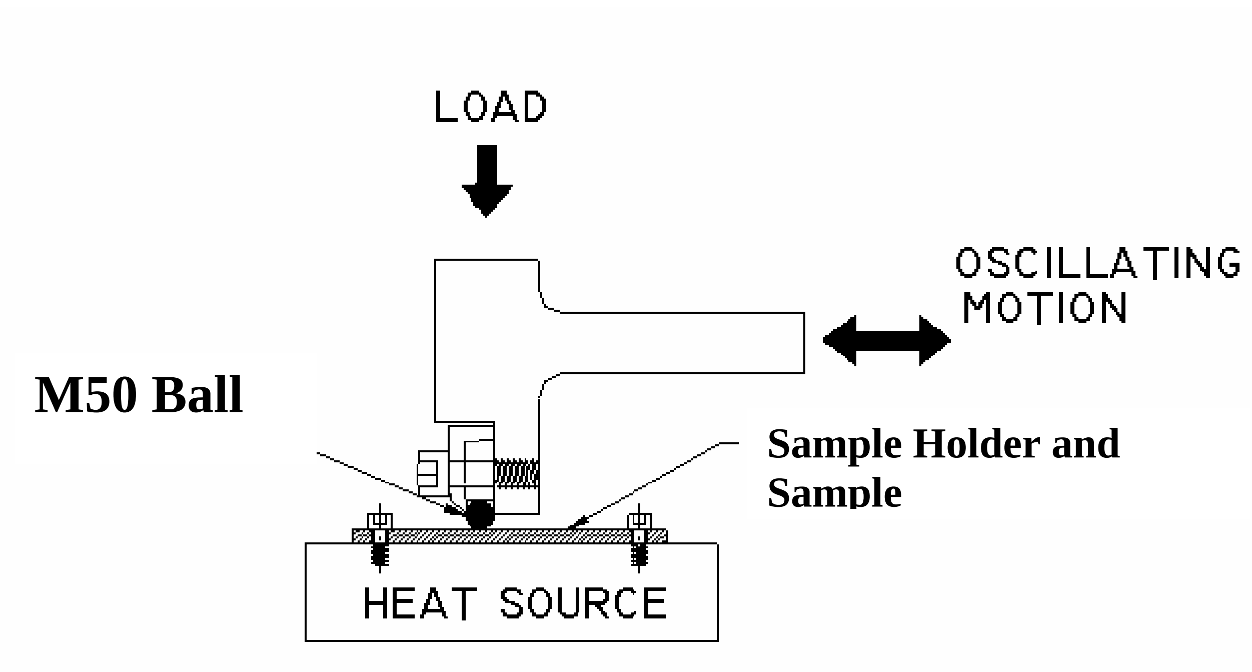

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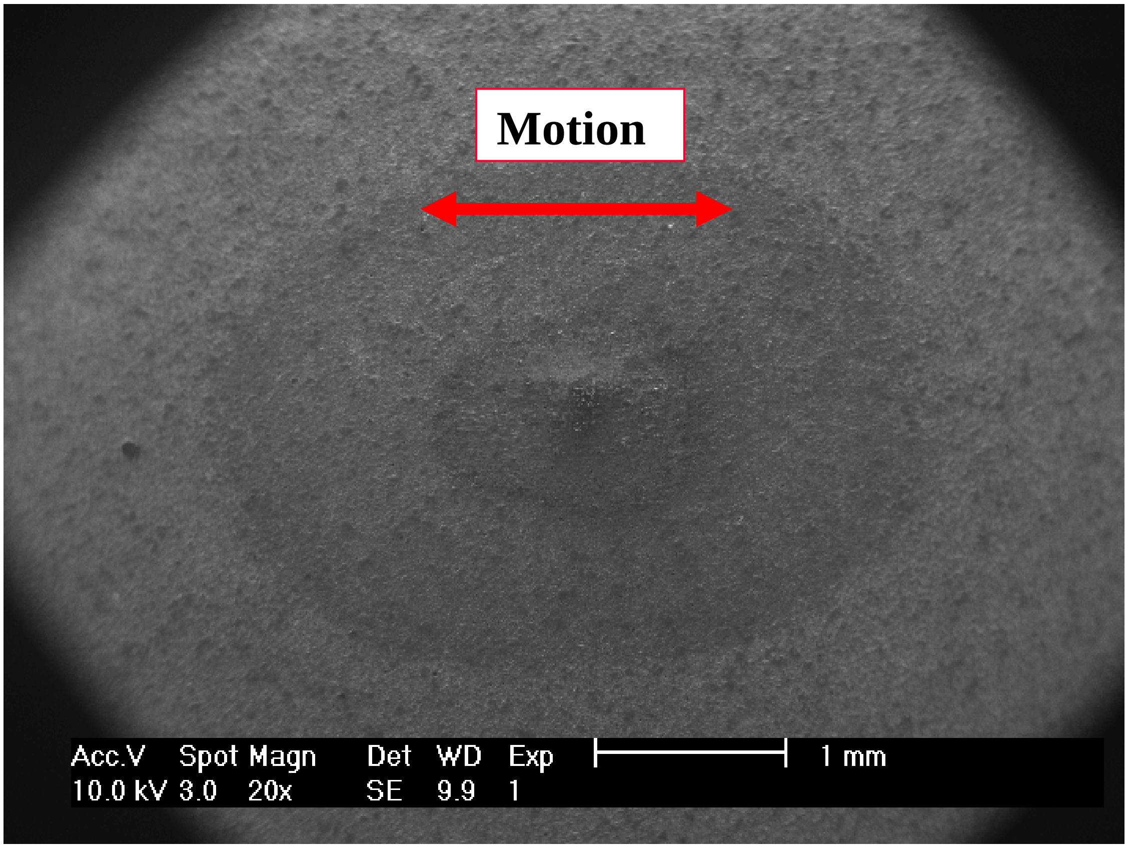

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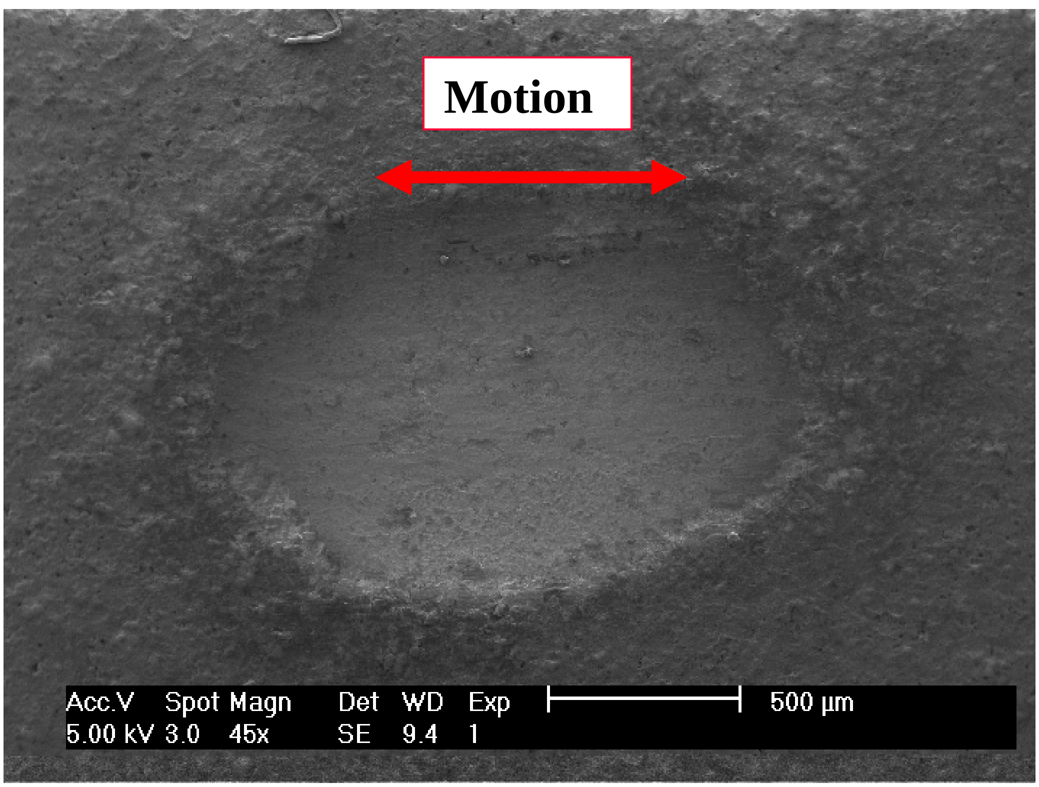

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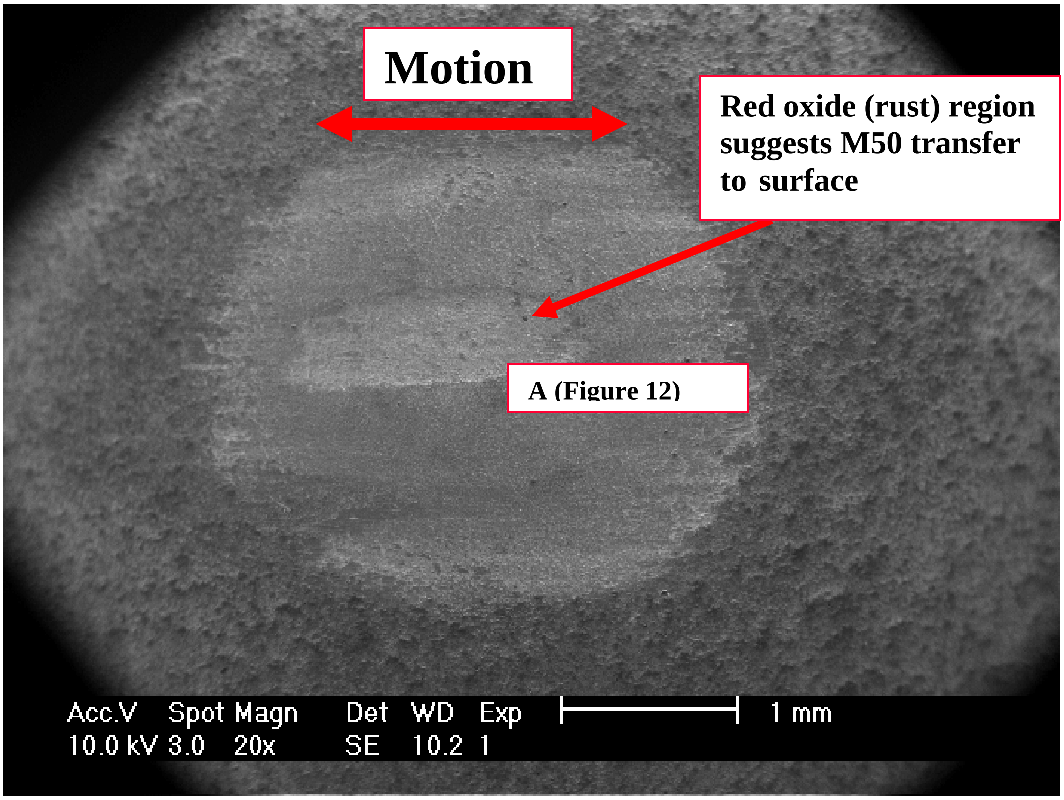

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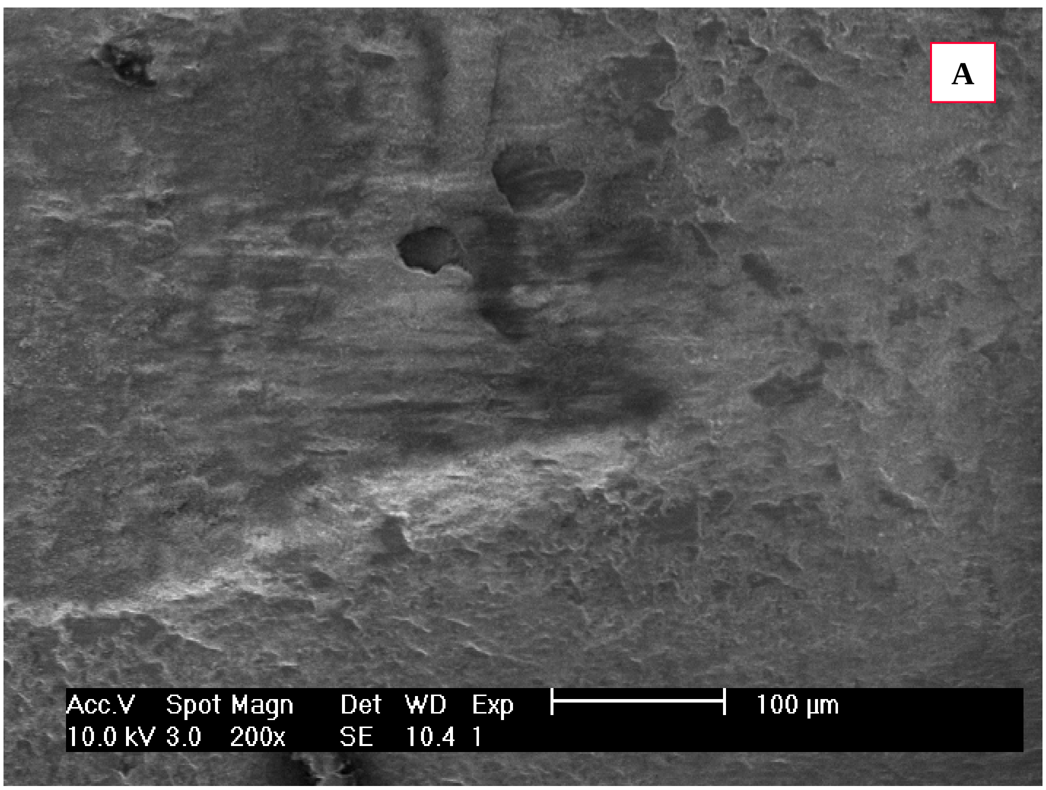

Figure 12.