STUDY OF WEAR BEHAVIOUR AND COATING QUALITY OF ZINC AND CHROMIUM METALLIC COATING ON MILD STEEL SUBSTRATE

By

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Submitted in partial fulfillment of
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(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

(AP Dr. Mustafar bin Sudin)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(FASYIHA AIDA BINTI AZMI)

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Last but not least, to anyone who has assisted me directly or indirectly in making my final year project success, thank you very much. May God repay your kindness.

Thank you

ABSTRACT

In order to provide protection to substrate and increasing substrate material properties, coating is introduced to industry to increase working efficiency and also for economic advantage. There are lot of type of materials used for coating in industry such as zinc, nickel and chromium. In short, this study was conducted to analyze the adhesion and wear behavior of metallic coating using zinc and chromium on mild steel substrate by varying the coating thickness. The coated mild steel sample then will go through several laboratory evaluations such as, friction and micro hardness test. The result from the tests was compared and analyzed. It was found that harder material with smooth surface increased the adhesion strength and wear resistance.

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CHAPTER 1
INTRODUCTION

1.1 PROJECT BACKGROUND

Using a pin-on-disc wear apparatus and adhesion-scratch tester, the wear behaviour and adhesion of zinc and chromium electroplated coatings will be studied. The most important wear mechanism of the above coatings was noted to be extensive plastic deformation and shearing of the coating, due to the ploughing action of the much harder steel spheres [1].

Coating is a covering that is applied to the surface of an object, usually referred to as the substrate. In many cases coatings are applied to improve surface properties of the substrate, such as appearance, adhesion, wetability, corrosion resistance, wear resistance, and scratch resistance. In other cases, in particular in printing processes and semiconductor device fabrication (where the substrate is a wafer), the coating forms an essential part of the finished product.

Through this project, the metallic coating will be used for coating mild steel substrate using zinc and chromium. Metallic coatings provide a layer that changes the surface properties of the substrate to those of the metal being applied. The substrate becomes a composite material exhibiting properties generally not achievable by either material if used alone [21].

1.2 PROBLEM STATEMENT

For rough handling part on component made of metal like mild steel could be prevented from damaging such as wears by coating the substrate material. The quality of this coating material is determine by the strength of the coated materials adhere to the substrate this solution could be prolong the life of mild steel material.

Coating has to be firmly adhered to the substrate to prevent damaging from wears. Therefore, good adhesion strength must be achieved in order to increase wear resistance on substrate material. This will in turn finally enhance the life of coated material because coating failure can be minimize.

However, at present no research on adhesion and wear behavior of locally produced coatings particularly metallic coatings was done. The consumer and the coating producers are unable to justify the adhesion properties i.e. adhesion strength of different metallic coatings to increase wear resistance due to unavailability of data.

The relationship of the coatings adhesion and wear behavior with other parameters such as coating thickness, surface roughness, coating-substrate hardness, coating microstructure is also unavailable. In other words, the effects of the said parameters on the adhesion and wear behavior of coating to base metal are unknown.

The adhesion and wear behavior for different coating properties will have different value. Thus, this study will compare the two metallic coating of zinc and chromium to discover which metallic coating posses greater adhesion properties in order to increase wear resistance.

1.3 OBJECTIVES AND SCOPE OF STUDY

1.3.1 Objectives

The purposes of this research are:

- To study the adhesion and wear of zinc and chromium metallic coating on mild steel substrate.
- To measure the adhesion strength between zinc and chromium metallic coating on mild steel substrate.
- To analyze result from laboratory tests and identify the suitability of using zinc and chromium metallic coating on mild steel substrate for industrial application.

The selection of relevance test will be conducted to establish data for adhesion property and wear behaviour of local made metallic coating using zinc and chromium on mild steel substrate. Its relationship with other property such as coating thickness, surface roughness, coating-substrate hardness, coating's microstructure, surface hardness and coating material are also analyzed.

1.3.2 Scope of Study

The scope of study for this project is to cover samples preparation prior to coating process, deciding the coating parameters and method of coating, allocating potential coating companies and performing essential tests and laboratory examinations to achieve those objectives.

Essentially, the relationship between the adhesion properties and wear behaviour of zinc and chromium metallic coating will be studied. The study of three different coating thicknesses of both zinc and chromium metallic coating on substrate of identical size 40mm x 40mm x 5mm of same base metal, mild steel had been decided.

The scope of study also included study on the factors that contribute to the efficient adhesion and wear of the coated substrate. The factors were substrates' hardness, coating-substrate hardness, substrates' surface roughness and coating-substrates' surface roughness.

The laboratory examination that will be used throughout this study are; microhardness testing, surface roughness testing, scratch testing to measure the adhesion properties and last but not least wear testing using pin on disc apparatus to examine the wear behaviour. Optical microscope also will be used to determine the surface condition after scratch and pin on disc test and also to measure the coating thickness.

CHAPTER 2
LITERATURE REVIEW

2.1 COATING

A continuous cohesive cover in form of a film of different thickness spread in the surfaces of flexible substrates or rigid substrates providing protection, comfort, decoration and durability may be commonly called a coating. Coating also being provided to fine drops of specified liquids and emulsions and to powdery or granular particles of specified solid chemicals, drugs and pharmaceuticals, fertilizers, pesticides and the like, to impart pressure-release or control-release characters to meet technology needs and for efficiency in material use, to minimize wastage and loss of potent materials and for working efficiency along with economic advantage [6].

Saving a surface is as important as, or even more important than, making the surface. Two main function of surface coating are decoration and protection, and in most surface coatings these functions are combined. There are some types of coatings available in industry and the one that will be used to run this project is electroplating.

Adding an extra layer of coating will increase the complexity of the wear process. The elastic properties of the surface contact change in a discontinuous way at the interface; extra stresses can be present between the coating and substrate and producing greater probability of crack initiation. [14]

2.1.1 Electroplating

Electroplating relates to the electrode position of an adherent metallic coating on and electrode to form a surface with properties different from those of the substrate. The substrate acts as an electrode that attracts oppositely charged particles of coating in the dip tank. Technically, the electrode position method is plating process that coat steel or other metal by electrochemical reduction of metallic ions.

The advantages of electroplating to the industries are [6]:

- Improve corrosion resistance
- Attractive appearance
- Improve frictional characteristic
- Higher wear resistance and hardness
- Some desirable and specified electrical properties

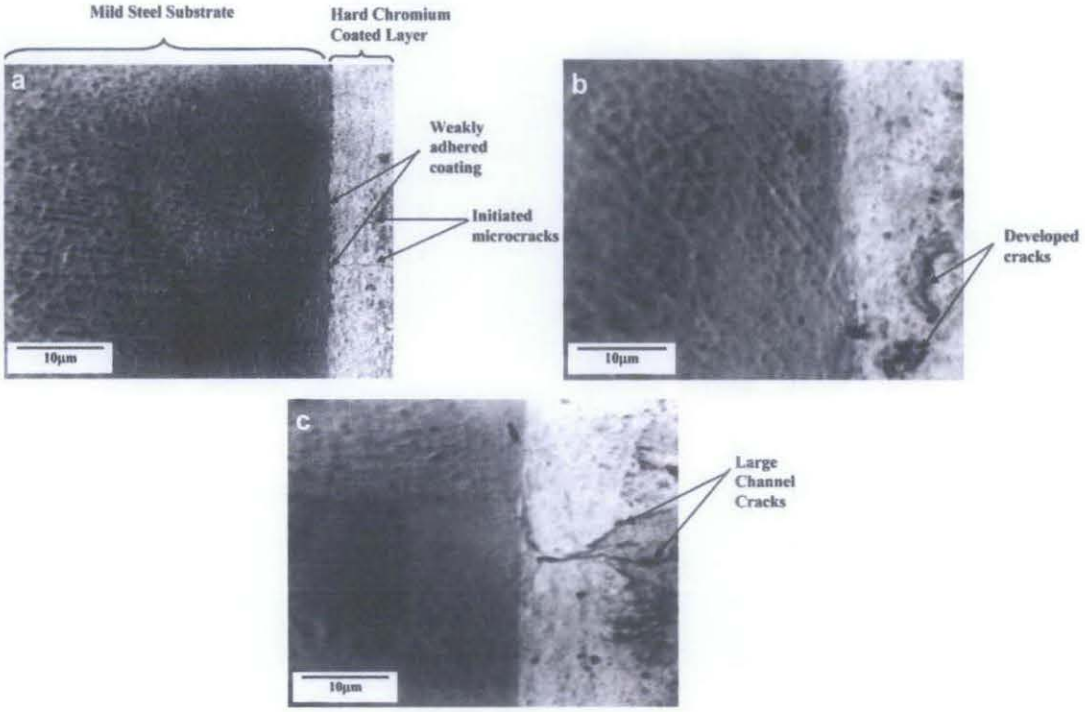

Figure 2.1: Optical micrograph of different coating thickness [22]

Figure 2.1 shows the optical micrograph of three different coating layer of hard chromium coating using electroplating. The different coating thickness was done by varying the coating times which was varied from 5 to 30 minutes [22].

2.2 COATING QUALITY

Coating quality is measured by determine its adhesion strength between the coating material and the substrate. In most cases, a test to measure the coating quality is from destructive quality test. Several laboratory tests are available to determine the coating quality such as Scratch Test and Mercedes Test (VDI 3189). Both scratch and Mercedes test used Rockwell-C indenter. From these test, adhesion properties, nature of coating failure and features of coating failure can be determined. Figure 2.2 and 2.3 shows the illustration of both scratch and Mercedes test. While Figure 2.4 shows the features of coating crack.

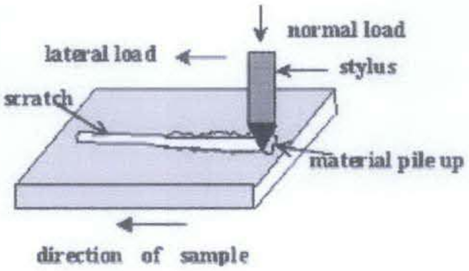

Figure 2.2: Illustration of Scratch Test

Figure 2. 3: Mercedes Test Illustration [23]

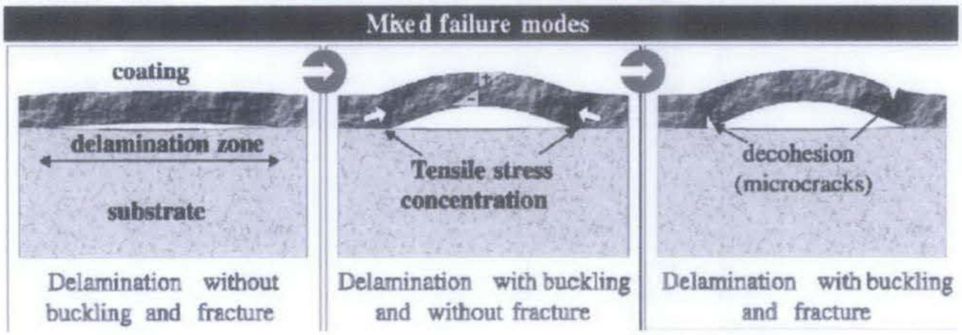

Figure 2.4: Features of Coating Crack [23]

2.2.1 Adhesion

Adhesion is a process by which the two similar or dissimilar adherent surfaces are partly or wholly held together in close contact by:

i. Surface attachment or interfacial forces of attraction consequent to interactions of molecules, atoms or irons in the two (adhesive-adherent) surface facing each other, or by
ii. Mechanical interlocking

The adhesion process is aided in most cases, by the presence of a thin interlayer of an organic resin or polymer, natural or synthetic, manipulated by spreading its solution or melt and allowing the spread-out interlayer to display cohesion by the interplay of solution or melt tack. The interlayer is finally allowed to set and harden by solvent evaporation and/or cooling for strength.

This concept is not to be conventionally applied to metal solders, even though one is inclined to view soldering as an adhesion process in every sense. The two bodies held together by adhesion are called adherents or substrates, even though the latter term may be broadly used for other bodies having different roles or functions. The term “bonding” with respect to adhesives is meant to denote the process of joining or fixing of surfaces together by a process of adhesion, i.e. by adhesive action. The adhesive interlayer, together with adherent-adhesive interfaces on the two sides, is commonly referred as glue-line [6].

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2.3 WEAR

In determining wear performance, we concentrate on tribological coating. The tribological process in a contact in which two surfaces are in relative motion is very complex, since it involves simultaneously friction, wear and deformation mechanism at different levels and of different types [7].

The laboratory test that widely used to measure wear behaviour is Pin on Disc Test. It can be tested by varying its load, temperature, sliding distance or speed. The wear behaviour is determined by interpreting the coefficient of friction, wear and weight loss.

For chromium coated substrate, the expected result for hardness using hardness Vickers with 500g load with different coating thickness was as in Figure 2.1. While Figure 2.2 shows the coefficient of friction of chromium coated mild steel after experienced pin on disc test.

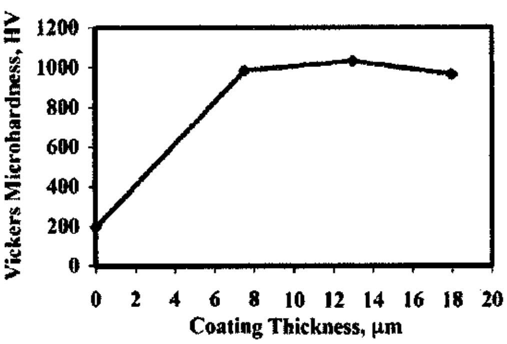

Figure 2.5: Effect of hardness with different coating thickness [22]

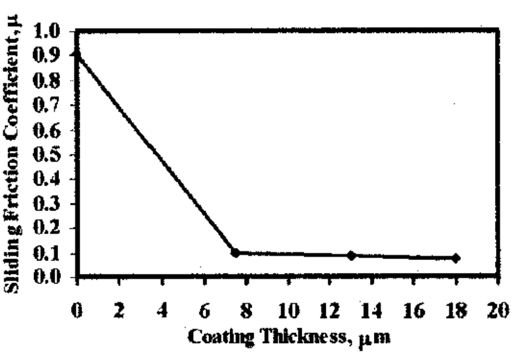

Figure 2.6: Coefficient of friction with different coating thickness [22]

2.4 SURFACE ROUGHNESS

Contact roughness can have a marked effect on the performance of electronic connectors. For example, the porosity of a deposit on the contact is directly related to substrate roughness [12]. Contact wear on engagement and separation has been related to roughness in certain systems, both lubricated and dry [13].

In the present study of sliding wear, it was found that are profoundly affected by surface roughness on a much finer scale then has heretofore, generally been recognize. To minimize wear and reduce friction, the clad metal should be mated to hard gold electrodeposit (i.e., Co- or Ni-doped gold from cyanide bath) [11].

2.5 EFFECT OF COATING THICNESS AND SURFACE ROUGHNESS TO THE COATING SUBSTRATE

As far as wear is concerned, the effect of roughness was much larger than that of coating thickness. From the wear map, it is apparent that for surface roughnesses of 0.1 µm or below, the wear rate does not vary and always remained low (around 10^{-5} mm^3/m). It appears that further reduction in Ra below 0.1 µm will not improve the wear performance. When Ra is above 0.1 µm, the wear increased more rapidly with surface roughness. The wear rate increased by about one order of magnitude when Ra increased from 0.1 to 1 µm. When Ra was 0.5 µm or larger, considerable improvement in wear performance was obtained by increasing the coating thickness from 0.5 to 1 µm. [14]

The extracted results indicated that the mechanical properties and the hardness significantly affect the cutting performance, especially in the case of the thinner coatings. However, in the case of thick coatings (8–10 mm) the effect of the strength and hardness becomes less significant and wear depends mainly on the thickness of the coating itself [15]. Figure 2.7 shows the potential coating microstructure and occurring grain size at various coating thickness.

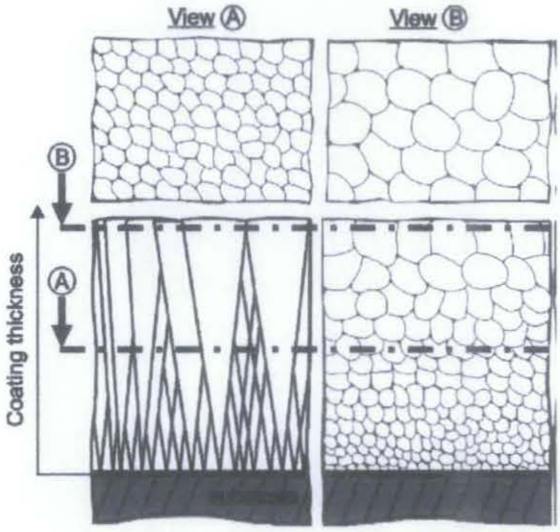

Figure 2.7: Potential coating microstructures and occurring grain sizes at various coating thickness [15]

CHAPTER 3

METHODOLOGY

Methodology section will discussed about the general procedure for mild steel (substrate) sample preparation prior to coating process. The detail procedures of laboratory tests also covered under every respective testing for future references. The explanation and technique used to collect data for every applied apparatus such as *Revest Scratch Tester, Ducom Multi Specimen Tester, Microhardness Tester, Mitutoyo Surface Roughness Tester SV 3000* and *Optical Microscope* also discussed by the author in this section.

3.1 SAMPLE PREPARATION

Before the substrate being coated by zinc and chromium metallic coating, the samples was prepared. Twelve samples will be used throughout this project. The description of each samples are as in Table 3.1 and 3.2.

Table 3.1: Samples for Chromium Coating

Chromium Coating		
Thickness	Surface	Test
1	Smooth	Pin on Disc and Scratch
2	Smooth	Pin on Disc and Scratch
3	Smooth	Pin on Disc and Scratch
1	Rough	Pin on Disc and Scratch
2	Rough	Pin on Disc and Scratch
3	Rough	Pin on Disc and Scratch
Total: 6 Samples		

Table 3.2: Samples for Zinc Coating

Zinc Coating		
Thickness	Surface	Test
1	Smooth	Pin on Disc and Scratch
2	Smooth	Pin on Disc and Scratch
3	Smooth	Pin on Disc and Scratch
1	Rough	`Pin on Disc and Scratch
2	Rough	Pin on Disc and Scratch
3	Rough	Pin on Disc and Scratch
Total: 6 Samples		

Each coating used six samples for different coating thickness and surface roughness. There were three coating thickness and two surface roughness chosen as variable to determine the wear behaviour and adhesion properties of both coating material. In total, twelve samples were being prepared using laboratory tools and apparatus. u

3.1.1 Substrate Material

A sample dimension is 40mm x 40mm x 5mm. Twelve samples were needed to carry out this study. Figure 3.1 shows the substrate material used for this project.

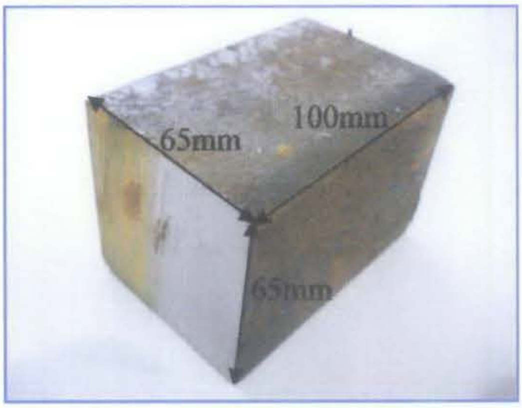

Figure 3.1: Raw Material

Mild steel were chosen for this study because it was widely use in industry for machinery components or parts such as screws, nuts, pipes, chains and many more. Besides, mild steel were cheap and readily available in most stores and hardware shops.

3.1.2 Size Reduction and Sample Cutting

Since the available size of the mild steel was outsized compare to required dimension, it need to be reduced using Conventional Milling Machine as shown in Figure 3.2. Face milled can cut every 0.5 mm linearly at all x, y and z direction. The milling process procedure was as below:

1. The sample was placed carefully on the machine's table. Then clamped on the table and knocked several time using rubber hammers to make sure it was perfectly clamped on the table.
2. Switch the cutting tool on and move the table upward until the sample touch the cutting tool.
3. Moved the table in x-direction until it fully cut and after that move the table upward (y-direction) for 0.5mm.
4. Step 3 was repeated continuously until the sample's size was 40mm x 40mm.

After milling process, the desired dimension of 40mm x 40mm achieved. The samples then wire cut to twelve pieces with 5mm thickness each. Figure 3.3 shows the samples after being cut using wire cut.

Figure 3.2: Milling Machine

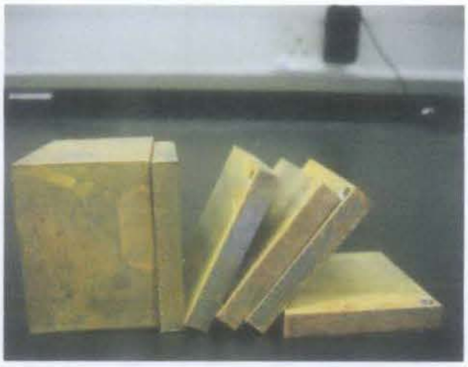

Figure 3.3: Samples with 40mmx40mmx5mm dimension

3.1.4 Drilling and Chamfering

For marking purposes, the samples were drilled with small hole (Ø 4mm) to differentiate each samples with different coating thickness. Using 4mm drill bid and Linear Drilling Machine as in Figure 3.4, holes was made for every samples. One hole represent thickness 1, two holes represent thickness 2 and three holes represent thickness 3. After making the holes, one side of the samples are chamfered using filer for remarking the side of each sample. Each side of the sample will go through different laboratory testing.

Figure 3.4: Drilling Holes for Marking

3.1.5 Grinding and Polishing

To prepare the smooth and rough surface, Metaserv rotating grinder machine was used. Each smooth and rough surface used different gird of sand paper. Figure 3.5 shows the grinding process and the samples after grinding. The procedure to prepare the surface was as below.

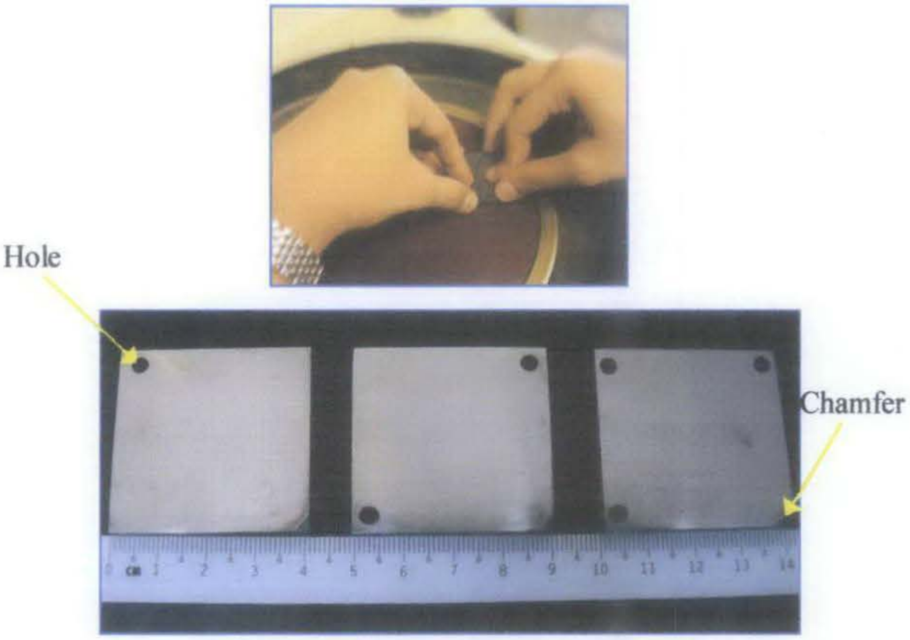

Figure 3.5: Grinding Samples and After Grinding

Grinding Procedure for Rough Sample:

1. First, the samples were polished with rough sand paper to remove thick deposit on top of the surface. The specification for the sand paper was as follow; Aluminum oxide cloth, P: 6
2. Then, the samples were grinded with Metaserv 2000 rotating grinder at 300 rpm with cloth grit 36.
3. After finish, the samples were dried using oven at low temperature and placed safely in dry chamber to prevent from corrosion.
4. Step 1 to 3 then repeated until all six rough samples finished.

Grinding Procedure for Smooth Sample:

1. First, the samples were polished with rough sand paper to remove thick deposit on top of the surface. The specification for the sand paper was as follow; Aluminum oxide cloth, P: 6
2. Then, grinding operation using Metaserv 2000 rotating grinder at 300 rpm with selected grinding cloth from the course to the smoothest cloth. Start with grinding cloth P: 60, P: 120, P: 200, P: 320, P: 400, P: 800, P: 1200, P: 2400 and P: 4000 respectively.
3. Next was the polishing process which used 3μ polishing cloth. The samples were polished until it looks like a mirror.
4. After finish, the samples were dried using oven at low temperature and placed safely in dry chamber to prevent from corrosion.
5. Step 1 to 4 then repeated until all six smooth samples finished.

Precautions:

To work with rotating grinder, water must be constantly supplied so that the samples' surfaces are protected from major scratches and to prevent the piece from getting warmer. This is due to friction and constant contact between the metal piece and rotating grinder for a quite period of time.

The samples were thin (5mm). So, it has to be extra careful. During grinding, fingers can easily injured if accidently touch the grinding cloth especially the course one since it was rotating at 300 rpm. In addition, it was more stable to hold the samples using both hands rather than single handedly hold.

During polishing, coolant must be sufficiently sprayed on the polishing cloth and suitable diamond paste should be used (3μ polishing cloth for 3μ diamond paste).

3.2 COATING

Two electroplating shops based in Ipoh, Perak were selected for chromium and zinc metallic coating for this study.

1. For chromium coating;
   Sun Hing Electroplating Works
   11 E, Lorong Lahat,
   30200 Ipoh,
   Perak Darul Ridzuan.
   Phone: 605-2412599

2. For zinc coating;
   I.E.P Electro-Plating Industries Sdn. Bhd.
   4, Hala Mengelembu Timur 12,
   Kawasan Perindustrian Ringan,
   31450 Mengelembu,
   Perak Darul Ridzuan.
   Phone Num: 605-2821519, 2826933
   Fax: 605-2826933

Three coating thickness was planned as discussed previously in scope of study. The coating thickness were measured based on time immersion in the electroplating bath since it does not have the proper electroplating machine that can measure the coating thickness. The assumption was; the longer immersion time will give thicker coating.

Electroplating Process (as witnessed at Sun Hing Electroplating Work workshop):

1. Surface of the metal is cleaned in alkaline detergent type solutions, and it is treated with acid, in order to remove any rust or surface scales. Cleanliness is essential for successful chromium electroplating, as the molecular layers of oil or rust can prevent adhesion of the coating. Then, the samples were cleaned under running water.
2. Next, copper wire hanger was used to hang samples in the electroplating bath. Appropriate bath condition is very crucial to obtain good result.
3. The samples then were deposited on the metal by immersing it in a chemical bath. Time of immersion in chemical bath was depended on the coating thickness requested. 10 minutes immersion for first coating thickness, 20 minutes immersion for second coating thickness and 30 minutes immersion for third coating thickness. (The exact coating thickness will be measured later by the author using optical microscope)
4. A DC current was applied, which results in zinc/chromium being deposited on the cathode. Alkaline zinc/chromium baths were used by the finished products, to produce a more consistent zinc/chromium thickness.
5. Finally, to enhance the surface appearance, the samples was cleaned with thinner and then dried.

Important Coating Information:

1. The chemical identification for the chromium molten bath for the electroplating process was $CrO_3H_2SO_4$. The chemical used can either be in Sulphur or Chloride.
2. The bath temperature during electroplating process was 57°C. It should be in range of 55°C to 60°C. Unsuitable coating temperature will affected the hardness of the coating. At very high temperature will produce shinier coating but result in reduction of hardness value.
3. The voltage applied for coating the sample was 4V. For acid sulfuric bath, lower voltage value also can be used. The voltage selection normally depends on the size of coating's sample.

4. The hanger of the sample must be made of copper. This is because of the superior electrical conductivity of copper as compared to other material.
5. The following pictures were taken during electroplating process at Sun Hing Electroplating Work workshop.

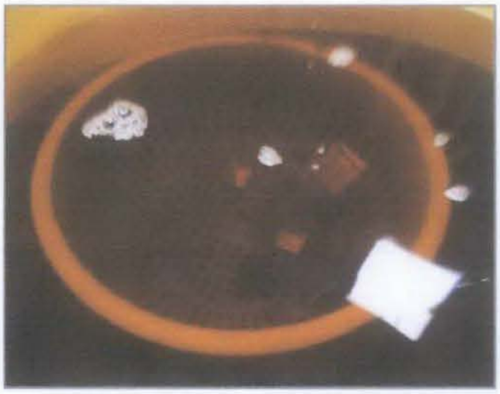

Figure 3.6: The Samples Immerse In Acid Solution

Figure 3.7: Immersion in Plating Bath

Figure 3.8: Immersion in Plating Bath

Figure 3.9: Thinner bath

Unfortunately, the zinc electroplating shop can only make one coating thickness for the sample because longer immersion time can affect other customers' coating product. Therefore, it had been decided to have one single coating thickness.

3.3 SURFACE PROFILING TEST

Surface roughness of the samples was tested twice; before and after coating. Using *Mitutoyo Surface Roughness Tester SV 3000* at Metrology Lab the surface condition of the samples was determined as one of the variables for this experiment. Software applied was Surfpak and only the Ra values were taken from the test.

3.2.1 Samples

All twelve samples were used to determining the surface profile as in Figure 3.10 and 3.11. The description of each samples were as below:

i. Cr T1R (Rough Surface with Thin Chromium Coating)
ii. Cr T2R (Rough Surface with Medium thickness Chromium Coating)
iii. Cr T3R (Rough Surface with Thick Chromium Coating)
iv. Cr T1S (Smooth Surface with Thin Chromium Coating)
v. Cr T2S (Smooth Surface with Medium thickness Chromium Coating)
vi. Cr T3S (Smooth Surface with Thick Chromium Coating)
vii. Zn T1R (Rough Surface with Thin Zinc Coating)
viii. Zn T2R (Rough Surface with Medium thickness Zinc Coating)
ix. Zn T3R (Rough Surface with Thick Zinc Coating)
x. Zn T1S (Smooth Surface with Thin Chromium Coating)
xi. Zn T2S (Smooth Surface with Medium thickness Chromium Coating)
xii. Zn T3S (Smooth Surface with Thick Zinc Coating)

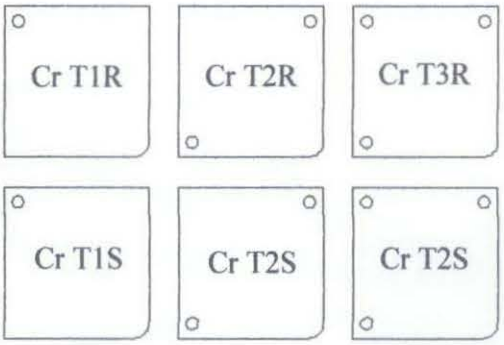

Figure 3.10: Chromium Samples

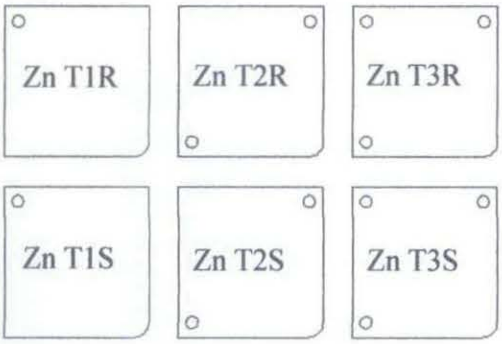

Figure 3.11: Zinc Samples

3.2.2 Surface Profiling Reading and Orientation

Ten reading was taken on each surface of the samples. 30mm trace length, Lt was used during the test. This was done to obtain high accurate average surface roughness and surface smoothness of the samples. Figure 3.12 shows the approximation location of the assessed-traverse line for the examined substrates. The surface test was executed with a uniform trend or configuration as shown in the figure, though the exact location was randomly picked (i.e. 6mm distance between each reading; n1 and n2).

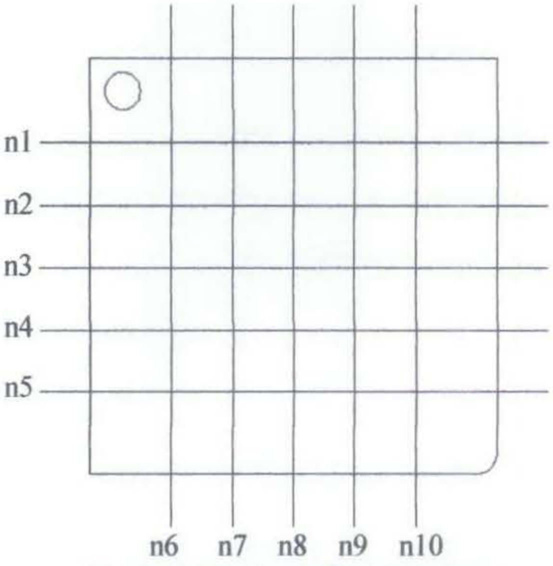

Figure 3.12: Surface Profiling Orientation

3.2.3 Surface Profiling Parameter

MEASUREMENT CONDITION	
Measurement Length :	30mm
Column Escape :	5mm
Range :	800um
Speed :	5 mm/s
Pitch :	5 um
Num Of Point :	6000
Machine :	SV-3000S4
Meassurement Axis :	100mm
Detector :	4mN
Stylus :	deep grove 10mm
EVALUATION CONDITION	
Kind Of Profile :	R
Sampling Length(Le) :	25mm
Lc :	5mm
Kind Of Filter :	Gaussian
Evaluation Length (Lm) :	25mm
Pre-Travel :	2.5mm
Post-Treavel :	2.5mm

Figure 3.13: Scratch Testing

3.3 HARDNESS TEST

Hardness test is conducted to determine the hardness effect of the substrate before and after coating. Hardness was used to measure weather the mechanical properties of the substrate increased after experienced metallic coating.

3.3.1 Samples

Twelve samples were been tested to determine its hardness using Micro-hardness Tester. The hardness was measured using Hardness Vickers (Hv_{25}). Hv25 was used as it was the lowest load which can visible a perfect diamond for measuring the hardness.

3.3.2 Hardness Sample Reading and Orientation

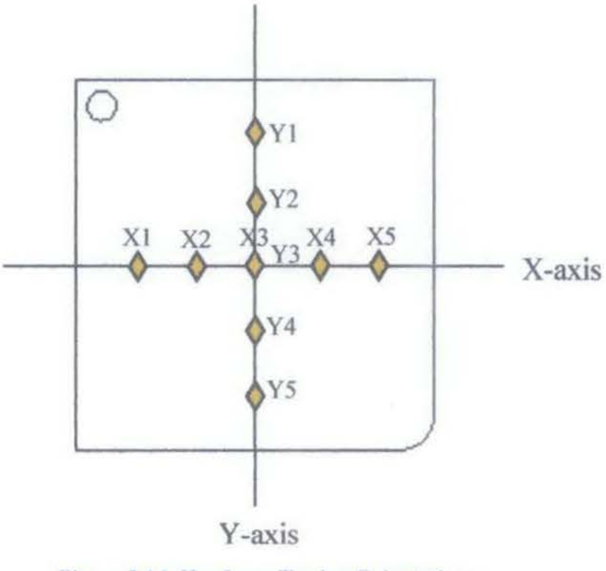

Figure 3.14: Hardness Testing Orientation

Nine hardness reading were taken from each sample according to its X-axis and Y-axis; five reading from each axis as in Figure 3.14. But, there is one cross section between X-axis and Y-axis at the middle, giving two same hardness values at the same two points.

3.3.3 Hardness Test Procedure

1. The sample is mounted on the Microhardness tester table.
2. The load for the test is set to 25N.
3. The microscope is adjusted until the microstructure is seen.
4. After that, start button is clicked and the indenter will indent 25N load to the sample.
5. A diamond will visible on the sample and the diamond diameter is determined.
6. The hardness reading will appear on the screen once both diamond diameter x-axis and y-axis were taken.
7. Procedure 3-6 is repeated to obtain readings for nine indentions as in Figure 3.14 for each sample.

Figure 3.15: Microhardness Tester

3.4 PIN ON DISC TEST

Pin on disc test was performed to determine the wear behaviour of the coated mild steel. Using Ducom Multispecimen Tester, pin on disc test was conducted for all twelve samples.

3.4.1 Pin on Disc Test Parameters

By referring to standard test method for wear testing with a pin-on-disc apparatus [24], several test parameters must be followed. The parameters were as below:

Table 3.3: Pin on Disc Test Parameters

Type :	Pin on Disc Test
Load (N) :	5N
Speed (m/s) :	100
Time (hr) :	0.2
Pin diameter (mm) :	5

3.4.2 Pin on Disc Test Procedure

1. The test piece is mounted on the disc casing and then tightens using screw.
2. Then, the pin is mounted at the pin holder.
3. Both pin and disc then positioned on the multi-specimen machine.
4. At the multi-specimen software, open the new file and set the test parameters except the load.
5. After that, run the software and adjusted all the load, speed, temperature, friction and wear reading to zero.
6. Then, the load added to the machine and the test ran.
7. All the reading appeared on the screen and waited until the time end.
8. After finish, stopped the test and saved all required file.
9. Procedure 1-8 then repeated to all other 12 samples to obtain wear reading for all the samples.

Figure 3.16: After pin on disc test

3.5 SCRATCH TEST

Scratch testing was performed using a commercial scratch tester (supplied by SCEM, Switzerland) fitted with Rockwell C diamond stylus (cone apex angle, 120°; 200μm tip radius). Scratches were performed using a progressive load for transfer length of 10mm. Initial load was 0.9N and ended at 100N. The loading rate was 50Nmin^{-1}. The scratch tester was equipped acoustic emission monitoring device that can detect acoustic emission within the vicinity of 10 kHz for failure determination. The instrument was further enhanced with microscopic examination capability. The available magnicication were 5x and 20x objection.

3.5.1 Scratch Test Parameters

Table 3.4: Scratch Test Parameters

Linear Scratch	
Type :	Progressive
Begin Load (N) :	0.9
End Load (N) :	100
Loading Rate (N/min) :	50
Speed (N/min) :	5.05
Length (mm) :	10
Position X (mm) :	2.982
AESensitivity :	1
Indenter	
Type :	Rockwell
Serial Number :	S/O 258
Material :	Diamond
Radius (μm) :	200

3.4.2 Scratch Test Procedure

1. First, the test piece is placed on the scratch table and clamped.
2. At scratch software, open new file and fill in the scratch group information
3. Next, click on "start new scratch test" for a new scratch test.
4. Then, the scratch test parameters entered as in Table 3.4 and the test was simple scratch.
5. Next, a pop-up massage box asked for "indenter-simple distance adjustment". So, the indenter tip is moved close to coating surface and then the lowering arm is locked.
6. As prompted, "Starts automatic indenter touch".
7. Then, another massage box appeared to adjust the Dz-range before the scratch test began.
8. After the scratch test completely executed, a prompt window appeared to initiate optical analysis. For the optical analysis, correct adhesive failure must be identified by understanding the features of the failure i.e coating flaking.
9. During the optical analysis, optical critical load were identified via microscopic examination. After the window was closed, more critical loads i.e acoustic emission critical load, were marked on the scratch test graph.
10. Finally, the sample is moved to next scratch position and procedure 2-10 proceeded for all twelve samples.

3.6 GANTT CHART

Table 3.5: Gantt Chart

Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sample Preparation	🟩	🟩	🟩											
Surface Profiling Test 1				🟩										
Hardness Test 1				🟩										
Coating					🟩									
Surface Profiling Test 2					🟩									
Hardness Test 2					🟩									
Pin on Disc Test 1						🟨								
Scratch Test 1							🟨							
Progress Report								●						
Pin on Disc Test 2									🟨					
Scratch Test 2									🟨					
Hardness Test 3										🟨				
SEM										🟨				
Pre-EDX											●			
Draft Report												●		
Final Report													●	
Technical Report													●	
Viva													●	
End of Semester														🟨

🟩 Work Done 🟨 Work Undone ● Mile Stone

CHAPTER 4

RESULTS AND DISCUSSION

Coating on mild steel substrate is done to increase the substrate's mechanical properties such as wear and adhesion. Coating failure usually caused during rough handling on components or parts of the material in industry.

The premise is that the harder the material, the greater the wear resistance [18], and it is predicted that smooth surface profile will contribute to greater coating adhesion as the assumption a smooth and uniform coating thickness are the result of adequate surface preparation of basis metal prior to coating. Therefore, hardness of the substrate is tested before and after coating to check and examine the hardness improvement of using coating.

4.1 EXPERIMENTAL RESULT

The full experimental result and sample calculation are shown and attached in Appendix.

4.2.1 Surface Profiling Test

A comparison was made to study the effect of surface roughness on the wear and adhesion properties of metallic coating. The outcome of electroplating on the surface roughness also studied. Therefore, comparison of the samples was made before and after coating. The result of surface profiling test for uncoated mild steel is as below. Over ten readings taken, the average value is used for determining the surface roughness and surface smoothness of each substrate as shown in Table 4.1.

Table 4.1: Surface Profile Result for Uncoated Mild Steel

SAMPLE	Top Side (SCRATCH), Ra average (µm)	Bottom Side (PIN ON DISC), Ra average (µm)
Cr T1R	1.59	1.49
Cr T2R	1.56	1.71
Cr T3R	1.83	1.83
Cr T1S	0.04	0.04
Cr T2S	0.05	0.05
Cr T3S	0.05	0.03
Zn T1R	2.42	2.41
Zn T2R	2.58	2.59
Zn T3R	2.55	2.73
Zn T1S	0.04	0.05
Zn T2S	0.04	0.04
Zn T3S	0.04	0.04

From the result, the value for rough surface is around Ra ± 2 µm, and Ra ± 0.04 µm for smooth surface. There were differences for about 1 µm between chromium and zinc rough surface. The result is caused by different procedure applied to the substrate during grinding and polishing. Figure 4.1 shows the trend of surface roughness for all 12 samples.

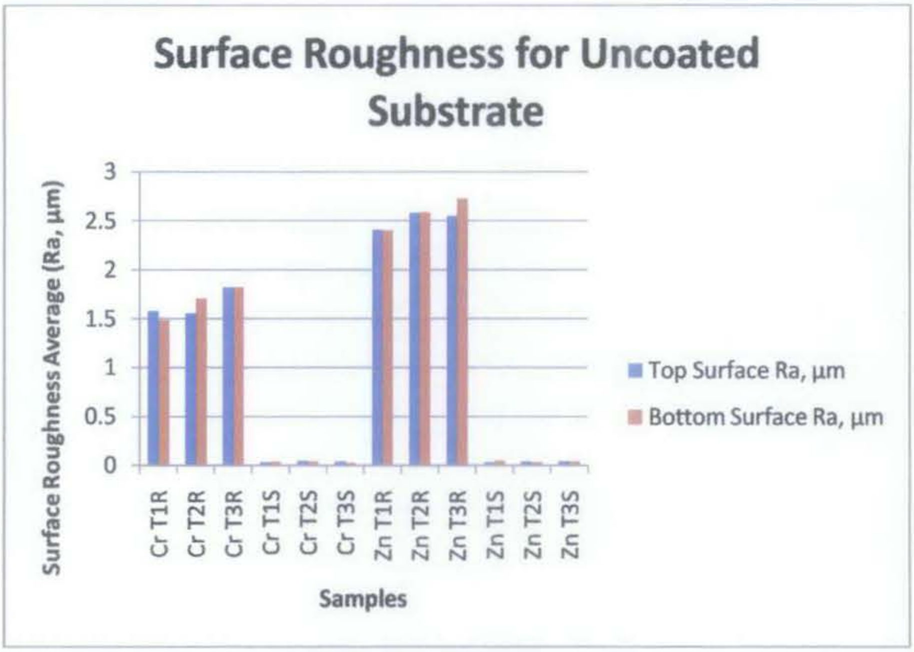

Figure 4.1: Surface Roughness Chart

4.2.1.1 Comparison Surface Condition Before and After Coating

Table 4.2 below shows the difference of the surface profile for the samples before and after coating for one side only. The thicker the coating experienced more improvement in the surface profile. In other word, electroplating had enhanced the surface quality of the rough substrate.

Table 4.2: Comparison of Surface Roughness Before Coating and After Coating

Samples	Before Coating (Ra, µm)	After Coating (Ra, µm)	Percentage Improvement
Cr T1R	1.59	1.33	**16.23%**
Cr T2R	1.56	1.39	**10.93%**
Cr T3R	1.82	1.17	**36.27%**
Cr T1S	0.04	0.06	**-33.33%**
Cr T2S	0.05	0.06	**-16/67%**
Cr T3S	0.05	0.09	**-44.44%**
Zn R	2.42	2.07	**14.46%**
Zn S	0.04	0.19	**-78.95%**

Thickest coating (Cr T3R), give the highest percentage of surface profile improvement which is 36.27%. But, all smooth surfaces give the negative percentage improvement which means coating gave bad surface roughness for smooth surface samples. In conclusion, coating had improved the surface roughness of rough substrate only regardless its coating thickness.

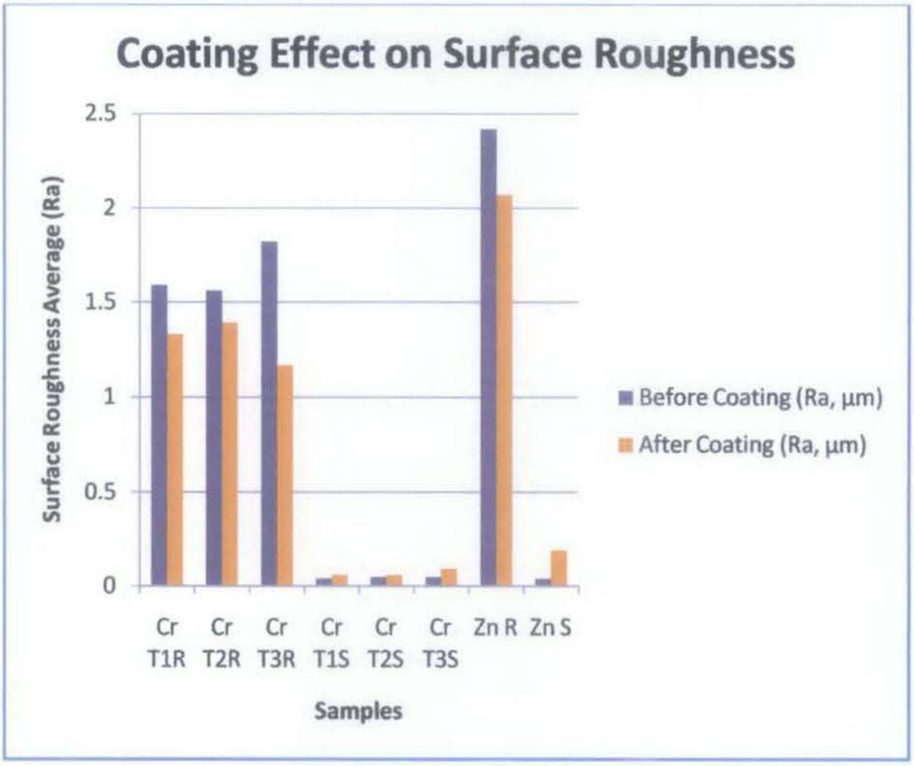

Figure 4.2: Surface Profile Comparison Chart

4.2.2 Hardness Test

The advantage of metallic coating is improving the hardness. To study the effect of coating, the hardness of the samples is tested before and after coating as well. The result then compared to measure the percentage of its improvement. 25N load was used as high load may cause composite effect to the substrate.

The effect of coating on the mild steel hardness is represented by the composite hardness. The composite hardness comes from the combination of coating and the base metal. The hardness result is as in Table 4.3.

Table 4.3: Hardness Test Result

	Uncoated	**T1**	**T2**	**T3**
Cr S	218.66	467.39	820.04	892.48
Cr R	211.68	468.65	620.51	754.84
Zn S	206.71	117.14	-	-
Zn R	215.73	121.61	-	-

From the result, substrates coated with chromium enhanced the hardness properties. Smooth surface give better hardness value compared to the rough surface samples. The thicker the coating, the harder the material. It shows that chromium had increased the mild steel mechanical properties by increasing its hardness.

However, the substrate electroplated with zinc has experienced reduction in the value of hardness. Both surfaces, smooth and rough were not showing any improvement in hardness after coating because it only measures the hardness of zinc layer only.

Line chart in Figure 4.3 shows the effect of coating on mild steel substrate. It is represented by composite hardness. The composite hardness comes from the combination of the coating and the base metal. For all chromium coating shows improvement in hardness while for zinc coating shows reduction in hardness.

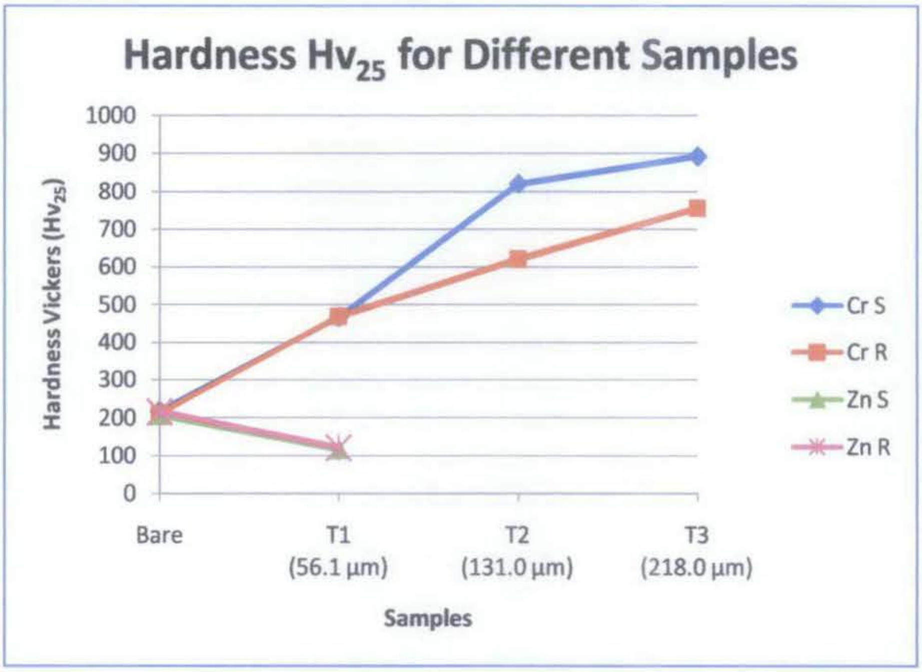

Figure 4.3: Comparison of Material Hardness by Varying Its Coating Thickness

Uncoated mild steel average hardness is 213.2 Hv_{25}. For chromium, sample with thin coating exhibit only little composite hardness than thickest coating. Since zinc did not give any improvement in hardness, zinc is not suitably used in industry for rough handling components.

4.1.3 Pin on Disc Test

For pin on disc test, the result was examined based on its wear and coefficient of friction. Excellent wear behaviour should have low value of wear which represent how much metal loss by pin diameter. It also can be determined by measuring weight before and after test and take the weight loss as wear value. A material also should have low value of coefficient of friction to smoothen the resistance during rough handling component. The pin on disc results is as in figure below.

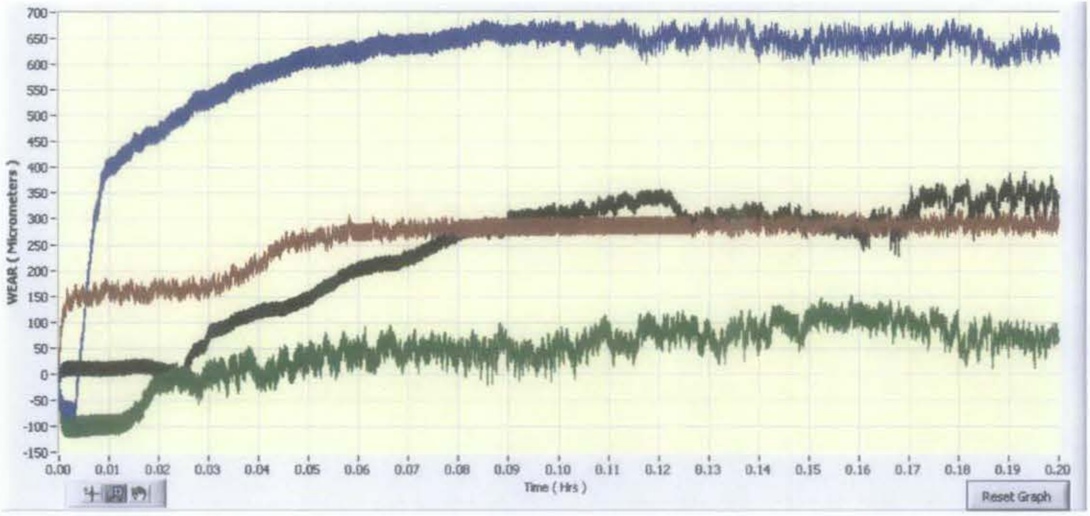

Figure 4.4: Comparison of Wear for Chromium Smooth Surface

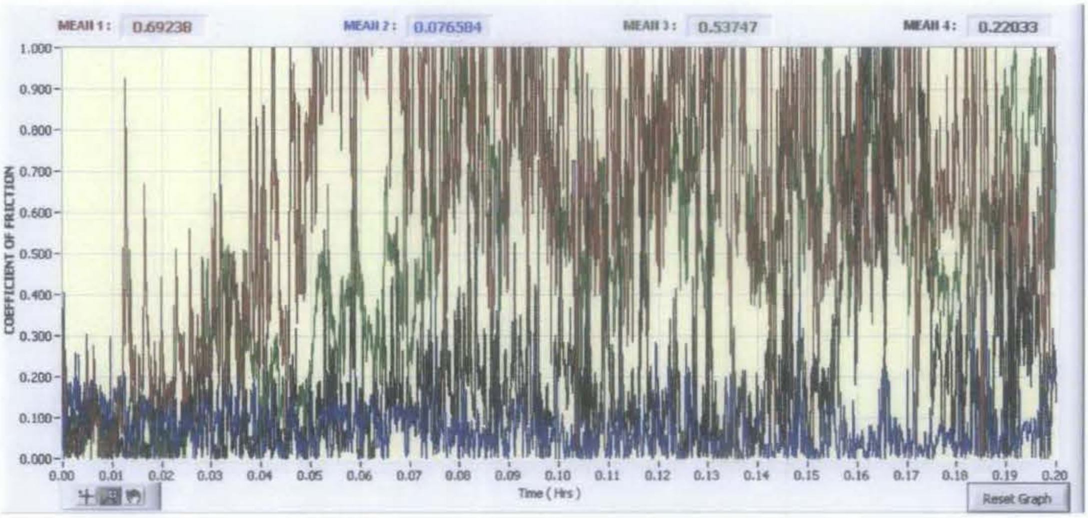

Figure 4.5: Comparison of Coefficient of Friction for Chromium Smooth Surface

🟥	Uncoated Sample	🟦	Thickness 1	🟩	Thickness 1	⬛	Thickness 1

Figure 4.6: Legend for Chromium Pin on Disc Test Result

Figure 4.4 and Figure 4.5 shows the comparison of wear result and coefficient of friction result for chromium smooth surface. Surprisingly, the results were not as expected. It is good to have low wear value and low coefficient of friction. The lowest value of wear is for Cr T2S and the lowest coefficient of friction is at Cr T1.

But both cannot be the best wear resistance as the coefficient of friction for Cr T2 is the highest which is 0.537 and wear for Cr T1 also the highest. So, the best wear behavior is Cr T3 which have low value of both wear and coefficient of friction.

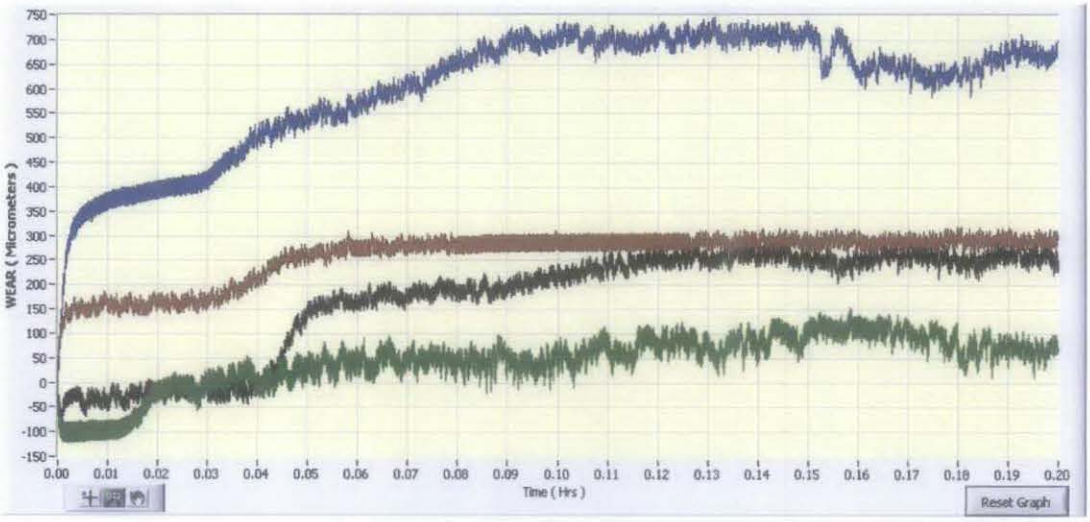

Figure 4.7: Comparison of Wear for Chromium Rough Surface

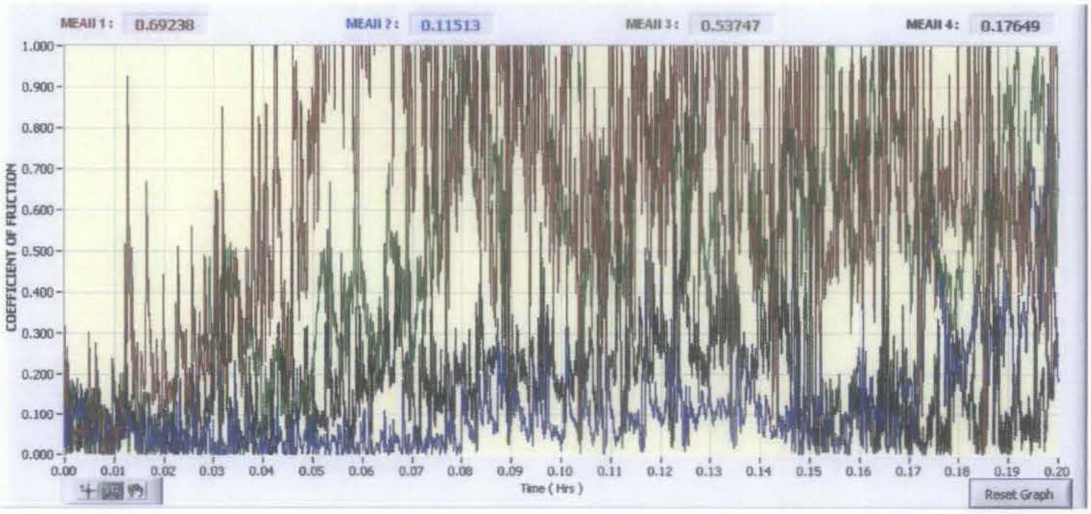

Figure 4.8: Comparison of Coefficient of Friction for Chromium Rough Surface

🟫	Uncoated Sample	🟦	Thickness 1	🟩	Thickness 1	⬛	Thickness 1

Figure 4.9: Legend for Chromium Pin on Disc Test Result

For rough surfaces, the result is similar to smooth surface. Also, for the best wear behaviour for chromium rough surface is at Cr T3 which has 200μm wear value and 0.176 coefficient of friction.

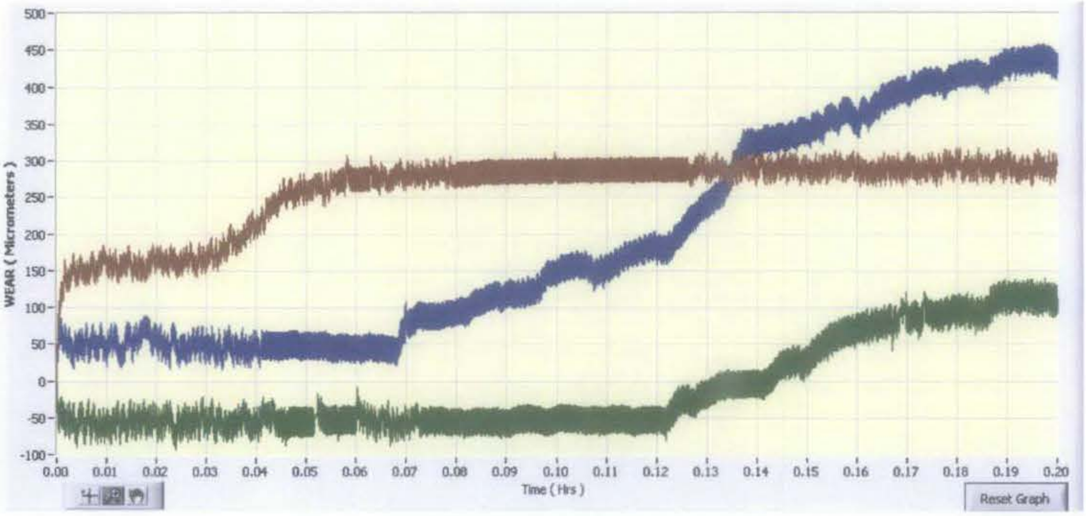

Figure 4.10: Comparison of Wear for Zinc Coated

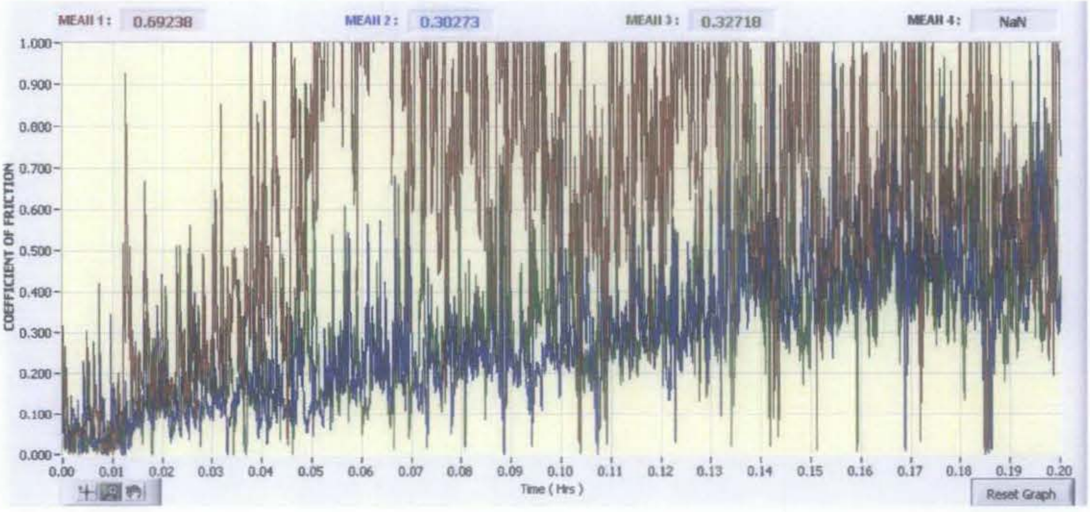

Figure 4.11: Comparison of Coefficient of Friction for Zinc Coated

🟫	Uncoated Sample	🟦	Smooth Surface	🟩	Rough Surface

Figure 4. 12: Legend for Zinc Pin on Disc Test Result

From Fugure 4.10 and 4.11 of zinc coated samples, smooth surface have low value of coefficient of friction which is 0.303. While the rough surface give low value of wear which is around 100µm. So, since the differences of coefficient of friction were very low, the best coating for zinc is at rough surface.

4.1.4 Scratch Test

For scratch test, smooth surface of chromium coated mild steel had shown good adhesion properties. This is because, from both acoustic emission and optical analysis, the failure of chromium coated mild steel initiate at high load. Therefore, the detachment of chromium coating at coating-substrate interface was not so easy to detach. Thicker coating also shown promising result compared to thin coating where the failure start to initiate at higher load.

Different situation occur at smooth surface of zinc coated mild steel where it can only sustain the load applied during scratch test for short distance. Means that zinc accept low load applied on it.

For rough sample, both zinc and chromium coated mild steel shows poor result. The rough samples were not finely coated so the zinc and chromium not adhered properly on the substrate giving low adhesion properties. Table 4.4 shows the critical load from scratch test result based on the failure distance from head using optical microscope.

Table 4.4: Critical Load measured by failure distance from tail

Samples	Failure Distance from Tail (mm)	Critical Load, Lc (N)
Cr T1S	3.11	31.72
Cr T2S	3.83	38.86
Cr T3S	6.00	60.36
Cr T1R	0.17	2.58
Cr T2R	0.21	2.98
Cr T3R	0.72	8.04
Zn S	1.42	14.97
Zn R	0.10	1.89

From the result, thickest chromium coating with smooth surface (Cr T3S) gives a good adhesion property where it can sustain up to 60.36 N loads. Compared to smooth zinc coating which only can accept 14.97 N loads which is still lower then thinnest chromium coating, 31.72 N, prove that chromium coating have better adhesion property compare to zinc.

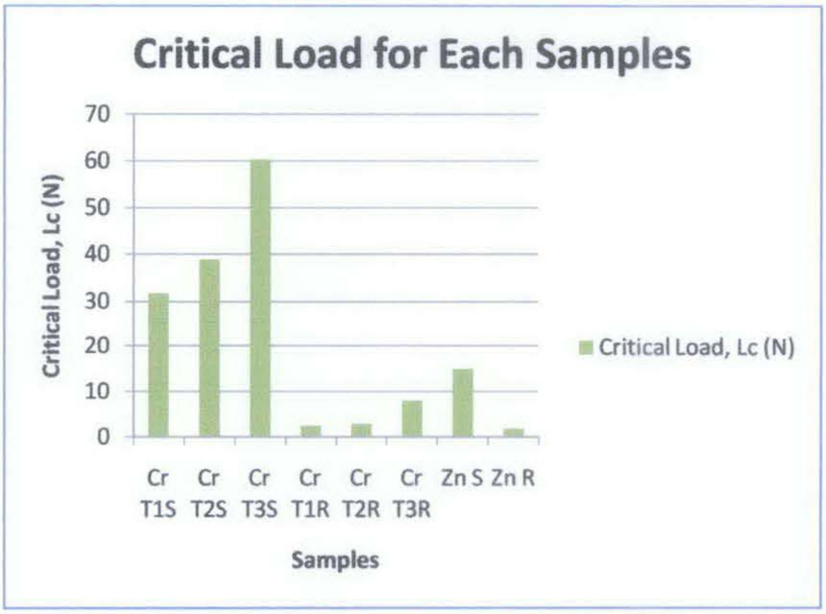

Figure 4.13: Critical Load Comparison Chart

The optical analysis in Figure 4.14 and 4.15 shown that the failure occur at short distance which means it began at very low scratch load indicate that the rough coating samples were very easy to detach. This is due to the surface of the sample which is not fully covered by coating material.

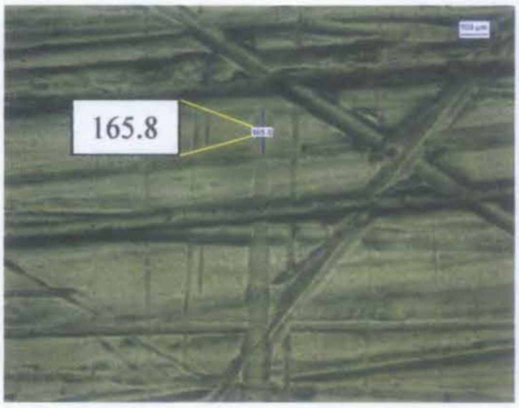

Figure 4.14: Crack distance for Cr T1R sample at 10x magnification

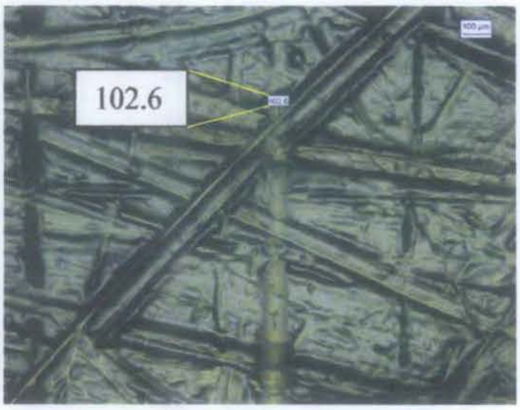

Figure 4.15: Crack Distance for Zinc Rough Sample at 10x magnification

Figure 4.16, 4.17 and 4.18 shows the result of scratch test for smooth chromium coated. The failure is determined based on the first cracking sound behaviour of Acoustic Emission.

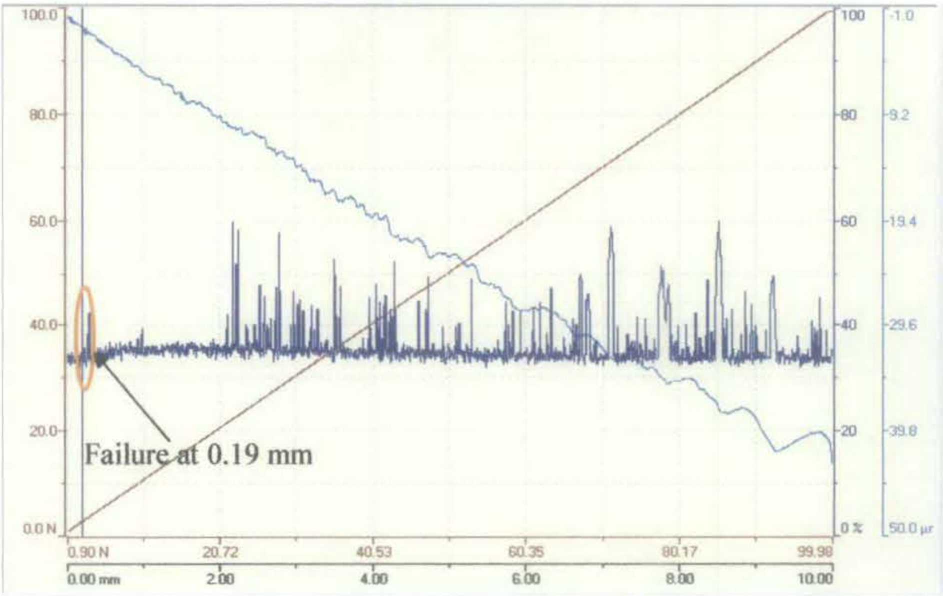

Figure 4.16: Scratch Test Result for Cr T1S

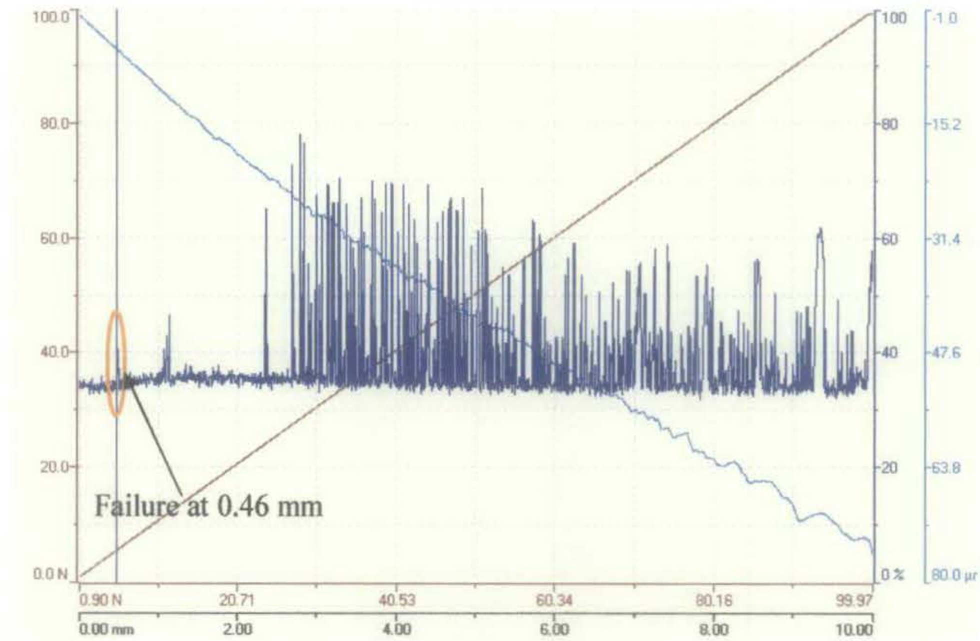

Figure 4.17: Scratch Test Result for Cr T2S

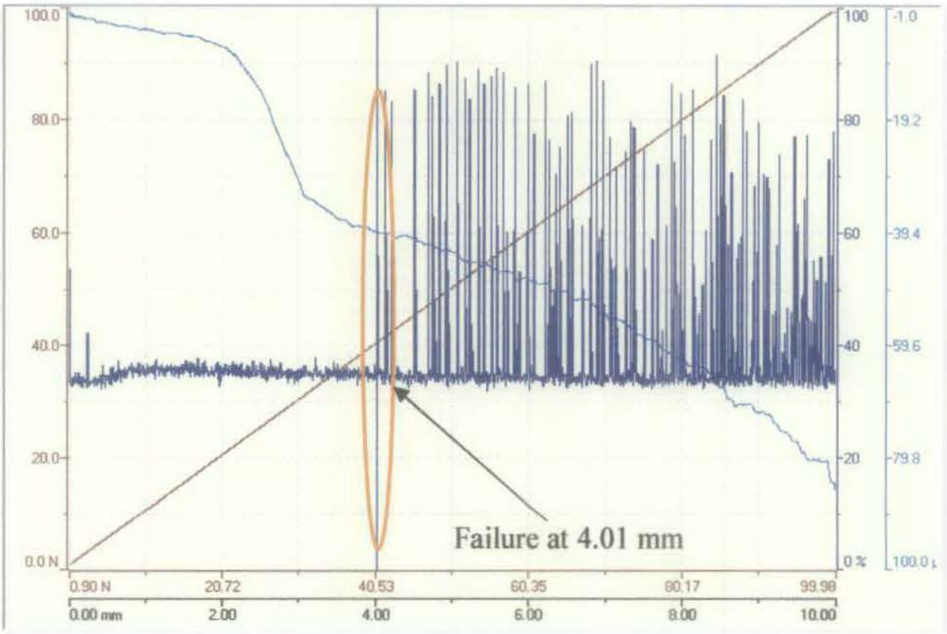

Figure 4.18: Scratch Test Result for Cr T3S

Figure 4.19: Scratch Test Result Legend

From the result obtain, thicker chromium coating gives good adhesion properties where the failure occur at high load. Figures below shows how the failure and the nature of crack look under optical microscope.

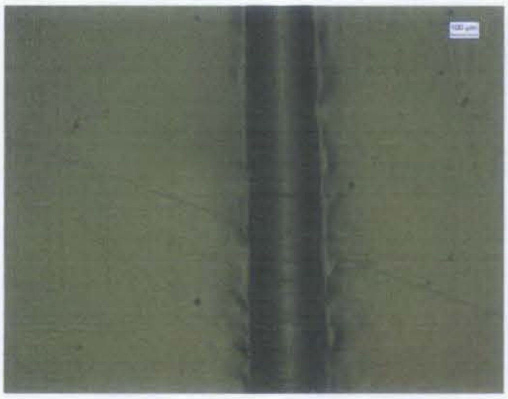

Figure 4.20: Nature of Crack on Chromium Coating T1S (initial crack, 10x magnificent)

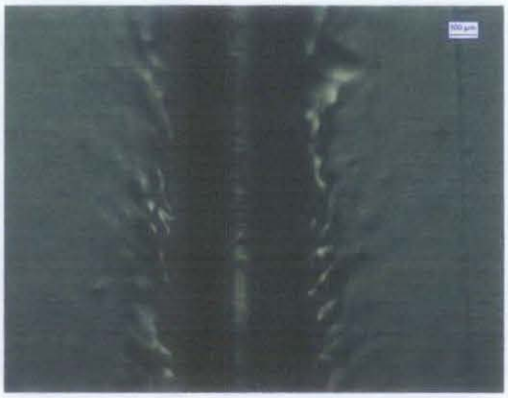

Figure 4.21: Nature of Crack on Chromuim Coating T2S (middle crack, 10x magnificent)

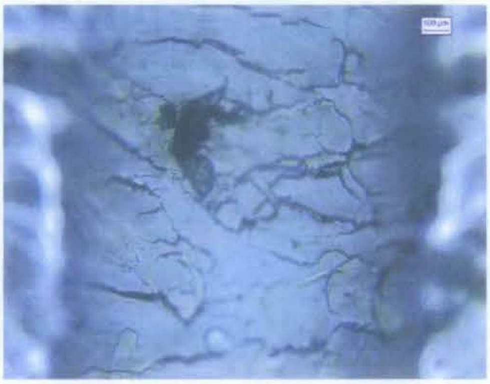

Figure 4.22: Nature of Crack on Chromium T1R at 50x magnificent

4.1.3.1 Scratch Test Features

Using optical microscope, the failure features was examined. It is to determine either the failure is tensive or compressive.

Zinc coated mild steel shown tensive crack as in Figure 4.23 and 4.24 based on the features on how the coating material peeled out from the substrate.

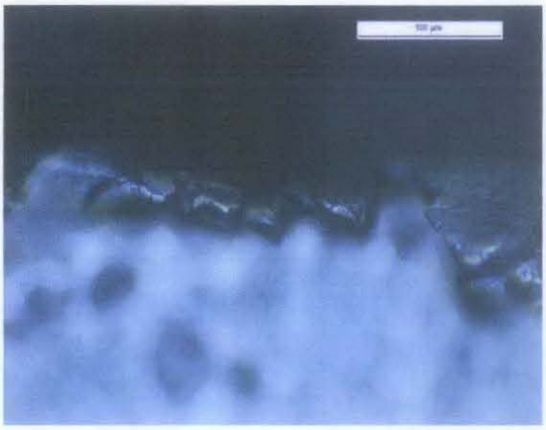

Figure 4.23: Features of Crack on Zinc Coating Rough Surface (50x magnificent)

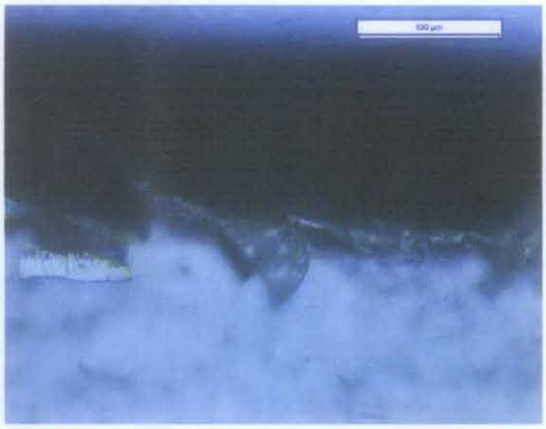

Figure 4.24: Features of Crack on Zinc Coating Smooth Surface (50x magnificent)

When using the scratch adhesion test to assess coating-substrate adhesion, it should be ensured that the failure event actually represents the loss of adhesion, since a range of failure modes can occur, only some of which are dependent on adhesion [20]. Other failure modes are mainly caused by fracture within the coatings. Bull [19] divided the failure modes found in the scratch testing of hard coatings into three categories:

- Through-thickness cracking - including tensile cracking behind the indenter, conformal cracking as the coating is bent into the scratch track, and Hertzian cracking;
- Spallation - including compressive spallation and buckling spallation ahead of indenter, or elastic recovery induced spallation behind the indenter;
- Chipping in the coating akin to lateral cracking in bulk ceramics.

Since zinc having tensive crack, it means that zinc experience brittle failure which is not good as a coating material. So, zinc is not suitable to be used to protect the substrate material.

4.2 DISCUSSION

4.2.1 Surface Roughness

The effect of surface roughness on the adhesion of the coating was analyzed after both pin on disc and scratch test completed. From optical microscope, the microstructure of smooth surface and rough surface were as in Figure 4.25 and 4.26.

Figure 4.25: Smooth Surface

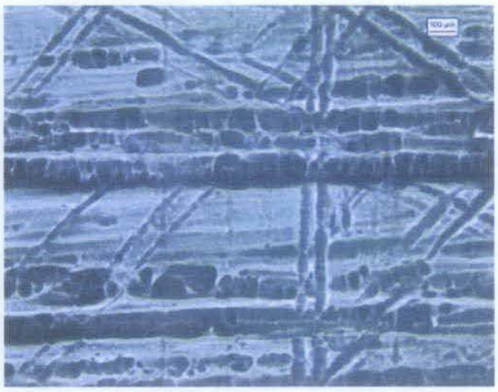

Figure 4.26: Rough Surface

Smooth surface was proven to produce better-adhered coatings. This might be explained by the existence of free contaminant surface. A polished surface with Ra ±0.04μm provided higher smoothness and uniformity but less contamination. This promoted good adhesion between the coatings applied to the substrate surface.

It was not really give any changes in wear behaviour as both smooth and rough surface have similar wear behaviour. So, surface condition did not have big impact on wear behaviour of material.

4.2.2 Hardness

Composite hardness is the hardness due to the combination of the substrate and its coating. It assumed that the indentation depth of the hardness indenter fully covered the coating layer and the substrate layer during the hardness measurement. Ideal hardness test for composite hardness is schematically illustrated in Figure 4.27.

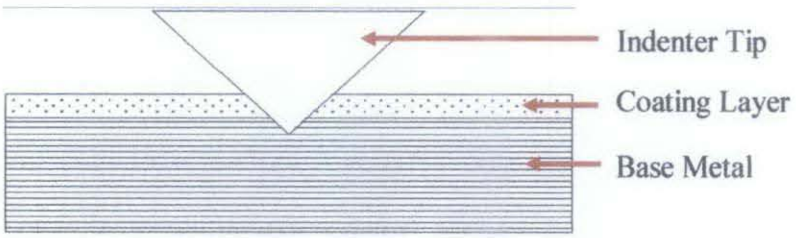

Figure 4.27: Sketch of ideal hardness test on composite material

If the indenter did not reach the substrate layer due to very thick coating, the hardness reading only represent the coating material hardness. This may occur at zinc coating sample where the hardness value is lower than the substrate. It also happens if the coating thickness is very thin. The hardness result for the coated sample will have similar value to the uncoated mild steel. This can occur if high hardness load was used because higher load will give deep indentation depth.

From the result obtain, chromium seen to have high composite hardness where it gives hardness value up to 892.48 Hv_{25}. Then, from scratch test, chromium appeared to be a good coating when its minimum critical load, Lc is higher than zinc coating. But, not much can be interpreted from pin on disc test since the result was not as expected. Hence, the thickest coating still gives the best result compare to others. So, for a better coating quality and wear resistance, thicker coating should be used.

In short, chromium coating give significant result in increasing substrate material properties regardless its surface condition.

4.2.3 Coating Layer

The assumption of using time of immersion for varying coating thickness was succeed. Longer time immersion gave thicker coating thickness as proven in the Figure 4.28, 4.29 and 4.30 using optical microscope.

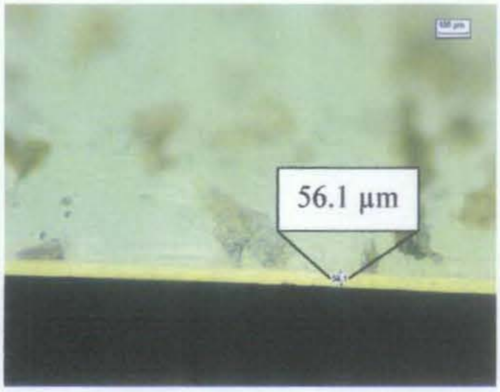

Figure 4.28: 10 minutes immersion in chromium electroplating bath

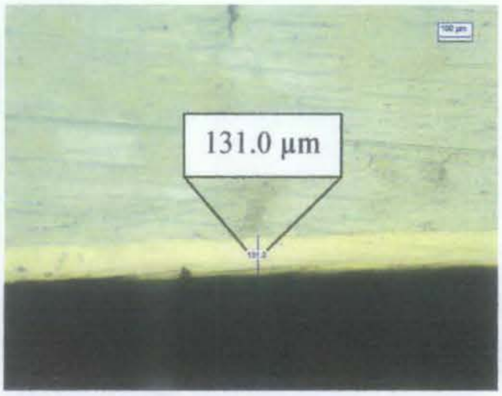

Figure 4.29: 20 minutes immersion in chromium electroplating bath

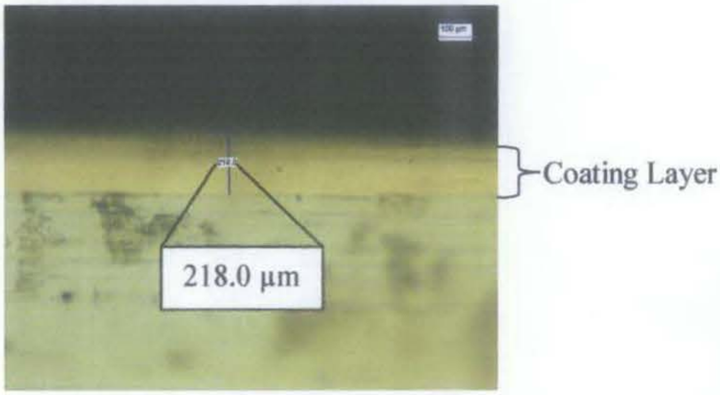

Figure 4.30: 30 minutes immersion in chromium electroplating bath

Different situation occur at zinc since coating company not be able to immerse the sample based on time required because it can affect other customer coating product. So, only one coating layer for zinc is available with two different surface conditions. Figure 4.31 and 4.32 shows the coating layer of zinc coating for rough and smooth surface condition.

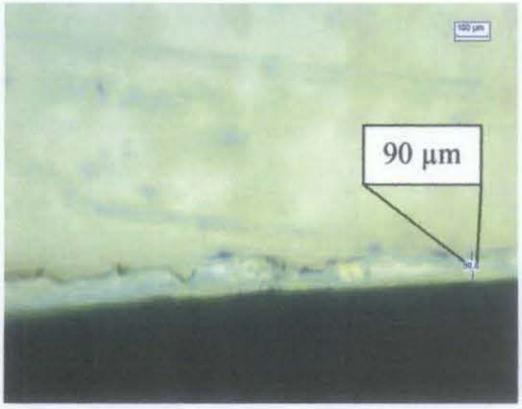

Figure 4. 31: Coating layer for rough zinc sample

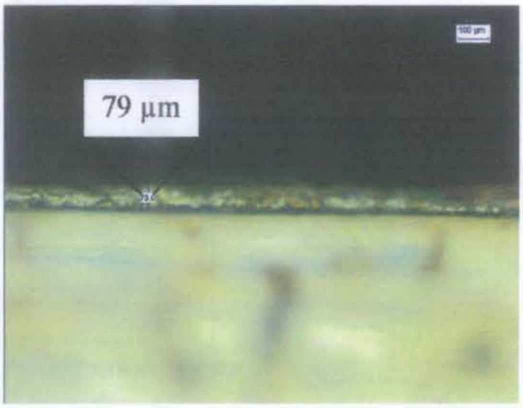

Figure 4. 32: Coating layer for smooth zinc sample

4.2.4 Pin on Disc Test

To determine the samples wear behaviour, pin on disc test was used. Result of coefficient of friction and wear was being interpreted. From the result it shows that thickest coating thickness has the best combination of good coefficient of friction and good wear value.

Figure 4.33: Cr T1S wear result

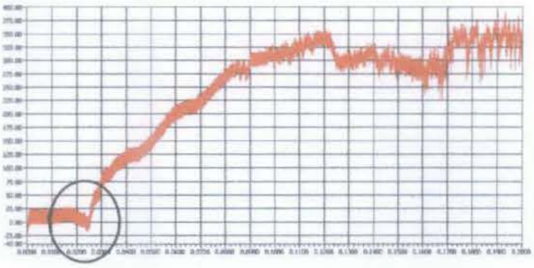

Figure 4.34: Cr T3S wear result

From Figure 4.33 and 4.34, the circle shows the time where the samples start to fail. Thin coating thickness not taking a long time before fail compared to thick coating. For Cr T1S, the coating start to fail after 14.4 second receiving 100m/s sliding distance with 5N load while Cr T3S fail after 90 second experiment started.

It proves that coating can improve the material wear behaviour. So, for good wear behaviour, thicker coating thickness should be used.

4.2.5 Scratch Test

Scratch test is suitable for estimating the coating quality such as adhesion, nature of crack failure and features of crack failure. A scratch mark will be visible on the coating surface as shown in Figure 4.35. Scratch mark is produced during scratch test using the scratch indenter with either uniform or progressive load.

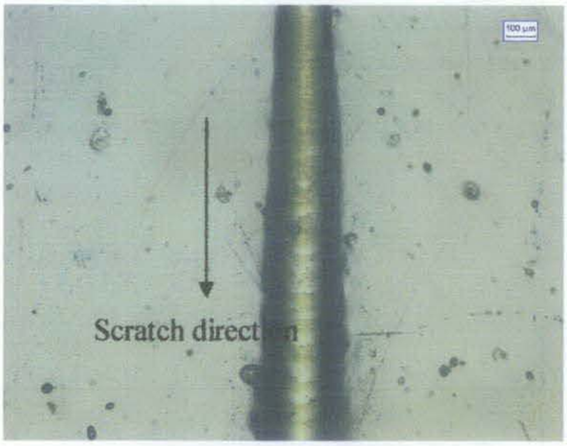

Figure 4.35: Scratch test on smooth zinc coating

The crack length and the loading force are dependent on the coating thickness. However, by optical microscopic examination alone, the critical load, Lc can be determined by manipulating the known loading rate and critical length. In this study, the critical load was obtained by taking the length of first crack from head.

In other way, the adhesion strength of tested sample also can be obtained from the software generated graph. The graph is produced by the measurement of tangential forces, normal forces and the measurement of Acoustic Emission signals.

From this scratch test, it was found that the frictional force, coefficient of frictional force and penetration depth increases with increase in the normal load applied. The thickest coating showed a very promising adhesion property.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The objective which is to study the wear behaviour and coating quality of zinc and chromium metallic coating on mild steel substrate was successfully achieved. The wear behaviour was interpreted based on pin on disc test and coating quality was determined by making scratch test where adhesion, nature and features of crack failure was determined using optical microscope.

All samples had go through several laboratory tests such as surface roughness test, hardness test, pin on disc test and scratch test. Based on the laboratory tests, the suitability of using zinc and chromium metallic coating on mild steel substrate for industrial application has been identified.

So, it is recommended that future study on wear behaviour and coating quality of local-made coating to increase in number. This is because some of these techniques have been widely used by overseas researches, therefore there are huge potential for comparison with if increased number of studies on wear behaviour and coating quality for locally produced coatings being done.

In addition, for a strong support to the experimental findings for the pin on disc and scratch test, it is suggested that Scanning Electron Microstructure (SEM) is used. It is because the difference between the coating and the substrate material are difficult to ascertain with optical microscopy, additional probe is essential.

For determining coating quality, it is advised to compare the test method either to use scratch test, Mercedes test, dolly test or other adhesion test method. The best method for determining coating quality is still undetermined.

Perhaps, the scope of study can be enhanced by adding some more variable such as varying load or temperature for pin on disc test or comparing with other type of coating. Other material for substrate also can be used.

Eventually, it can be concluded as follow. Metallic coating application through electroplating process had improved the surface roughness of rough surface sample. Coating will increase the surface roughness of smooth surface due to rough handling during coating process. Smoother chromium coated substrates which imply proper surface preparation generally, resulted in an increase of the adhesion properties. Zinc coating did not give any promising result in both pin on disc and scratch tests. So, chromium coating is highly proposed to use in industry for rough handling part on component made of metal like mild steel.

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APPENDICES

APPENDIX 1: Surface Roughness Result
APPENDIX 2: Hardness Test Result
APPENDIX 3: Pin on Disc Test Result
APPENDIX 4: Scratch Test Result
APPENDIX 5: Standard Test Method for Wear Testing with Pin on Disc Apparatus

BEFORE COATING (CHROMIUM)

Cr T1R

READING	SIDE 1	SIDE 2
n1	1.115	1.638
n2	1.485	1.742
n3	1.412	1.966
n4	1.148	1.877
n5	1.277	1.638
n6	1.754	1.335
n7	1.637	1.271
n8	1.989	1.065
n9	2.003	1.087
n10	2.033	1.271
AVEREGE	**1.5853**	**1.489**

Cr T1S

READING	SIDE 1	SIDE 2
n1	0.039	0.058
n2	0.025	0.056
n3	0.032	0.054
n4	0.035	0.05
n5	0.03	0.049
n6	0.041	0.05
n7	0.047	0.036
n8	0.047	0.03
n9	0.043	0.026
n10	0.054	0.023
AVEREGE	**0.0393**	**0.0432**

Cr T2R

READING	SIDE 1	SIDE 2
n1	2.145	1.721
n2	1.929	1.138
n3	1.795	1.088
n4	1.639	1.373
n5	1.683	1.683
n6	1.482	2.017
n7	1.217	1.822
n8	1.026	1.948
n9	1.21	2.082
n10	1.469	2.233
AVEREGE	**1.5595**	**1.7105**

Cr T2S

READING	SIDE 1	SIDE 2
n1	0.029	0.069
n2	0.029	0.058
n3	0.027	0.053
n4	0.038	0.046
n5	0.053	0.045
n6	0.064	0.05
n7	0.068	0.045
n8	0.063	0.041
n9	0.067	0.032
n10	0.062	0.033
AVEREGE	**0.05**	**0.0472**

Cr T3R

READING	SIDE 1	SIDE 2
n1	1.77	2.384
n2	1.615	2.424
n3	1.265	2.113
n4	1.058	1.945
n5	2.061	1.612
n6	2.052	1.625
n7	1.843	1.583
n8	1.907	1.312
n9	2.548	1.655
n10	2.163	1.598
AVEREGE	**1.8282**	**1.8251**

Cr T3S

READING	SIDE 1	SIDE 2
n1	0.027	0.05
n2	0.031	0.045
n3	0.039	0.042
n4	0.03	0.044
n5	0.026	0.037
n6	0.046	0.026
n7	0.067	0.025
n8	0.053	0.026
n9	0.068	0.025
n10	0.07	0.025
AVEREGE	**0.0457**	**0.0345**

AFTER COATING (CHROMIUM)

Cr T1R

READING	SIDE 1	SIDE 2
n1	1.711	1.123
n2	1.796	1.085
n3	1.856	0.936
n4	1.745	0.748
n5	1.448	1.203
n6	1.004	1.648
n7	1.313	1.732
n8	0.877	1.939
n9	0.678	1.952
n10	0.852	1.911
AVEREGE	**1.328**	**1.4277**

Cr T1S

READING	SIDE 1	SIDE 2
n1	0.084	0.045
n2	0.073	0.048
n3	0.069	0.05
n4	0.079	0.046
n5	0.071	0.055
n6	0.042	0.079
n7	0.047	0.075
n8	0.05	0.071
n9	0.047	0.073
n10	0.052	0.079
AVEREGE	**0.0614**	**0.0621**

Cr T2R

READING	SIDE 1	SIDE 2
n1	0.831	1.508
n2	0.876	1.67
n3	1.302	1.702
n4	0.993	1.798
n5	1.246	1.768
n6	1.927	1.134
n7	1.926	1.066
n8	1.783	0.589
n9	1.429	0.737
n10	1.577	1.016
AVEREGE	**1.389**	**1.2988**

Cr T2S

READING	SIDE 1	SIDE 2
n1	0.082	0.055
n2	0.048	0.046
n3	0.048	0.048
n4	0.059	0.049
n5	0.072	0.049
n6	0.047	0.065
n7	0.047	0.046
n8	0.061	0.048
n9	0.043	0.059
n10	0.049	0.073
AVEREGE	**0.0556**	**0.0538**

Cr T3R

READING	SIDE 1	SIDE 2
n1	0.936	1.858
n2	1.19	1.853
n3	0.729	1.738
n4	0.805	1.68
n5	0.838	1.135
n6	1.219	1.02
n7	1.284	1.053
n8	1.492	1.174
n9	1.552	1.075
n10	1.607	0.859
AVEREGE	**1.1652**	**1.3445**

Cr T3S

READING	SIDE 1	SIDE 2
n1	0.074	0.088
n2	0.081	0.114
n3	0.115	0.109
n4	0.117	0.075
n5	0.111	0.066
n6	0.086	0.084
n7	0.127	0.092
n8	0.094	0.112
n9	0.071	0.119
n10	0.078	0.122
AVEREGE	**0.0954**	**0.0981**

BEFORE COATING (ZINC)

Zn R

READING	SIDE 1	SIDE 2
n1	2.535	2.694
n2	2.336	2.749
n3	2.947	2.508
n4	2.368	2.051
n5	2.42	2.113
n6	2.571	2.556
n7	2.399	2.27
n8	2.4	2.285
n9	2.155	2.272
n10	2.04	2.596
AVEREGE	**2.4171**	**2.4094**

Zn S

READING	SIDE 1	SIDE 2
n1	0.023	0.048
n2	0.023	0.049
n3	0.024	0.048
n4	0.022	0.055
n5	0.03	0.053
n6	0.056	0.056
n7	0.052	0.043
n8	0.056	0.044
n9	0.049	0.039
n10	0.053	0.053
AVEREGE	**0.0388**	**0.0488**

AFTER COATING (ZINC)

Zn R

READING	SIDE 1	SIDE 2
n1	1.959	2.553
n2	2.204	1.696
n3	2.101	1.529
n4	2.234	1.439
n5	2.535	1.925
n6	2.276	2.324
n7	1.962	2.356
n8	1.783	2.197
n9	1.746	2.818
n10	1.891	2.595
AVEREGE	**2.0691**	**2.1432**

Zn S

READING	SIDE 1	SIDE 2
n1	0.219	0.242
n2	0.203	0.273
n3	0.194	0.217
n4	0.164	0.363
n5	0.164	0.242
n6	0.167	0.258
n7	0.15	0.276
n8	0.174	0.251
n9	0.213	0.213
n10	0.296	0.252
AVEREGE	**0.1944**	**0.2587**

HARDNESS TEST RESULT

Cr Uncoated1

	d1	d2	Hv
y1	13.03	13.45	256.3
y2	14.73	15.57	191.2
y3	15.58	14.09	233.5
y4	17.7	17.25	155.8
y5	14.59	14.26	228
x1	12.92	13.45	256.3
x2	17.22	15.92	182.9
x3	15.58	14.09	233.5
x4	13.8	14.13	232.2
x5	13.3	14.62	216.9
Average			218.66

Cr Smooth1

	d1	d2	Hv
y1	9.31	10	463.6
y2	10.81	10.06	458.1
y3	10.1	9.93	470.2
y4	9.27	9.9	473
y5	9.73	9.85	477.8
x1	9.67	9.9	473
x2	9.93	10.17	448.2
x3	10.1	9.93	470.2
x4	10.44	10.05	459
x5	10.05	9.82	480.8
Average			467.39

Cr Rough1

	d1	d2	Hv
y1	7.78	10.39	429.4
y2	7.54	12.65	289.7
y3	9.26	9.72	490.7
y4	10.64	9.81	481.7
y5	10.16	10.13	451.8
x1	9.49	11.39	357.4
x2	10.1	9.26	540.7
x3	9.26	9.72	490.7
x4	9.37	8.84	593.3
x5	10.35	9.09	561.1
Average			468.65

Cr Uncoated2

	d1	d2	Hv
y1	17.11	19.75	118.9
y2	14.36	15.03	205.2
y3	15.36	14.59	217.8
y4	13.77	13.24	264.5
y5	14.65	13.79	243.8
x1	14.07	14.68	215.1
x2	14.46	15.51	192.7
x3	15.36	14.59	217.8
x4	14.03	14.53	219.6
x5	13.62	14.47	221.4
Average			211.68

Cr Smooth2

	d1	d2	Hv
y1	6.88	7.57	806.9
y2	7.41	7.93	737.2
y3	7.18	7.39	848.9
y4	7.71	7.44	837.5
y5	7.52	7.68	786
x1	7.65	7.4	846.6
x2	7.27	7.41	844.3
x3	7.18	7.39	848.9
x4	7.43	7.56	833
x5	7.27	7.56	811.1
Average			820.04

Cr Rough2

	d1	d2	Hv
y1	8.38	7.54	815.5
y2	8.79	8.32	669.7
y3	8.14	8.57	631.2
y4	9.81	9.02	569.8
y5	8.38	8.11	704.9
x1	7.69	8.84	593.3
x2	9.13	10.28	438.7
x3	8.14	8.57	631.2
x4	8.72	9.13	556.2
x5	8.11	8.83	594.6
Average			620.51

Cr Uncoated3

	d1	d2	Hv
y1	12.7	14.64	216.3
y2	20.18	21.88	96.6
y3	14.44	13.98	237.2
y4	14.58	15.32	197.5
y5	13.9	14.07	234.2
x1	14.04	15.65	189.3
x2	13.95	14.43	222.6
x3	14.44	13.98	237.2
x4	14.47	15.82	185.2
x5	13.94	13.59	251
Average			206.71

Cr Smooth3

	d1	d2	Hv
y1	7.05	7.18	899.3
y2	7.22	7.15	906.8
y3	7.03	7.23	886.9
y4	7.1	7.34	860.5
y5	6.44	7.01	943.4
x1	7	7.33	862.9
x2	7.23	7.23	886.9
x3	7.03	7.23	886.9
x4	7.11	7.15	906.8
x5	7.13	7.24	884.4
Average			892.48

Cr Rough3

	d1	d2	Hv
y1	8.44	8.06	713.6
y2	9.4	8.26	679.5
y3	8.69	7.38	851.2
y4	7.81	8.7	612.5
y5	9.1	7.64	794.2
x1	7.17	8.42	701.4
x2	7.12	7.79	764
x3	8.69	7.38	851.2
x4	8.27	8.01	722.6
x5	10.69	7.35	858.2
Average			754.84

Zn Uncoated

	d1	d2	Hv
y1	13.03	13.45	256.3
y2	14.44	13.98	237.2
y3	13.9	14.07	234.2
y4	14.46	15.51	192.7
y5	14.59	14.26	228
x1	12.92	13.45	256.3
x2	14.47	15.82	185.2
x3	12.7	14.64	216.3
x4	13.8	14.13	232.2
x5	17.11	19.75	118.9
Average			215.73

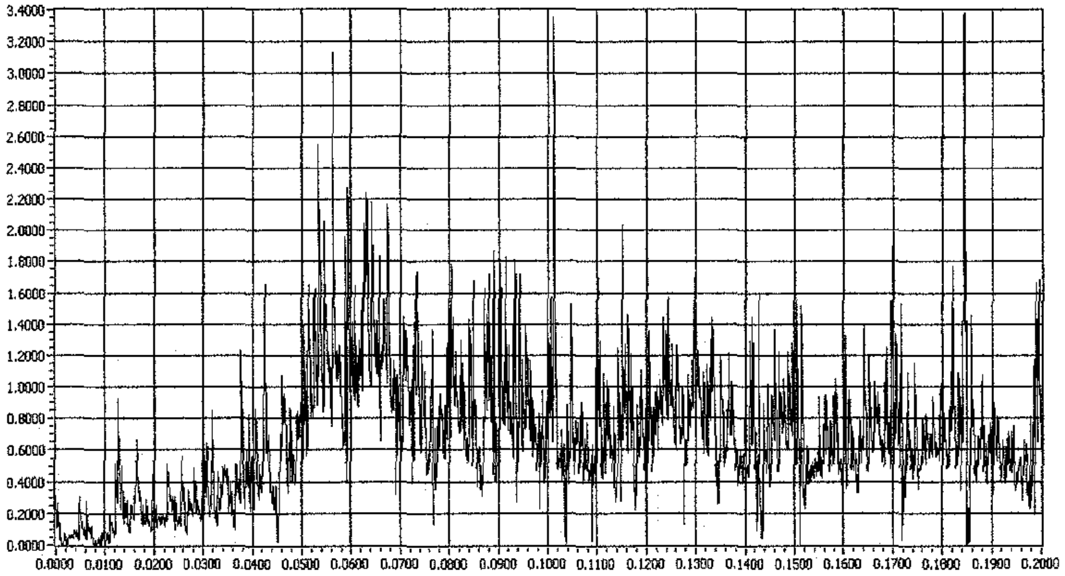
Zn Smooth

	d1	d2	Hv
y1	20.1	20.49	110.4
y2	19.43	19.26	125
y3	18.66	19.21	125.6
y4	19.16	20.03	115.6
y5	20.75	20.05	115.3
x1	19.9	19.92	116.8
x2	19.32	19.59	120.8
x3	18.66	19.21	125.6
x4	18.91	19.77	118.6
x5	20.76	21.78	97.7
Average			117.14

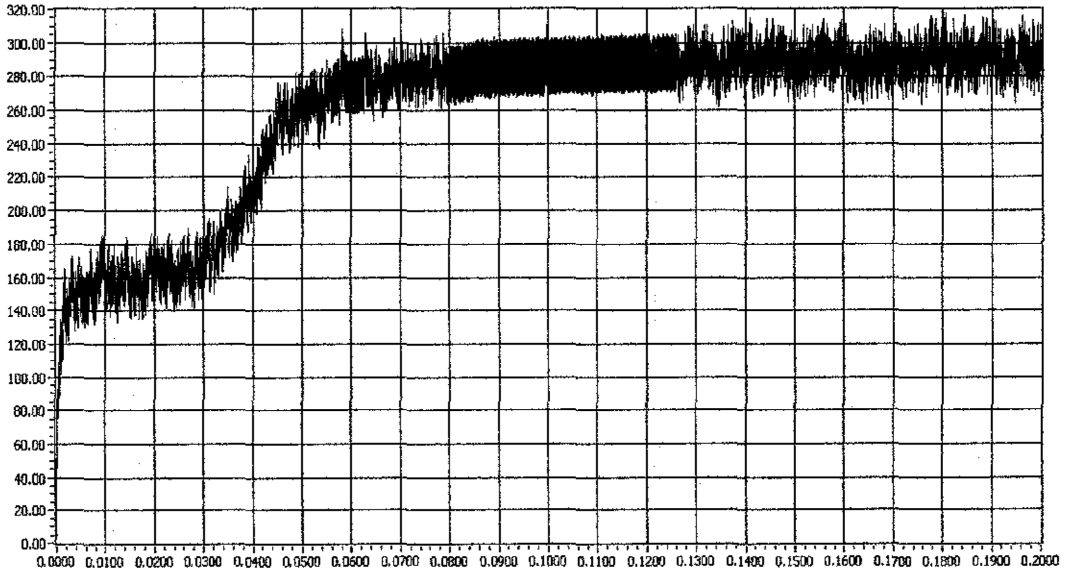
Zn Rough

	d1	d2	Hv
y1	17.75	20.12	114.5
y2	20.3	18.84	130.6
y3	18.55	20.12	114.5
y4	20.22	20.22	113.4
y5	19.41	20.08	115
x1	17.19	17.49	151.6
x2	20.88	19.33	124.1
x3	18.55	20.12	114.5
x4	20.14	19.47	122.3
x5	20.83	20.03	115.6
Average			121.61

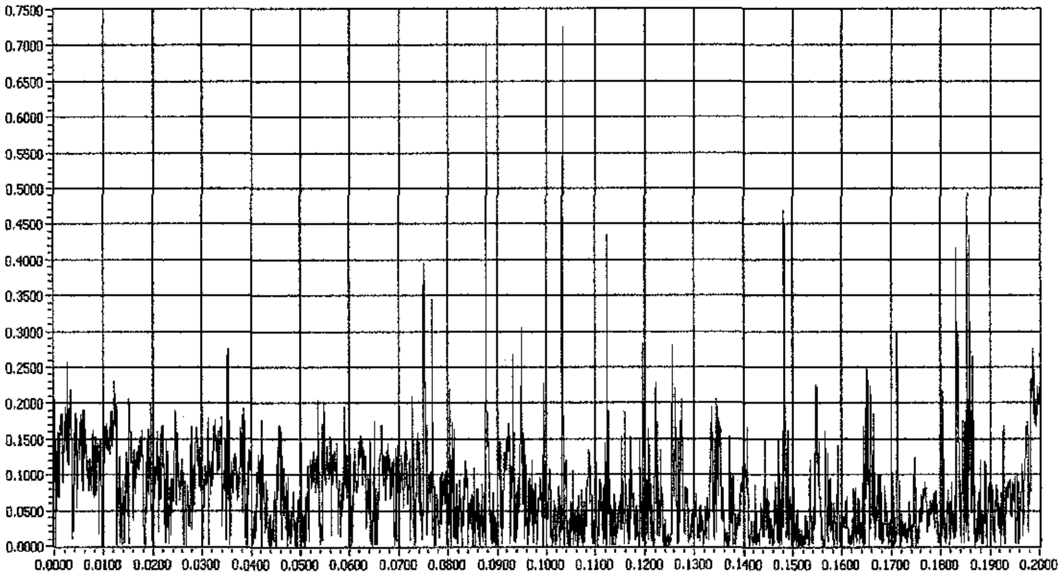
PIN ON DISC TEST RESULT



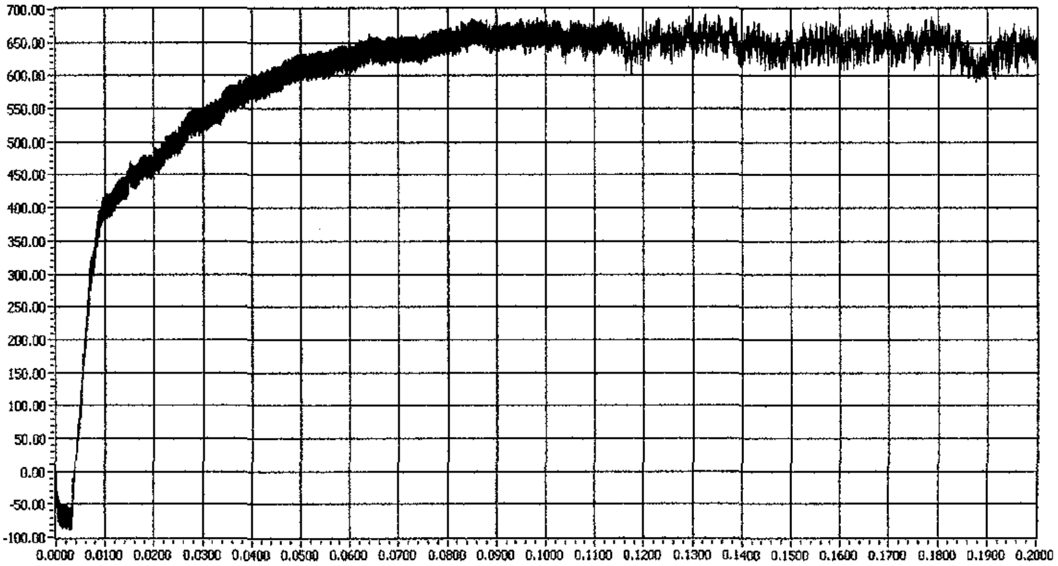
Uncoated: Coefficient of Friction



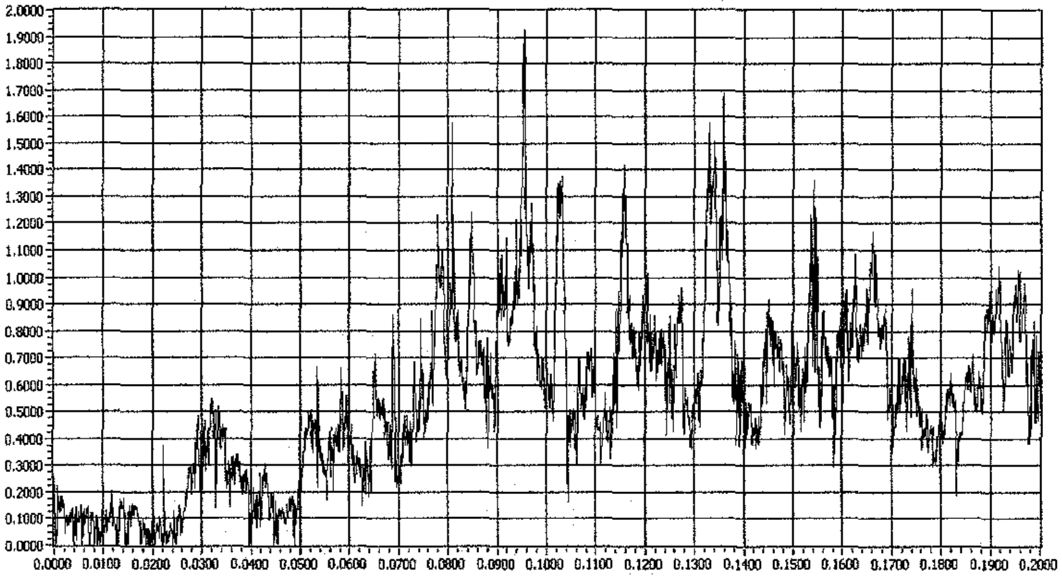
Uncoated: Wear



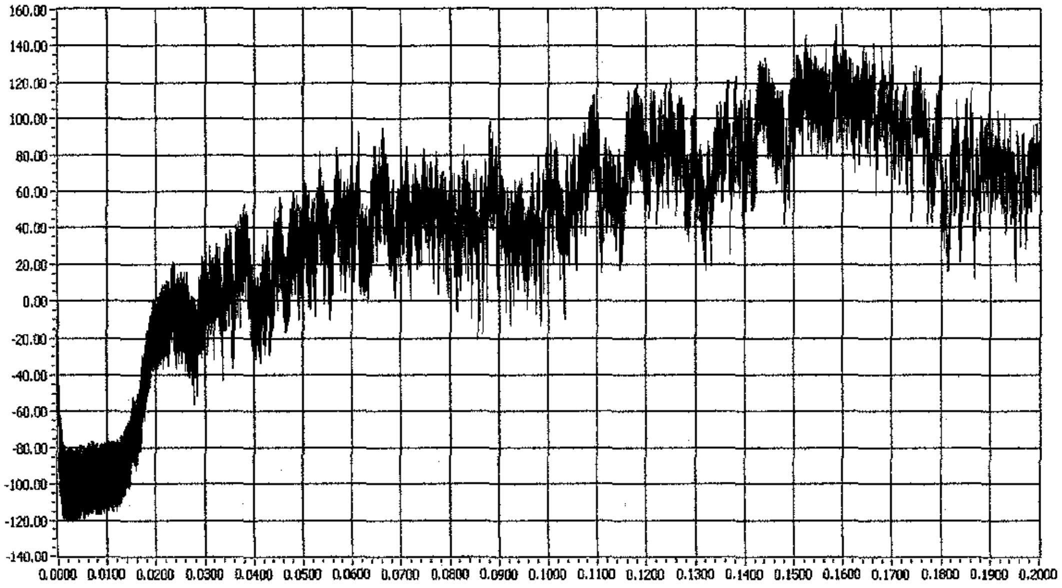
Cr T1S: Coefficient of Friction



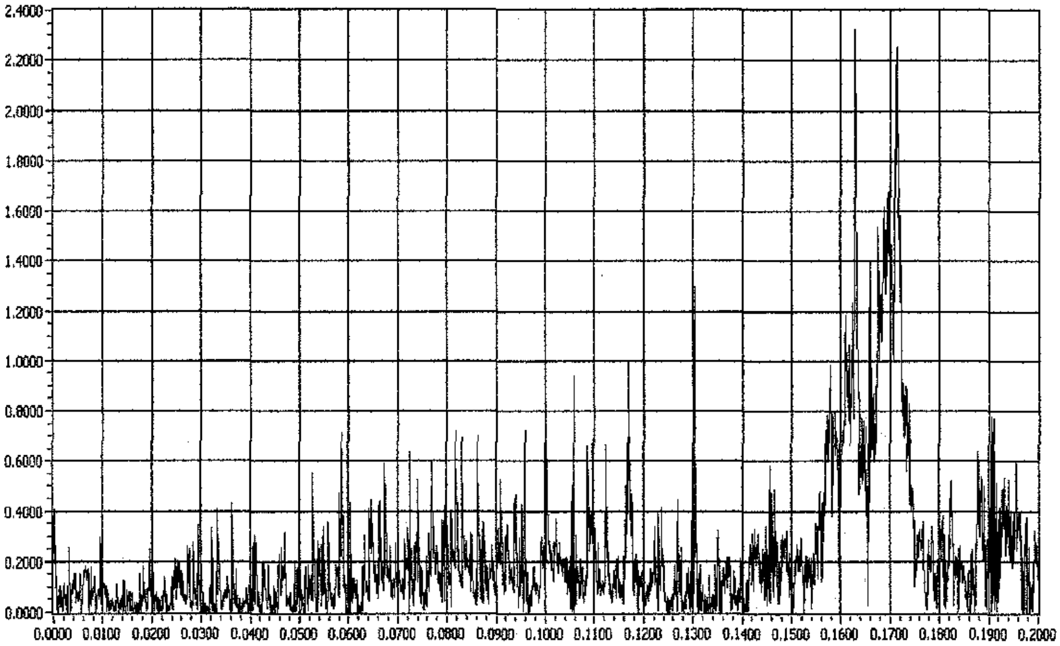
Cr T1S: Wear



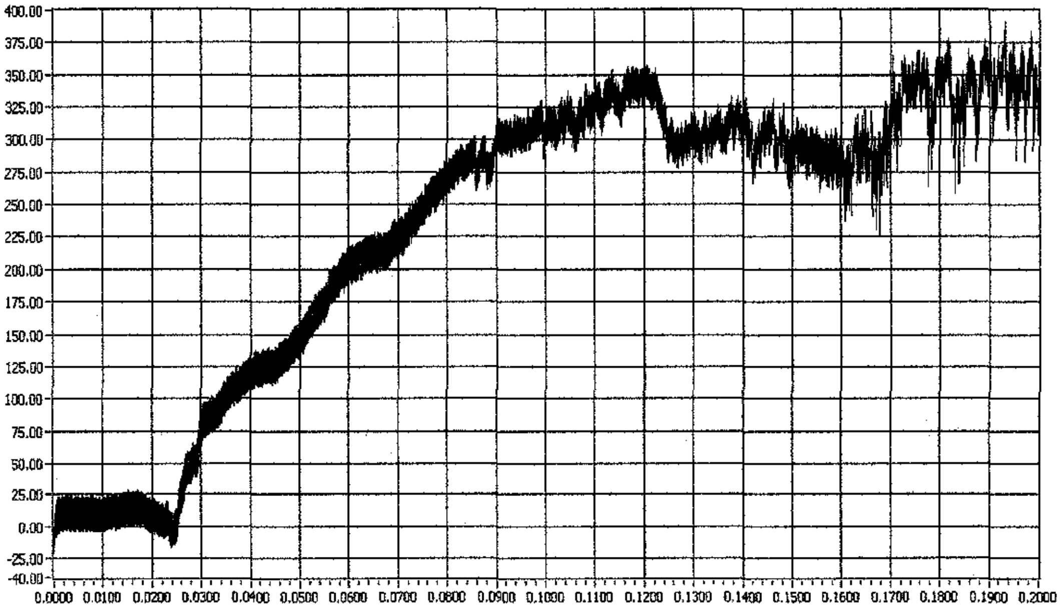
Cr T2S: Coefficient of Friction



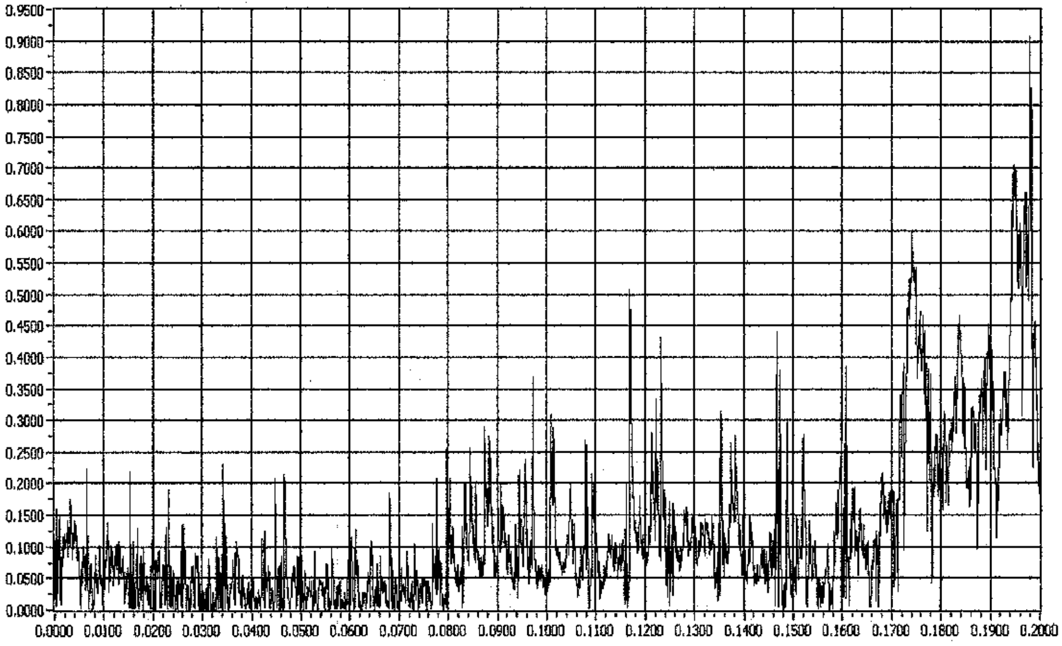
Cr T2S: Wear



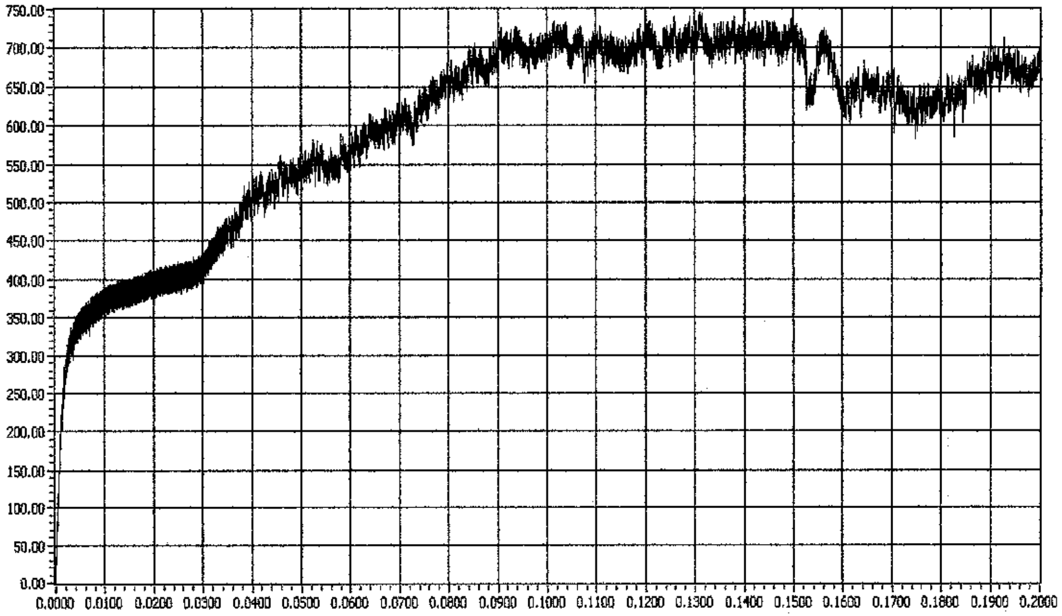
Cr T3S: Coefficient of Friction



Cr T3S: Wear



Cr T1R: Coefficient of Friction



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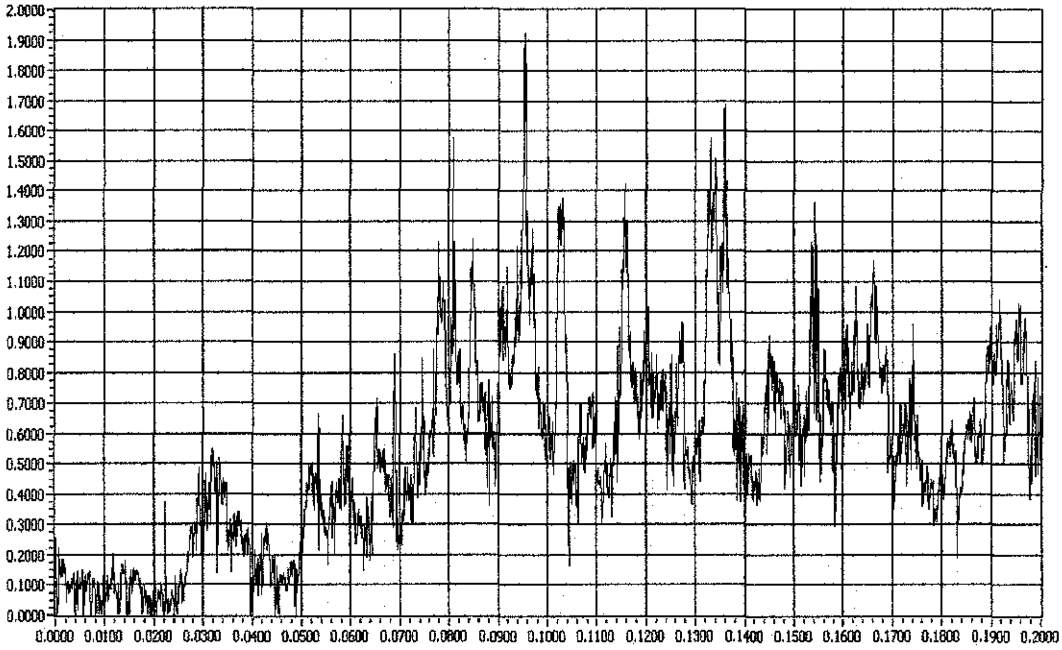
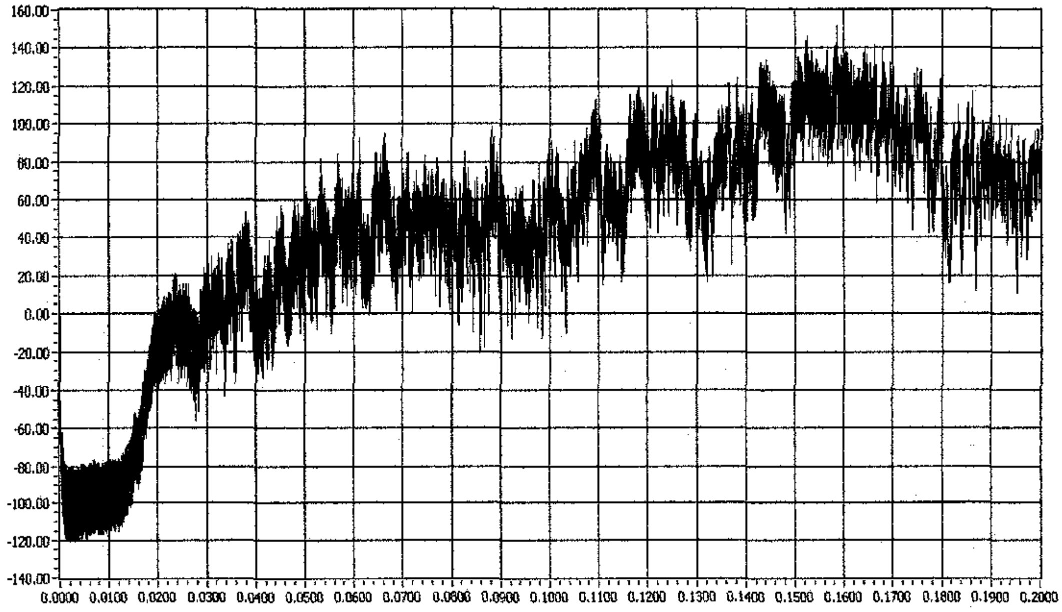
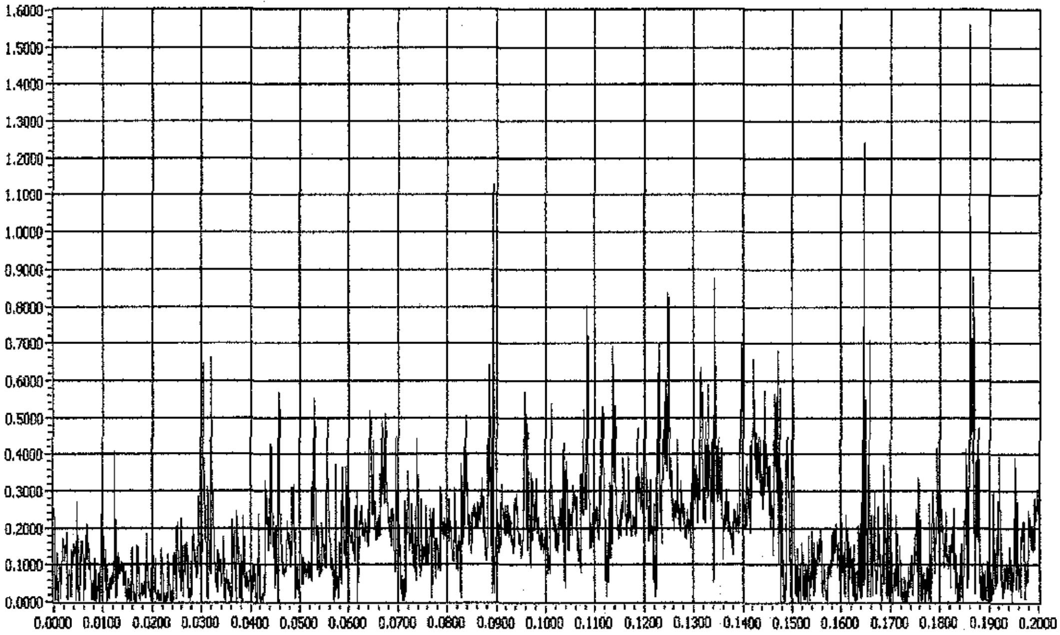


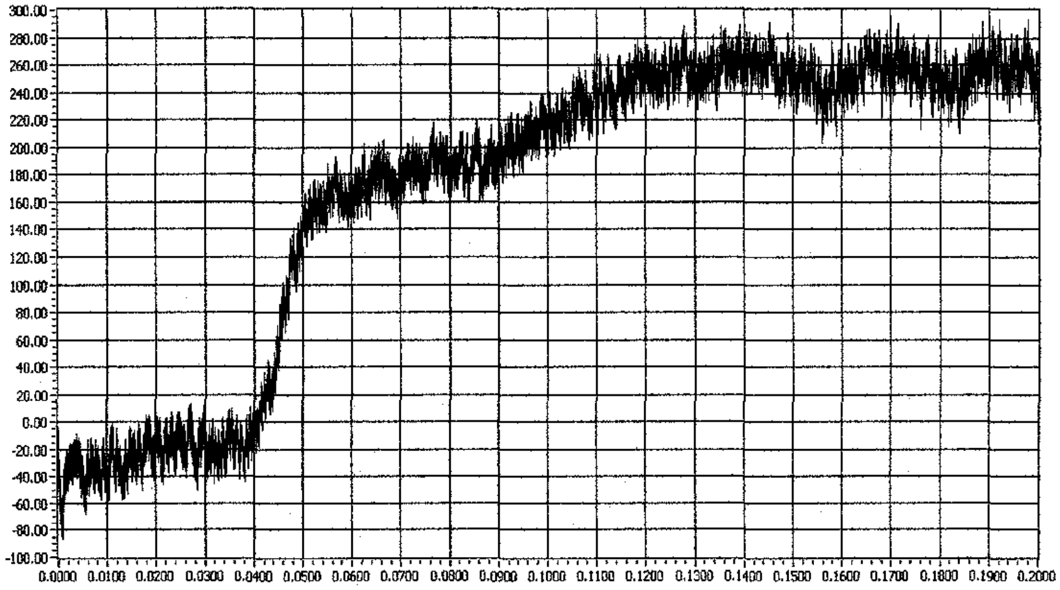
Cr T2R: Coefficient of Friction



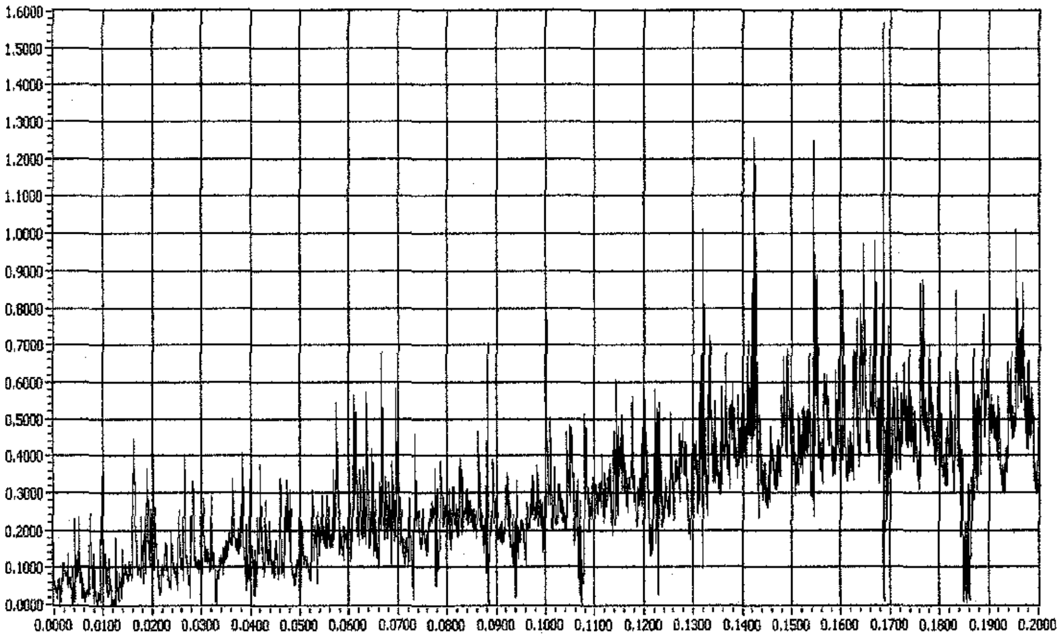
Cr T2R: Wear



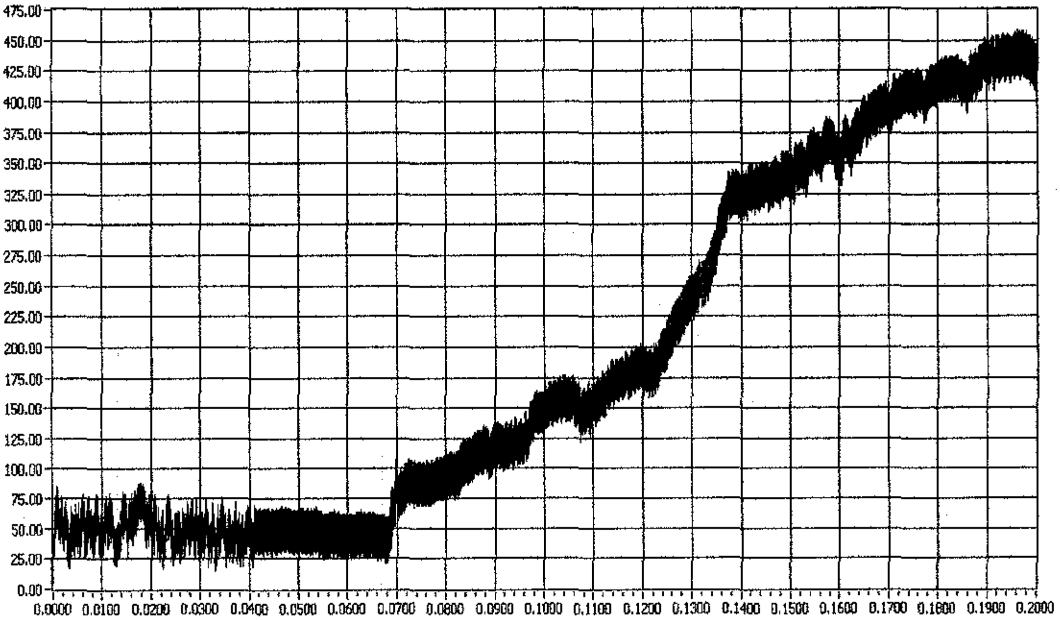
Cr T3R: Coefficient of Friction



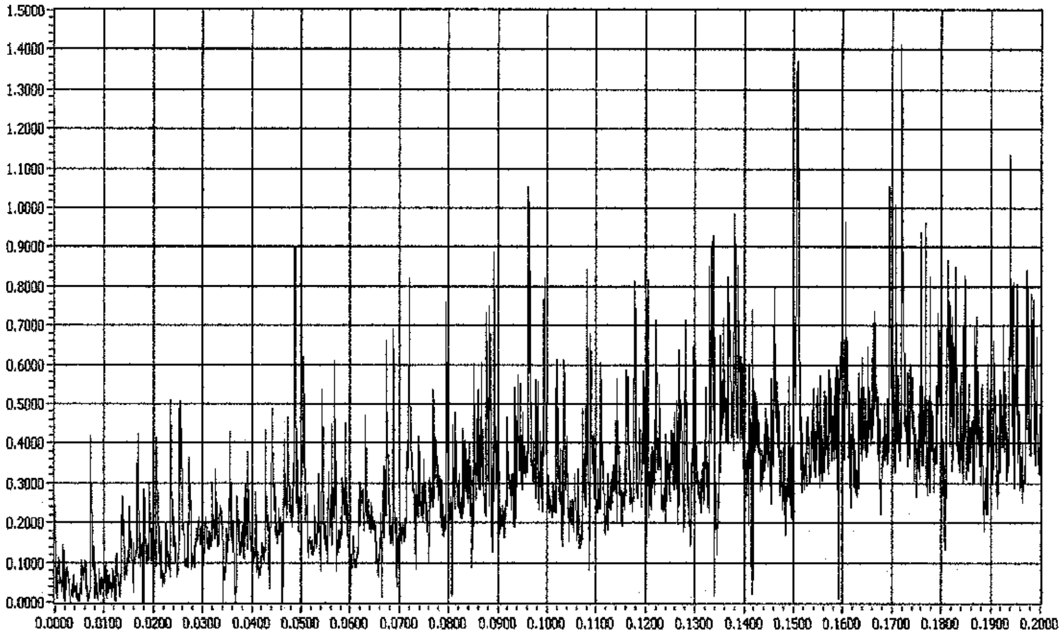
Cr T3R: Wear



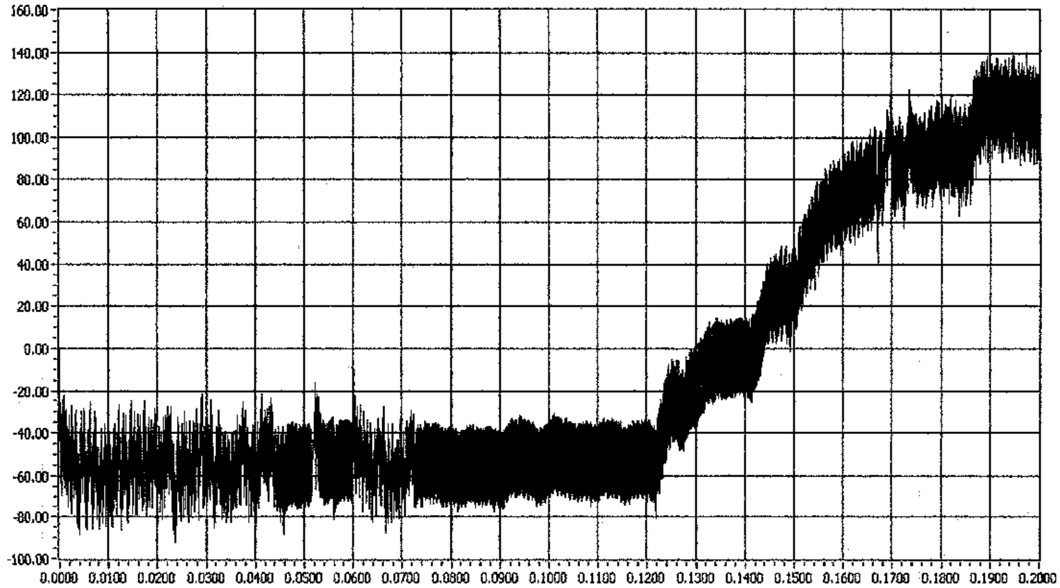
ZnS: Coefficient of Friction



ZnS: Wear

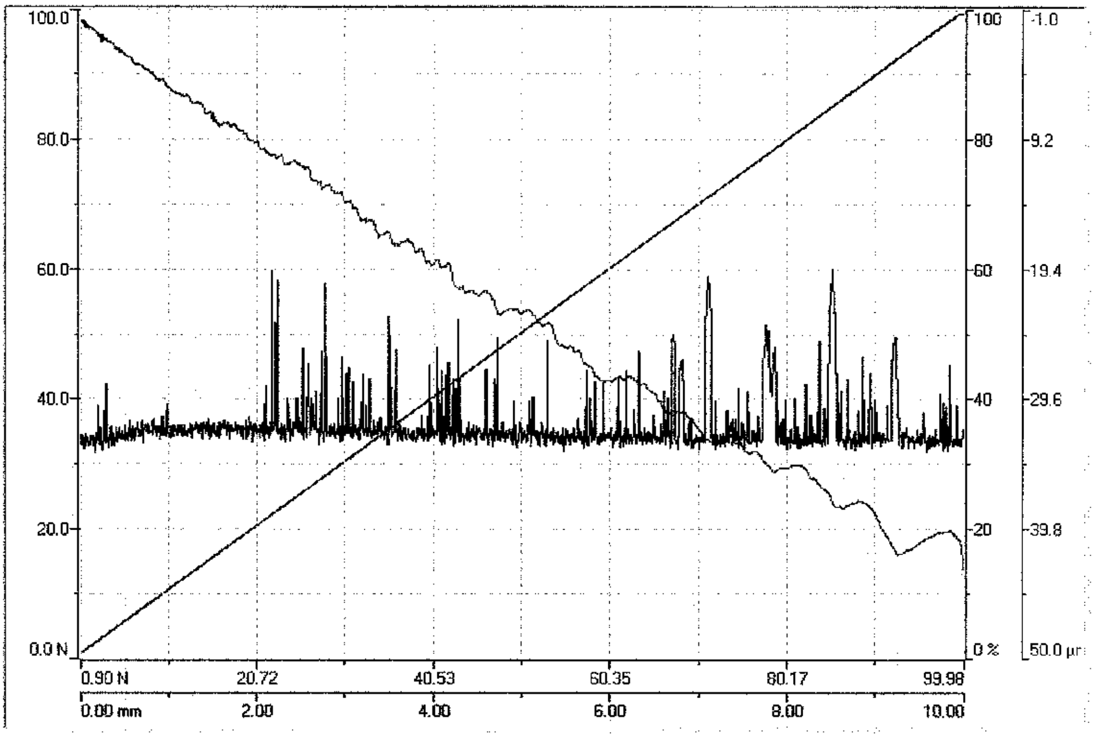


ZnR: Coefficient of Friction

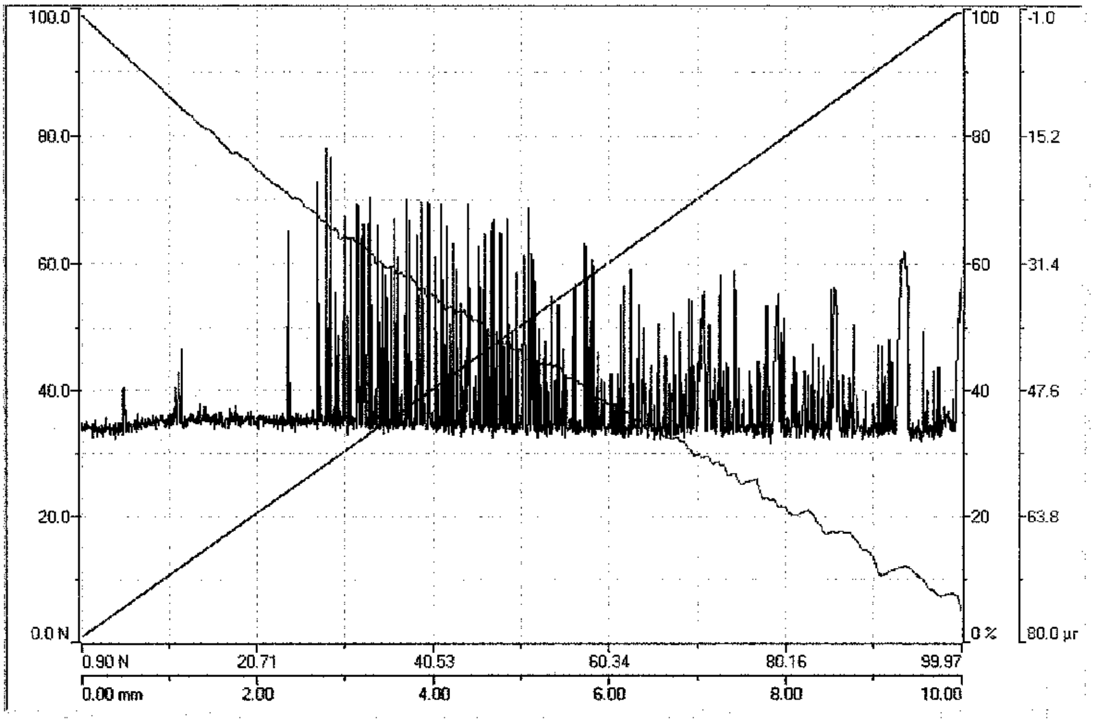


ZnR: Wear

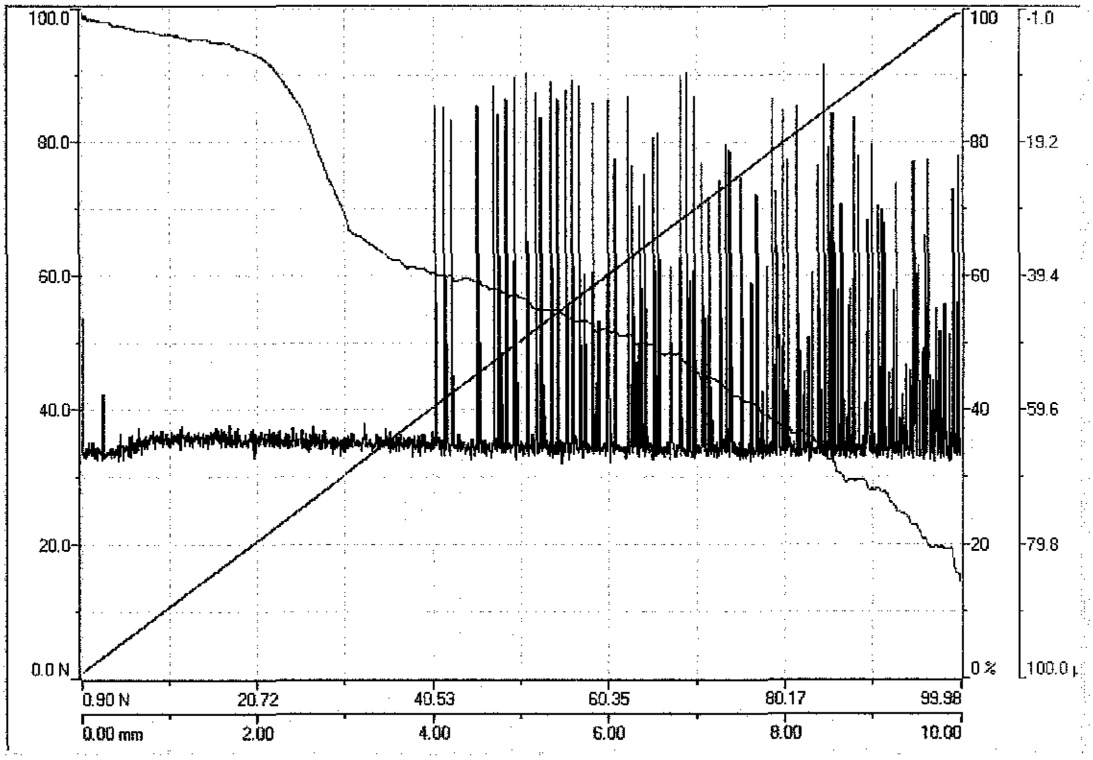
SCRATCH TEST RESULT



Cr T1S



Cr T2S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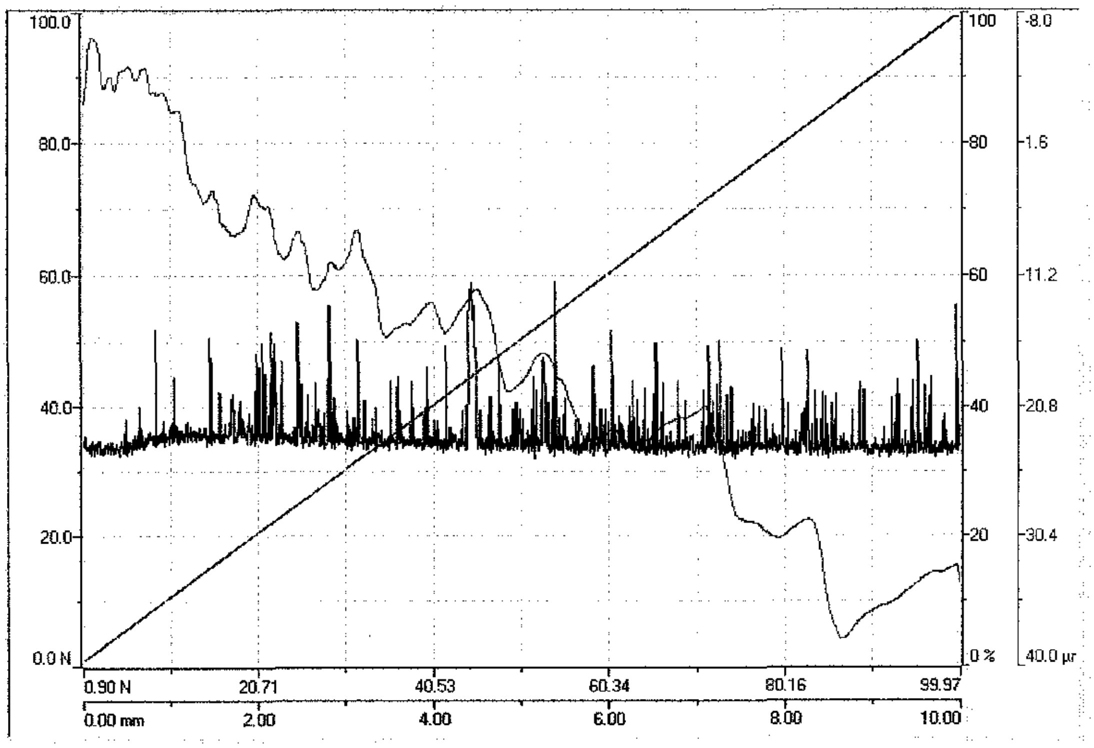
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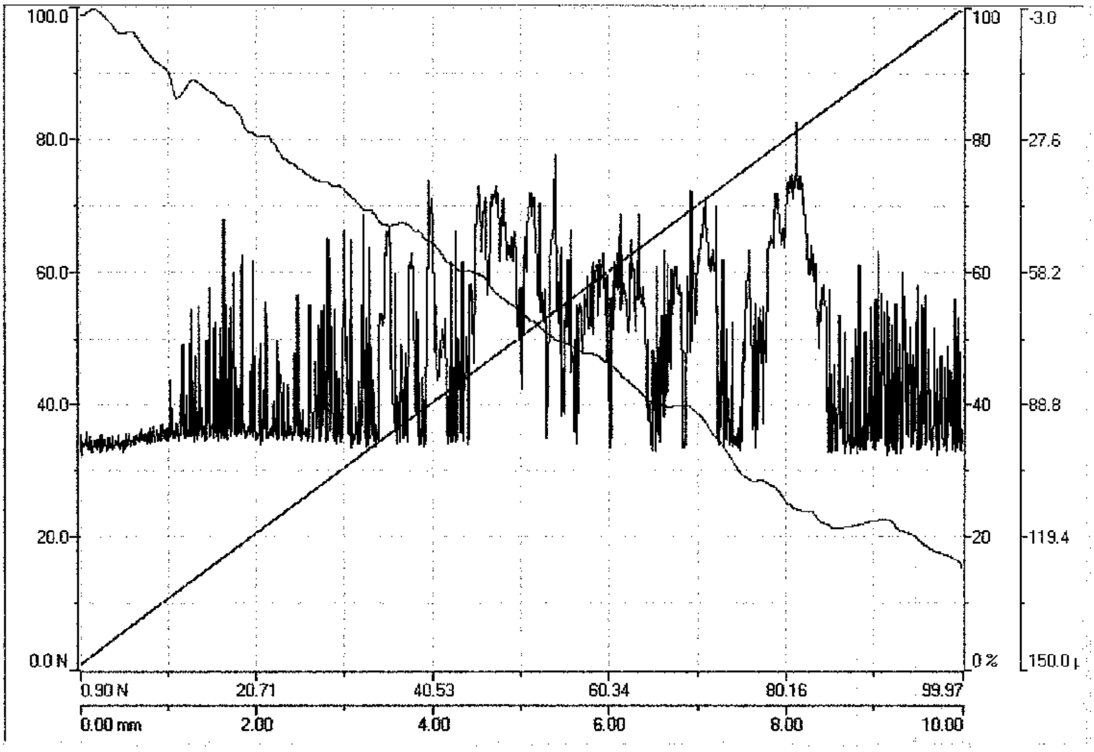
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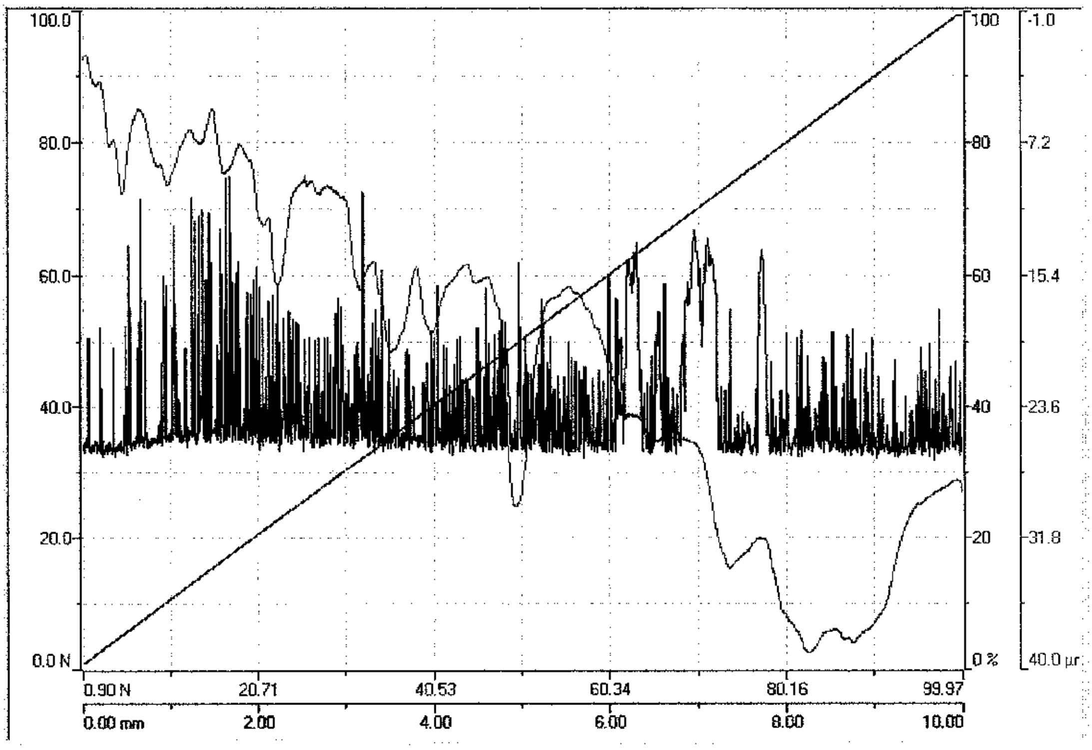
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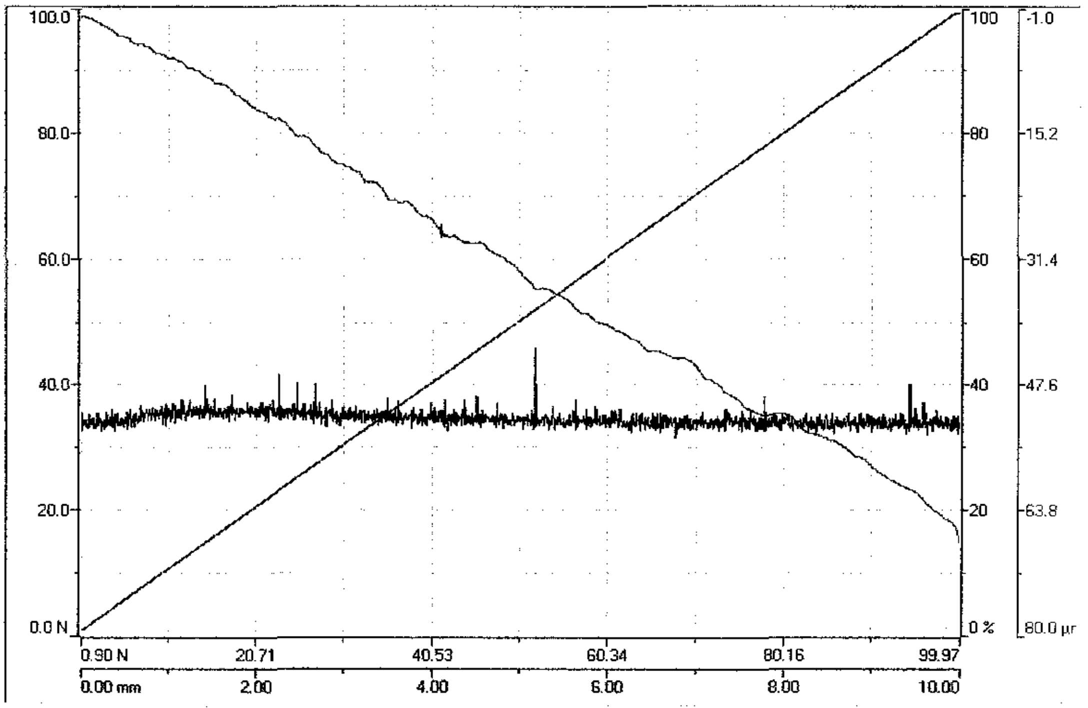
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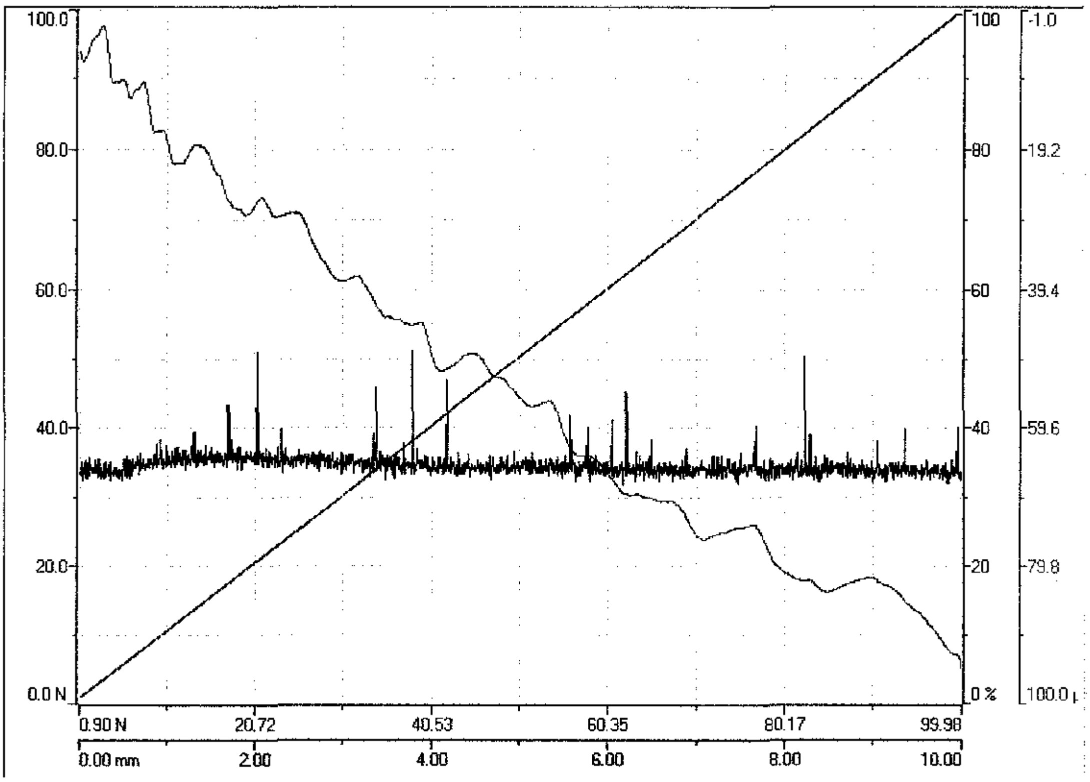
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Zn R

Designation: G 99 – 05

Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus[1]

This standard is issued under the fixed designation G 99; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a laboratory procedure for determining the wear of materials during sliding using a pin-on-disk apparatus. Materials are tested in pairs under nominally non-abrasive conditions. The principal areas of experimental attention in using this type of apparatus to measure wear are described. The coefficient of friction may also be determined.

1.2 The values stated in SI units are to be regarded as standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:* [2]

E 178 Practice for Dealing with Outlying Observations

G 40 Terminology Relating to Wear and Erosion

G 117 Guide for Calculating and Reporting Measures of Precision using Data from Interlaboratory Wear or Erosion Tests

2.2 *Other Standard:*[3]

DIN-50324 Testing of Friction and Wear

3. Summary of Test Method

3.1 For the pin-on-disk wear test, two specimens are required. One, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as the pin specimen. The test machine causes either the disk specimen or the pin specimen to revolve about the disk center. In either case, the sliding path is a circle on the disk surface. The plane of the disk may be oriented either horizontally or vertically.

NOTE 1—Wear results may differ for different orientations.

3.1.1 The pin specimen is pressed against the disk at a specified load usually by means of an arm or lever and attached weights. Other loading methods have been used, such as hydraulic or pneumatic.

NOTE 2—Wear results may differ for different loading methods.

3.2 Wear results are reported as volume loss in cubic millimetres for the pin and the disk separately. When two different materials are tested, it is recommended that each material be tested in both the pin and disk positions.

3.3 The amount of wear is determined by measuring appropriate linear dimensions of both specimens before and after the test, or by weighing both specimens before and after the test. If linear measures of wear are used, the length change or shape change of the pin, and the depth or shape change of the disk wear track (in millimetres) are determined by any suitable metrological technique, such as electronic distance gaging or stylus profiling. Linear measures of wear are converted to wear volume (in cubic millimetres) by using appropriate geometric relations. Linear measures of wear are used frequently in practice since mass loss is often too small to measure precisely. If loss of mass is measured, the mass loss value is converted to volume loss (in cubic millimetres) using an appropriate value for the specimen density.

3.4 Wear results are usually obtained by conducting a test for a selected sliding distance and for selected values of load and speed. One set of test conditions that was used in an interlaboratory measurement series is given in Table 1 and Table 2 as a guide. Other test conditions may be selected depending on the purpose of the test.

3.5 Wear results may in some cases be reported as plots of wear volume versus sliding distance using different specimens for different distances. Such plots may display non-linear relationships between wear volume and distance over certain portions of the total sliding distance, and linear relationships over other portions. Causes for such differing relationships include initial "break-in" processes, transitions between regions of different dominant wear mechanisms, and so forth.

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[1] This test method is under the jurisdiction of ASTM Committee G02 on Wear and Erosion and is the direct responsibility of Subcommittee G02.40 on Non-Abrasive Wear.

Current edition approved May 1, 2005. Published May 2005. Originally approved in 1990. Last previous edition approved in 2004 as G 99 – 04a.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from Beuth Verlag GmbH, Burggrafenstrasse 6, 1000 Berlin 30, Germany.

TABLE 1 Characteristics of the Interlaboratory Wear Test Specimens

NOTE—See Note 4 in 10.3.1 for information.

	Composition (weight%)	Microstructure	Hardness (HV 10)	Roughness[A]	
				R_z(mean) (μm)	R_a(mean) (
Steel ball (100 Cr6) (AISI 52 100)[B] Diameter 10 mm	1.35 to 1.65 Cr ← 0.95 to 1.10 C 0.15 to 0.35 Si 0.25 to 0.45 Mn	martensitic with minor carbides and austenite	838 ± 21	0.100	0.010
Steel disc (100 Cr6) (AISI 52 100)[C] Diameter 40 mm	← <0.030 P <0.030 S	martensitic with minor carbides and austenite	852 ± 14	0.952	0.113
Alumina ball, diameter = 10 mm[D]	← 95 % Al_2O_3 (with additives of TiO_2,	equi-granular alpha alumina with very minor secondary phases	1610 ± 101 (HV 0.2)	1.369	0.123
Alumina disc, diameter = 40.6 mm[D]	← MgO, and ZnO)		1599 ± 144 (HV 0.2)	0.968	0.041

[A] Measured by stylus profilometry. R_z is maximum peak-to-valley roughness. R_a is arithmetic average roughness.

[B] Standard ball-bearing balls (SKF).

[C] Standard spacers for thrust bearings (INA).

[D] Manufactured by Compagnie Industrielle des Ceramiques Electroniques, France.

TABLE 2 Results of the Interlaboratory Tests[A]

NOTE 1— See Note 4 in 10.3.1.

NOTE 2—Numbers in parentheses refer to all data received in the tests. In accordance with Practice E 178, outlier data values were identified in cases and discarded, resulting in the numbers without parentheses. The differences are seen to be small.

NOTE 3—Values preceded by ± are one standard deviation.

NOTE 4—Data were provided by 28 laboratories.

NOTE 5—Calculated quantities (for example, wear volume) are given as mean values only.

NOTE 6—Values labeled "NM" were found to be smaller than the reproducible limit of measurement.

NOTE 7—A similar compilation of test data is given in DIN-50324.

Results (ball) (disk)	Specimen Pairs			
	Steel-steel	Alumina-steel	Steel-alumina	Alumina-alumina
Ball wear scar diameter (mm)	2.11 ± 0.27 (2.11 ± 0.27)	NM	2.08 ± 0.35 (2.03 ± 0.41)	0.3± 0.06 (0.3 ± 0.06)
Ball wear volume (10^{-3} mm^3)	198 (198)	...	186 (169)	0.08 (0.08)
Number of values	102 (102)	...	60 (64)	56 (59)
Disk wear scar width (mm)	NM	0.64 ± 0.12 (0.64 ± 0.12)	NM	NM
Disk wear volume (10^{-3} mm^3)	...	480 (480)	...	...
Number of values	...	60 (60)	...	...
Friction coefficient	0.60 ± 0.11	0.76 ± 0.14	0.60 ± 0.12	0.41 ± 0.08
Number of values	109	75	64	76

[A] Test conditions: $F = 10$ N; $v = 0.1$ ms $^{-1}$, $T = 23°C$; relative humidity range 12 to 78 %; laboratory air; sliding distance 1000 m; wear track (nominal) diameter = materials: steel = AISI 52 100; and alumina = α-Al_2O_3.

The extent of such non-linear periods depends on the details of the test system, materials, and test conditions.

3.6 It is not recommended that continuous wear depth data obtained from position-sensing gages be used because of the complicated effects of wear debris and transfer films present in the contact gap, and interferences from thermal expansion or contraction.

4. Significance and Use

4.1 The amount of wear in any system will, in general, depend upon the number of system factors such as the applied load, machine characteristics, sliding speed, sliding distance, the environment, and the material properties. The value of any wear test method lies in predicting the relative ranking of material combinations. Since the pin-on-disk test method does not attempt to duplicate all the conditions that may be experienced in service (for example; lubrication, load, pressure, contact geometry, removal of wear debris, and pr of corrosive environment), there is no insurance that t will predict the wear rate of a given material under con differing from those in the test.

5. Apparatus

5.1 *General Description*—Fig. 1 shows a schematic ing of a typical pin-on-disk wear test system.[4] One t typical system consists of a driven spindle and chu holding the revolving disk, a lever-arm device to hold t

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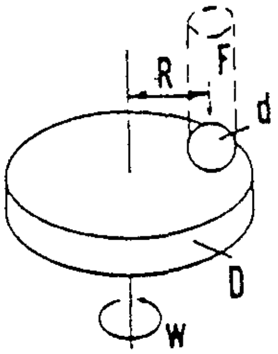
[4] A number of other reported designs for pin-on-disk systems are giv Catalog of Friction and Wear Devices," American Society of Lubrication E (1973). Three commercially-built pin-on-disk machines were either involv interlaboratory testing for this standard or submitted test data that c adequately to the interlaboratory test data. Further information on these can be found in Research Report RR: G02–1008.



Note—*F* is the normal force on the pin, *d* is the pin or ball diameter, *D* is the disk diameter, *R* is the wear track radius, and *w* is the rotation velocity the disk.

FIG. 1 Schematic of pin-on-disk wear test system.

d attachments to allow the pin specimen to be forced against revolving disk specimen with a controlled load. Another pe of system loads a pin revolving about the disk center inst a stationary disk. In any case the wear track on the disk a circle, involving multiple wear passes on the e track. The system may have a friction force measuring stem, for example, a load cell, that allows the coefficient of ction to be determined.

5.2 *Motor Drive*—A variable speed motor, capable of main- ning constant speed (±1 % of rated full load motor speed) der load is required. The motor should be mounted in such manner that its vibration does not affect the test. Rotating eeds are typically in the range 0.3 to 3 rad/s (60 to 600 min).

5.3 *Revolution Counter*—The machine shall be equipped th a revolution counter or its equivalent that will record the mber of disk revolutions, and preferably have the ability to t off the machine after a pre-selected number of revolutions.

5.4 *Pin Specimen Holder and Lever Arm*—In one typical stem, the stationary specimen holder is attached to a lever n that has a pivot. Adding weights, as one option of loading, duces a test force proportional to the mass of the weights plied. Ideally, the pivot of the arm should be located in the ne of the wearing contact to avoid extraneous loading forces e to the sliding friction. The pin holder and arm must be of stantial construction to reduce vibrational motion during the t.

5.5 *Wear Measuring Systems*—Instruments to obtain linear asures of wear should have a sensitivity of 2.5 µm or better. y balance used to measure the mass loss of the test specimen ll have a sensitivity of 0.1 mg or better; in low wear ations greater sensitivity may be needed.

Test Specimens and Sample Preparation

.1 *Materials*—This test method may be applied to a variety naterials. The only requirement is that specimens having the cified dimensions can be prepared and that they will nstand the stresses imposed during the test without failure excessive flexure. The materials being tested shall be cribed by dimensions, surface finish, material type, form, position, microstructure, processing treatments, and inden- n hardness (if appropriate).

6.2 *Test Specimens*—The typical pin specimen is cylindrical or spherical in shape. Typical cylindrical or spherical pin specimen diameters range from 2 to 10 mm. The typical disk specimen diameters range from 30 to 100 mm and have a thickness in the range of 2 to 10 mm. Specimen dimensions used in an interlaboratory test with pin-on-disk systems are given in Table 1.

6.3 *Surface Finish*—A ground surface roughness of 0.8 µm (32 µin.) arithmetic average or less is usually recommended.

Note 3—Rough surfaces make wear scar measurement difficult.

6.3.1 Care must be taken in surface preparation to avoid subsurface damage that alters the material significantly. Special surface preparation may be appropriate for some test programs. State the type of surface and surface preparation in the report.

7. Test Parameters

7.1 *Load*—Values of the force in Newtons at the wearing contact.

7.2 *Speed*—The relative sliding speed between the contacting surfaces in metres per second.

7.3 *Distance*—The accumulated sliding distance in meters.

7.4 *Temperature*—The temperature of one or both specimens at locations close to the wearing contact.

7.5 *Atmosphere*—The atmosphere (laboratory air, relative humidity, argon, lubricant, and so forth.) surrounding the wearing contact.

8. Procedure

8.1 Immediately prior to testing, and prior to measuring or weighing, clean and dry the specimens. Take care to remove all dirt and foreign matter from the specimens. Use non-chlorinated, non-film-forming cleaning agents and solvents. Dry materials with open grains to remove all traces of the cleaning fluids that may be entrapped in the material. Steel (ferromagnetic) specimens having residual magnetism should be demagnetized. Report the methods used for cleaning.

8.2 Measure appropriate specimen dimensions to the nearest 2.5 µm or weigh the specimens to the nearest 0.0001 g.

8.3 Insert the disk securely in the holding device so that the disk is fixed perpendicular (±1°) to the axis of the resolution.

8.4 Insert the pin specimen securely in its holder and, if necessary, adjust so that the specimen is perpendicular (±1°) to the disk surface when in contact, in order to maintain the necessary contact conditions.

8.5 Add the proper mass to the system lever or bale to develop the selected force pressing the pin against the disk.

8.6 Start the motor and adjust the speed to the desired value while holding the pin specimen out of contact with the disk. Stop the motor.

8.7 Set the revolution counter (or equivalent) to the desired number of revolutions.

8.8 Begin the test with the specimens in contact under load. The test is stopped when the desired number of revolutions is achieved. Tests should not be interrupted or restarted.

8.9 Remove the specimens and clean off any loose wear debris. Note the existence of features on or near the wear scar such as: protrusions, displaced metal, discoloration, microcracking, or spotting.

8.10 Remeasure the specimen dimensions to the nearest 2.5 µm or reweigh the specimens to the nearest 0.0001 g, as appropriate.

8.11 Repeat the test with additional specimens to obtain sufficient data for statistically significant results.

9. Calculation and Reporting

9.1 The wear measurements should be reported as the volume loss in cubic millimetres for the pin and disk, separately.

9.1.1 Use the following equations for calculating volume losses when the pin has initially a spherical end shape of radius *R* and the disk is initially flat, under the conditions that only one of the two members wears significantly:

$$\text{pin (spherical end) volume loss, mm}^3 = \frac{\pi\,(\text{wear scar diameter, mm})^4}{64\,(\text{sphere radius, mm})} \qquad (1)$$

assuming that there is *no significant disk wear*. This is an approximate geometric relation that is correct to 1 % for (wear scar diameter/sphere radius) <0.3, and is correct to 5 % for (wear scar diameter/sphere radius) <0.7. The exact equation is given in Appendix X1.

$$\text{disk volume loss, mm}^3 = \frac{\pi\,(\text{wear track radius, mm})(\text{ track width, mm})^3}{6\,(\text{sphere radius, mm})} \qquad (2)$$

assuming that there is *no significant pin wear*. This is an approximate geometric relation that is correct to 1 % for (wear track width/sphere radius) <0.3, and is correct to 5 % for (wear track width/sphere radius) <0.8. The exact equation is given in Appendix X1.

9.1.2 Calculation of wear volumes for pin shapes of other geometries use the appropriate geometric relations, recognizing that assumptions regarding wear of each member may be required to justify the assumed final geometry.

9.1.3 Wear scar measurements should be done at least at two representative locations on the pin surfaces and disk surfaces, and the final results averaged.

9.1.4 In situations where both the pin and the disk wear significantly, it will be necessary to measure the wear depth profile on both members. A suitable method uses stylus profiling. Profiling is the only approach to determine the exa final shape of the wear surfaces and thereby to calculate t volume of material lost due to wear. In the case of disk wea the average wear track profile can be integrated to obtain t track cross-section area, and multiplied by the average trac length to obtain disk wear volume. In the case of pin wear, t wear scar profile can be measured in two orthogonal direction the profile results averaged, and used in a figure-of-revolutio calculated for pin wear volume.

9.1.5 While mass loss results may be used internally laboratories to compare materials of equivalent densities, th test method reports wear as volume loss so that there is n confusion caused by variations in density. Take care to use an report the best available density value for the materials teste when calculating volume loss from measured mass loss.

9.1.6 Use the following equation for conversion of ma loss to volume loss.

$$\text{volume loss, mm}^3 = \frac{\text{mass loss, g}}{\text{density, g/cm}^3} \times 1000. \qquad ($$

9.2 If the materials being tested exhibit considerable tran fer between specimens without loss from the system, volum loss may not adequately reflect the actual amount or severity wear. In these cases, this test method for reporting wear shoul not be used.

9.3 Friction coefficient (defined in Terminology G 4 should be reported when available. Describe the conditio associated with the friction measurements, for example, initia steady-state, and so forth.

9.4 Adequate specification of the materials tested is impo tant. As a minimum, the report should specify material typ form, processing treatments, surface finish, and specime preparation procedures. If appropriate, indentation hardne should be reported.

10. Precision and Bias [5]

10.1 *Statement of Precision:*

10.1.1 The precision of the measurements obtained with th test method will depend upon the test parameters chosen. T reproducibility of repeated tests on the same material wi depend upon material homogeneity, machine and materi interaction, and careful adherence to the specified procedure b the machine operator. Normal variations in the wear te procedure will tend to reduce the precision of the test metho as compared to the precision of such material property tests a hardness or density.

10.1.2 Table 2 contains wear data obtained from interlabo ratory tests[6]. Mean and standard deviation values are given f all measured quantities.

10.1.3 Statistical analysis (using Guide G 117) of the ste vs. steel ball wear scar diameter results for 24 laboratorie leads to a mean and standard deviation of 2.14 and 0.29 mm respectively. The 95 % repeatability limit (within-lab) was 0.3 mm, and the 95 % reproducibility limit (between-labs) wa

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[5] Additional data are available at ASTM International Headquarters. Reque Research Report RR: G02–1008.

[6] Supporting data have been filed at ASTM International Headquarters and ma be obtained by requesting Research Report RR: G02–1008.

Statistical analysis of the steel vs. steel ball friction
or 25 laboratories leads to a mean and standard
of 0.60 and 0.11, respectively. The 95 % repeatability
thin-lab) was 0.19, and the 95 % reproducibility limit
-labs) was 0.32.

tatement of Bias

No bias can be assigned to these results since there
solute accepted values for wear.

eneral Considerations

Participants in the interlaboratory testing that led to
nents of precision and bias given above involved 28
ies, 2 different materials (4 material pairs), 1 test
, and 3 to 5 replicate measurements each[6] (see Note
quent to this testing, data were received from another laboratory that utilized a commercial test machine. These data were found consistent with the results in the interlaboratory study.[6]

NOTE 4—The interlaboratory data given in Table 1 and Table 2 resulted through the cooperation of thirty one institutions in seven countries with the help of national representatives within the Versailles Advanced Materials and Standards (VAMAS) working party on wear test methods[7].

11. Keywords

11.1 ceramic wear; friction; metal wear; non-abrasive; pin-on-disk; wear

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[7] A summary is published: Czichos, H., Becker, S., and Lexow, J., *J. Wear*, vol. 114, 1987, pp. 109–130, and *J. Wear*, vol. 118, 1987, pp. 379–380.

APPENDIX

(Nonmandatory Information)

X1. EQUATIONS

Exact equations for determining wear volume loss are
s for:

A spherical ended pin:

$$\text{pin volume loss} = (\pi h/6)[3d^2/4 + h^2] \quad \text{(X1.1)}$$

$- [r^2 - d^2/4]^{1/2}$
ear scar diameter, and
in end radius.

Assuming no significant disk wear.

X1.1.2 A disk:

$$\text{disk volume loss} = 2\pi R\,[r^2 \sin^{-1}(d/2r) - (d/4)(4r^2 - d^2)^{1/2}] \quad \text{(X1.2)}$$

where:

R = wear track radius, and
d = wear track width.

Assuming no significant pin wear.