Wear investigation of elastically similar sliding bodies material

by

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CERTIFICATION OF APPROVAL

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Approved by,

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TRONOH, PERAK

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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.

MUHAMAD MUHAIDI BIN MAZLAN

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Abstract

From the practical point of view to obtain the friction and wear characteristic of materials used in machinery, various types of wear testing machines have been developed and deployed. To obtain useful data for practical application, it is desirable that the investigation is carried out by a full scale wear testing apparatus having approximately similar contact conditions. There are two parameters in the wear testing machines, such as configuration of contact surface and form of the relative motion between test specimens. Thus, in this report, the effect of unidirectional sliding friction in linear sliding direction between contacting pair and friction obtained test results are investigated. The reciprocating pin-on-flat experimental technique of similar specimen's material was modified to obtain the test results desired. The microscopic structures of the pin specimen were varied due to frictional and wear properties. Pressure distribution using selected formula during normal condition and the wear effect on the leading and trailing edge due to the movement of pin specimen were varied due to the load and number of cycles applied. Comparison between theoretical wear depth and experimental result been analyzed.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

When two solid bodies undergo relative motion while in contact for prolong time, the surfaces wear. The wear can be due to one or more of the various mechanisms, such as abrasion, adhesion, fatigue, and delamination [1]. It is important to estimate wear characteristics appropriately. However, it is rare for friction or wear characteristics of materials or machine elements to be estimated from a full scale test. To obtain useful data for practical applications, it is desirable that the investigation is carried out by a full scale wear testing apparatus having approximately similar contact conditions.

The friction or contact modes in such model apparatuses for estimation are as follows [2]: pin (or ball)/disk (unidirectional friction type), pin (or ball)/flat (reciprocating friction type), cylinder/cylinder (contact with end surface), pin/cylinder, four-ball, two-parallel cylinder type. All the model apparatuses consist of three modes in practical contact surface which are point contact, line contact and surface contact.

As mentioned above, there are many types of wear-testing machine and contact mode. Therefore, based on the combination of concepts between unidirectional friction and reciprocating friction type, a modified model apparatus of reciprocating pin-on-flat experimental technique will be developed in order to investigate the wear characteristics and behaviors of surface contact between two similar specimens material in linear motion. Compared to model apparatus of pin-on-disk (unidirectional friction type) where having continuous sliding contact in rotational motion and pin-on-flat (reciprocating friction type) where having sliding contact between a stationary pin against flat sample that is moved backwards and forwards in a reciprocating motion, this modified model apparatus of reciprocating pin-on-flat working principle is having two different behaviors of movement in two strokes of reciprocating motion where, one stroke encounter surface contact between two specimens and the other stroke having non-contact movement in linear motion.

The effect of relative motion between contacting pair of similar materials and friction process through obtained test results which should cover the leading and trailing edge, microstructure of the pin specimen, hardness value of worn area and pressure distribution are being investigated. Simulation of wear to obtain the pressure distribution during normal condition was done using selected formula. The simulation using selected formula has been compared with the result from the laboratory wear testing results.

1.2 PROBLEM STATEMENT

In the industrial wear problems, adhesive wear, phenomena of surface damage and material removal which can occur when two smooth surfaces rub against each other, which this type of wear is having approximate percentage of 26% contribution to the cost of wear [3]. This type of wear can occur in plain bearings and other interacting machine components, particularly if they are inadequately lubricated.

Actual testing needs a huge of resources, costly and time consuming. Because of that, experimental technique by using test specimens and application of simulation studies are selected rather than actual testing. In addition, the modification of the established reciprocating pin-on-flat wear tester by applying different working principle will lead to new approach of wear modeling and the comparison of results can be accomplished.

1.3 OBJECTIVES AND SCOPE OF STUDY

The objectives of this research are:

- To analyze wear mechanisms, behaviors and characteristics on the laboratory wear testing results.

- To predict the wear rate of pin-on-flat contacts and the effect on leading and trailing edge.
- To simulate the stress/pressure distribution at contact area.

The scope of research can be simplified as follows:

- The laboratory wear test is using couple of same specimen material (pin and flat).
- Surfaces slides in non-lubricated condition where the surface contact slides in air without a lubricant.
- The procedures of the laboratory wear test scope within codes and standard of ASTM G133 - Standard Test Method for Linearly Reciprocating Pin-on-Flat Sliding Wear.
- Result from the stress/pressure distribution using selected formula been compared to laboratory wear test result.

CHAPTER 2

LITERATURE REVIEW

2.1 ADHESIVE WEAR

Sliding is the most common tribological contact condition. Adhesive wear was for many years thought occur when no abrasive substances can be found and where there is tangential sliding of one clean surface over another. Oxides and adsorbed species are usually ignored [3, 4]. In most practical applications sliding surfaces are lubricated in some way and the wear that occurs in then termed lubricated sliding wear. However, in laboratory investigations, surfaces slide in air without lubricant which called dry sliding wear [2].

2.2 CODES AND STANDARD

The codes and standard of the laboratory wear test according to sliding wear – reciprocating motion, ASTM G133 [3].

2.2.1 Test conditions

- Test load: up to 10 000 N
- Frequency: 0.1 – 50 Hz
- Stroke: 0.25 – 50 mm
- Contact geometry: pin with 6.00 mm radius end
- Test duration: $10^3 - 10^6$ s

2.2.2 Measurement modes

- Volume of wear (measured directly by profilometry or calculated from mass loss and density measurements or calculated from size wear scar)
- Examination of worn surface

- Wear displacement (progressive movement of the samples during wear)

2.3 TABER® LINEAR ABRASER

2.3.1 Description

TABER® Linear Abraser uses a free floating head to follow the contours of every sample, permitting testing of finished products. With virtually no limit on sample size or shape, the TABER® Linear Abraser is ideal for testing plastics, automotive components, painted parts, printed graphic, optical products, rubber, leather, textiles, and for use in testing laboratories [5].

2.3.2 Specifications

The parameters for TABER® Linear Abraser also can be altered, which enables the user to determine the optimal setting of each product or material [5]. The parameters are shown in Table 2.1.

Table 2.1: TABER® Linear Abraser Parameters

Parameters	**Description**
Load	Ranging from 350 – 2100 grams with optional weight disc
Stroke Lengths	0.5", 1.0", 2.0", 3.0", 4.0"
Stroke Speed	2 -75 cycles per minute

2.4 WEAR MODEL

The wear process can be treated as a dynamic process, depending on many parameters and the prediction of that process as an initial value problem. The wear rate may then be described by a general equation given by

$$\frac{dh}{ds} = f \qquad (1)$$

Where h is the wear depth (m) and s is the sliding distance (m). Many wear models are available in the literature. Their mathematical expressions vary from simple empirical relationships to complicated equations relying on physical concepts and definitions [4].

The most frequently used model is the linear wear equation $\tilde{Q} = K\tilde{p}$, where $\tilde{Q}$ is dimensionless normalized wear rate; K is wear coefficient; $\tilde{p}$ is dimensionless normalized pressure; which the volume wear rate is proportional to the normal load. This model is often referred to as the Archard's wear law; though its basic form was first published by Holm [6][7]. The model was based on experimental observations and written in the form

$$\frac{V}{s} = K\frac{F_N}{H} \qquad (2)$$

Where V is volume wear (m^3); s sliding distance (m); K is wear coefficient; F_N is normal load (N); H is hardness (Pa).

The wear coefficient K was introduced to provide agreement between theory and experiment. Holm treated it as a constant, representing the number of abraded atoms per atomic encounter. In Archard's work it corresponds to the probability that an asperity interaction results in a wear particle formation [8]. However, that is not the only possible interpretation. Lim and Ashby [9] calculated it regarding the delamination or plasticity dominated wear mechanism as governing. For steels they suggested to use the values

$$\begin{cases} K = 5\cdot 10^{-5} & \text{if } \tilde{p} < 3\cdot 10^{-4} \\ K = 5\cdot 10^{-3} & \text{if } \tilde{p} > 3\cdot 10^{-4} \end{cases} \qquad (3)$$

Where

$$\tilde{p} = \frac{F_N}{AH} \qquad (4)$$

F_N is normal load (N); H is hardness (Pa); A is the apparent contact area (m^2).

The wear depth is preferred to determine the pin-on-flat profile evolution. For engineering applications the wear depth is of more interest, than wear volume. Here Archard proposed to divide both sides of equation (2) by the apparent contact area A [8], giving

$$\frac{V}{sA}=\frac{h}{s}=kp \tag{5}$$

Where h is the wear depth (m), k is the dimensional wear coefficient (Pa^{-1}) and p is the normal contact pressure (Pa). The wear model can then be described by a differential equation, which for the linear case, equation (2) can be formulated as

$$\frac{dh}{ds}=kp \tag{6}$$

When two nominally plane and parallel surfaces are brought gently together, contact will initially occur at only few points. When a rigid cylinder (pin) is pressed into an elastic half-space, under a normal load F_N, it creates a pressure distribution described by Hertzian contact stress for contact between a rigid cylinder and an elastic half-space [10] [11].

$$p(r) = p_0\left(1-\frac{r^2}{a^2}\right)^{1/2} \tag{7}$$

Where a is the radius of the cylinder; p_0 is the maximum contact pressure given by

$$p_0 = \frac{3F}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6FE^{*2}}{R^2}\right)^{1/3} \tag{8}$$

Where d is indentation depth; E* is equivalent modulus of elasticity given by

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \tag{9}$$

E_1,E_2 are the elastic modulus and v_1,v_2 the Poisson's ratios associated with each body. The relation between the indentation depth and the normal force is given by

$$a^3 = \frac{3FR}{4E^*} \qquad (10)$$

CHAPTER 3

METHODOLOGY

Methodology section will discuss about the TABER® Linear Abraser (Abrader) - Model 5750 modification's model design of the specimen mounting on Universal Specimen Table prior to have vertical movement thus allowing single stroke surface contact. After that, researches continue with the model fabrication and precede with the detail procedures of several laboratory tests on experimental analysis under every respective testing for future references. The principle of all laboratory tests involved were based on standard operation manual and American Society for Testing and Materials (ASTM) which will be discussed by the author in this section.

3.1 TABLE MODEL DESIGN

Model design been utilized as the simulation with detail dimension, requirement and material selection. Design of the model has been appropriately constructed based upon the requirement of the research to obtain one stroke contact between two surfaces. The design based on the mechanism of jack's application where the table will be controlled manually. This design will give a clear picture on the modification of the specimen mounting of Universal Specimen Table of TABER® Linear Abraser (Abrader) - Model 5750 as shown in Figure 3.1 and been as the constraint for the fabrication part to be carried out.

Figure 3.1: Universal Specimen Table of TABER® Linear Abraser

Model design consists of three stages:

1. Dimensional conformance

All the dimensions and constraint will be specified according to ASTM G133 - Standard Test Method for Linearly Reciprocating Pin-on-Flat Sliding Wear and Universal Specimen Table of TABER® Linear Abraser (Abrader) - Model 5750 design specifications and interchangeability factors as shown in Figure 3.2.

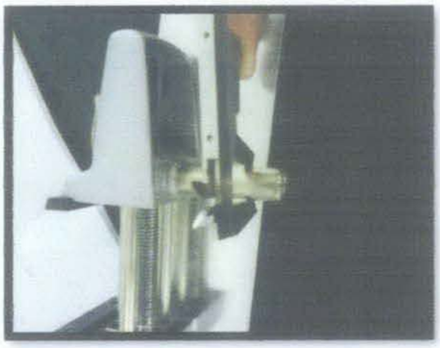

Figure 3.2: Caliper's base dimensioning

2. Design sketches

Initial rough ideas of the development of the model design to suit with the requirement of the research. Variation of model design has been determined to come up with final idea.

3. Model simulation

Design software been utilized in this designing part in order to establish high accuracy and precision of the design as well on better illustration of the function. AutoCad software has been used to design the model. The design consists of isometric, orthographic and exploded view. See Appendix I, II and III.

3.2 TABLE MODEL FABRICATION

Fabrication of the model will follow the dimensions and constraint been specified in the model design. Step by step of fabrication's procedure been clearly followed according to the design. All manufacturing steps been organized efficiently to avoid any clashing on the procedure which could affect the final fabricated model. Material selected in table model fabrication is aluminum alloy as per specification of aluminum alloy, see Appendix IV, aluminum alloy is a soft material thus material handling for fabrication is much easier. On the other side, aluminum alloy is non rusting material which applicable for long term application.

For preparing the modified table, conventional lathe machine and milling machine as shown in Figure 3.3 and Figure 3.4 has been utilized to machine 50mm diameter of cylindrical aluminum as mounting part for the clamper. Center drill of 16mm diameter been performed to make a hole as attachment part to the clamper. The cylindrical aluminum been attached to 15mm x 16mm x 7mm aluminum plate as table's base with a simple jack. Drilling machine and steered threader been utilized to make inner thread for the attachment's screw as shown in Figure 3.5.

Figure 3.3: Center Drill with Lathe Machine

Figure 3.4: Milling Machine

Figure 3.5: Attachment's part

All fabrication parts have been attached according to the design following the exploded view of Appendix III as shown in Figure 3.6. Grease lubricant has been applied at jack part in the center hole of the mounting to reduce the friction for a smoother movement of the caliper.

Figure 3.6: Modified Specimen Table

3.3 SPECIMEN PREPARATION

Based on the terminology of this research, both specimens of pin and flat should be any material as long as both of them are same material with same specifications. Therefore, aluminum alloy has been selected as the material for both specimens. The material selection was based upon the high elasticity and ductility of aluminum alloy which categorized as soft material thus wear mechanism can be better visualized. All specimens' preparation work was done at manufacturing lab and material lab under supervision of designated technicians from both labs.

There were six samples of pin specimen followed by six samples of flat specimen. Both specimens undergo different method of preparation and fabrication.

3.3.1 Pin Specimens

Pin's size was according to ASTM G133 - Standard Test Method for Linearly Reciprocating Pin-on-Flat Sliding Wear. Pin specimens been produced into four units of cylindrical and two units of squared shape. The dimension of cylindrical pin specimen is 6mm diameter x 10mm height while shaped pin specimen is 6mm x 6mm x 10mm. The descriptions of each sample are as in Table 3.1 based on variables chosen.

Table 3.1: Specimen's Categorization

Type	Label	Linear Wear Test
Cylindrical Specimen (Ø6mm x 10mm)	Specimen A	10 Cycles
	Specimen B	20 Cycles
	Specimen C	40 Cycles
	Specimen D	60 Cycles
Squared Specimen (6mm x 6mm x 10mm)	Specimen E	40 Cycles
	Specimen F	60 Cycles

Since all of the specimens are small and required high precision in dimension, 100mm x 100mm x 10mm aluminum alloy plate been used to produce the pin specimen by using Electrical Discharge Machining, EDM Wire Cut as shown in Figure 3.7. Figure 3.8 shows the pin specimens produced by EDM Wire Cut.

Figure 3.7: EDM Wire Cut

Figure 3.8: Pin Specimens (diameter 6mm, length 10mm)

3.3.2 Flat Specimens

Flat specimen's dimension was based on the stroke length of the TABER® Linear Abraser (Abrader) - Model 5750 where stroke length used in this research was 4 inches or 101.6mm. Therefore, length of the flat specimen must be greater than the stroke length. Thus, the required flat specimen's dimension is 150mm x 35mm x 7mm. Aluminum alloy plate with 150mm x 210mm x 7mm has been cut into six samples according to the required dimension with metal band saw.

The oxide layer or scale on the aluminum alloy surface must be removed in order to avoid the wear is due to the oxide layer and not the aluminum alloy itself. Therefore, the flat specimens were grinding and polishing to remove the oxide layer and obtain smooth surface. Metaserv 2000 rotating grinder machine been used to perform this task. Figure 3.9 shows the flat specimen before and after been grinded and polished.

Different grid of sand paper been used to obtain smooth surface and the grinding procedures were as follow:

1. Flat specimen was polished with rough sand paper to remove deposits, scale and oxide layer on top of the surface where the specification of the sand paper using aluminum oxide cloth, P: 6.
2. Top surface been grinded using Metaserv 2000 rotating grinder machine with rotating speed of 350 rpm and grinding cloth from the course to smoothest cloth at the range of P: 60 until P: 4000.
3. 3μ polishing cloth been used to polish the flat specimen until it looks shiny.

4. Step 1 until step 3 been repeated for all six flat specimens.

Precautions must be taken when dealing with rotating grinder by ensuring that water must be constantly supplied to avoid any major scratches and temperature rise due to friction between rotating grinder and specimens.

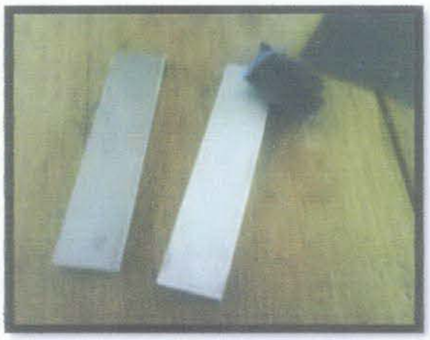

Figure 3.9: Flat specimens (150mm x 35mm x 7mm) before and after grinded

3.4 PIN ON FLAT TEST

The pin on flat test was conducted according to ASTM G133 - Standard Test Method for Linearly Reciprocating Pin-on-Flat Sliding Wear with TABER® Linear Abraser (Abrader) - Model 5750 as experiment apparatus.

3.4.1 Pin on Flat Test Parameters

Each specimen was having different set of parameters. Test parameters were specified according to Table 3.2.

Table 3.2: Pin on Flat Test Parameters

Type	Linearly Reciprocating Pin-on-Flat Sliding Wear
Load (g)	350, 600, 850, 1100,1350
Speed (cycle/min)	15
Stroke length (inch)	4
Number of cycles	10,20,40,60,

In this research, five sets of load been applied to the pin with constant time cycle and constant stroke length. Maximum stroke length of 4 inches or 101.6mm been chosen to have much clearer wear mechanism and more time of surface contact between two specimens. Each cylindrical specimen will assigned to each number of cycles with five sets of load while squared specimens were assigned to 40 and 60 cycles respectively.

3.4.2 Pin on Flat Test Procedure

1. Caliper been attached to the Modified Specimen Table.
2. Spline shaft been tied with the stroke length to avoid any movements in vertical direction to have surface contact in backward stroke as shown in Figure 3.10.
3. Two connecting links attached to Modified Specimen Table to ensure it does not move during testing.
4. Stroke length been adjusted to 4 inch at Adjustable Stroke Length and Safety Off Switch had been closed down.
5. TABER® Linear Abraser (Abrader) - Model 5750 been turned on and the testing parameters of 15 cycles/min and number of cycles been set by selecting ENTER button. After the data been input, CLEAR button been selected which mean clear to proceed with testing.
6. Pin specimen been weigh up using Digital Weighing Scale and initial mass been taken as shown in Figure 3.11.
7. After that, pin specimen been attached to Wearaser Collet.
8. Flat specimen been mounted at Modified Specimen Table.
9. Weigh disc (load) been applied according to parameters.
10. Jack of Modified Specimen Table been pressed to move the flat specimen and have surface contact with pin specimen and START button been selected.
11. Jack of Modified Specimen Table been released after one stroke been completed to complete one cycle before been pressed again for another stroke to have surface contact. This will be repeated until the end number of cycles.
12. Then, pin specimen been weighing up again to measure its final mass.
13. Step 5 to 12 been repeated with set of load as specified in parameters.

14. Step 5 to 13 been repeated with another specimen with different set of cycles with same set of load applied.

Figure 3.10: Specimen's mounting

Figure 3.11: Digital Weighing Scale

3.5 MACROSCOPIC EXAMINATION

Macroscopic examination is carried out with unaided eye or a low power optical microscope with a magnification generally below 100 diameters. This methodology has capability to have general appreciation of the features of the wear pin specimen, in particular, the surface wear pattern. The purpose of this macroscopic examination in this inspection to reveal remarkable features on the wear pattern and predict the wear mechanism based on visualization of the pin specimen's surface metallographic. The examination was according to ASTM E7 - 03(2009) Standard Terminology Relating to Metallography.

Main focus of the examination was to clarify the wear formation mechanism of the leading edge, center and trailing edge of the pin specimen and to examine the effect of the difference in number of cycles on the experimental results, the microscopic structure of the pin specimen is observed by Metallurgy Optical Microscope – NIKON Model as shown in Figure 3.12.

Figure 3.12: Macroscopic Examination

3.5.1 Specimen Preparation Procedure

Before macroscopic examination been carried out, all the specimens need to be prepared in order to obtain clear picture of pin specimen's surface wear metallographic structure. The preparation was according to ASTM E3 - 11 Standard Guide for Preparation of Metallographic Specimens. The specimen preparation procedure as follows:

1. Precautions need to be taken to avoid grinding the pin specimen's wear surface because macroscopic examination was to analyze the pattern of the wear on the surface.
2. As an alternative to obtain shiny surface is by rubbing the surface gently with 3μ polishing cloth to avoid any disturbance to the wear scar of the pin specimen. Metal polish liquid had been applied as the polished media.
3. Step 1 to 2 been repeated for all six specimens.

3.5.2 Macroscopic Examination Procedure

1. Before the operation had been carried out, the machine must be in good condition and safety first.
2. Power supply for the microscope been switched ON.
3. Computer data station was started up and AQCUISS program been selected.
4. The specimen has been placed at the microscope table stage below the lens.

5. By turning to lowest magnification (5x objective lens), the microscope table stage been risen up to the lens.
6. Through microscope eye piece, the table is turned down until get focus to microstructure surface.
7. The magnification been adjusted to 500x by turning the lens and adjusting the focus.
8. For AQCUISS program, new file been selected and live camera action. After that, the witch at microscope been pulled to BINO for see through the microscope or PHOTO for capture image in AQCUISS program.
9. Capture image been clicked and file has been saved as usual.
10. Step 4 to 9 were been repeated for different pin specimens and image been captured at different point of location which at leading, center and trailing edge.
11. The computer been shut down and the microscope been switch off after used.
12. Power has been switched off and cleaning process being done.

3.6 HARDNESS TEST

Hardness test is conducted to determine the hardness effect at the worn surface area on the pin specimen. From this hardness value, the effect of worn area on the hardness value can be determined either worn area will decrease the hardness value of the material or not. Since the pin specimens were small thus microhardness test need to be chosen. Micro-Hardness Tester been used to determine the hardness and be measured by Hardness Vickers. Hardness test was according ASTM E92 Standard Test Method for Vickers Hardness of Metallic Materials.

3.6.1 Hardness Test Parameters

The test parameters were according to the aluminum alloys material specifications for Hardness Vickers Test and ASTM E92 Standard Test Method for Vickers Hardness of Metallic Materials. Test parameters were as follows:

Table 3.3: Hardness Test Parameters

Hardness Test	Hardness Vickers Test (HV)
Apparatus	Micro-Hardness Testing Machine
Load	100kgf
Dwell time	15 seconds
Points	5 points of location

3.6.2 Hardness Specimen Reading and Orientation

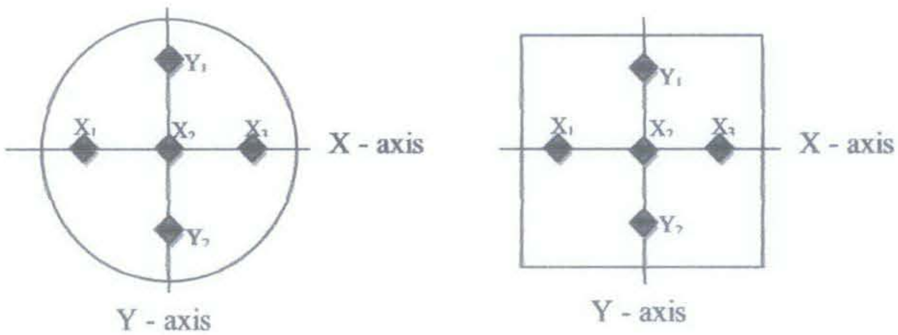

Figure 3.13: Hardness Testing Orientation

Hardness reading has been taken at different points of location on the surface of the pin specimens either cylindrical pin specimen or squared pin specimen. Five hardness readings were taken from each specimen based on X-axis and Y-axis orientation as shown in Figure 3.13. Based on that orientation, the hardness value at the leading (X_3), center (X_2) and trailing edge (X_1) can be obtained and comparison can be made.

3.6.3 Specimen's Mounting Procedure

Since the specimens are small, thus specimens need to have hot mounting procedure to hold the specimen during microhardness testing. This mounting procedure been applied for all specimens. Hot mounting been done under the supervision of material lab technician. Automatic Mounting Press Machine Buehler SIMPLIMET 1000 been used to perform this hot mounting. The parameters of the hot mounting were as follows:

Table 3.4: Hot Mounting Parameters

Mounting Type	Hot Mounting
Apparatus	Automatic Mounting Press Buehler Machine SIMPLIMET 1000
Mounting Material	Thermosetting Resin (Phenolic)
Pressure	4000 Psi
Heat Time	3 minutes
Cool Time	2 minutes

The procedure of hot mounting as follows:

1. Automatic Mounting Press Machine SIMPLIMET 1000 been switched ON.
2. Upper button been pressed at control panel to push the mold out of the heating closure.
3. The mold area needs to be cleaned up first by using release agent as shown in Figure 3.14.

Figure 3.14: Mold Cleaning

4. Lower button pressed at control panel to move the mold into the heating closure.

5. Pin specimen been placed into the mold and thermosetting resin, the mounting material been placed together inside the mold until it covers the entire pin specimen as shown in Figure 3.15.

Figure 3.15: Specimen and resin placement into the mold

6. Insulated bayonet closure been closing down to the mold and locked up.
7. Parameters have been input into the control panel and START button been pressed.
8. Notifications been given by the machine shows the mounting process had been done and the insulated bayonet closure been opened up.
9. Upper button been pressed at control panel to push the mold out of the heating closure and the mounting's specimen been obtained.
10. Step 3 to 9 been repeated and applied for all specimens.

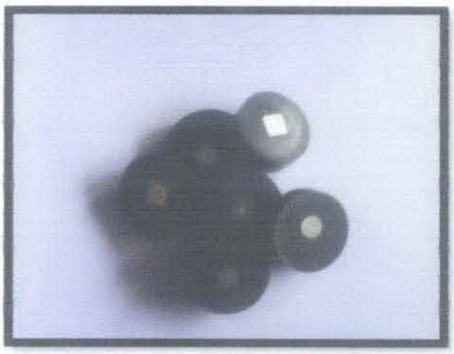

Figure 3.16: Mounting's Specimens

3.6.4. Hardness Test Procedure

1. The Microhardness machine been switched ON.
2. The specimen is mounted on the Microhardness Tester table.
3. The load of test and dwell time are set according to test parameters.
4. The Microhardness Tester table stage been risen up to the lens.
5. Through microscope eye piece, the table is turned down until get focus to microstructure surface and point of hardness measuring been located.
6. After that, start button been selected and the indenter will indent the specimen to the specimen at the set location.
7. Table is turned down once again to get focus until the diamond shaped to be visible.
8. Both diamond diameter in X-axis and Y-axis been taken and hardness reading will be automatically viewed on control panel.
9. Data is been recorded and data been reset and clear again for another measurement.
10. Step 2-9 been repeated for all five points location as shown in Figure 3.13 for each specimen.
11. Microhardness Tester table has been cleaned up and switched OFF.

Figure 3.17: Vickers Hardness Testing

3.7 SIMULATION USING SELECTED FORMULA

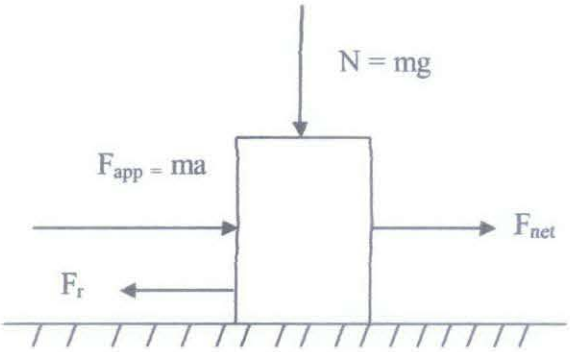

Figure 3.18: Pin on flat scheme

3.7.1 Pressure distribution

By using the illustration of free body diagram as shown in Figure 3.18, the pressure distribution been calculated through contact area mark created when top of an elastic pin of radius, r and equivalent modulus of elasticity pressed with normal load, N been applied. The pin will move along its linear movement with speed, v and due to the normal force, linear velocity and coefficient of friction μ, reaction force will be occurred [12][13]. This can be shown with the formula:

$$Fnet = Fapp - \mu N$$

The contact patch between the pin specimen and flat specimen where the pressure distribution can be illustrated is defined as region A in xy- plane identification where:

$$A = \{(x, y): x^2 + y^2 \leq r^2$$

The normal stress is calculated in z- direction of the xy-plane, P_z is given by:

$$Pz(x, y) = Po\sqrt{(1} - \left(\frac{x}{r}\right)^2 - \left(\frac{y}{r}\right)^2)$$

P_o is the maximum pressure which been calculated using formula:

$$Po = 3N/2\pi r^2$$

By using this formula the pressure distribution area at longitudinal distance, y-direction and latitudinal distance, x-direction along geometrical surface contact of pin specimen can be calculated.

3.7.2 Wear depth prediction

The prediction of wear depth been calculated using the wear model on Archard's law:

$$\frac{V}{s} = K\frac{F_N}{H}$$

Where V is volume wear (m^3); s sliding distance (m); K is wear coefficient; F_N is normal load (N); H is hardness (Pa).In this research, hardness is included as part of wear coefficient.

The wear depth been calculated from Δz, which is at the center of the mesh element in pressure distribution where the pressure distribution at the maximum with coordinate (x,y) [12][13]. This illustrated by the formula:

$$\Delta z = k \cdot Pz(x,y) \cdot s(x,y)/H$$

Where Pz is the pressure in z-direction, s is the sliding distance. By using this formula, the prediction of wear depth been determined and the values been compared with the experimental result.

3.8 GANTT CHART

Table 3.5: Gantt Chart

Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Model Design	■	■													
Model Fabrication			■	■	■										
Sample Preparation						■	■								
Pin on Flat Test							■	■							
Macroscopic Examination								■	■						
Hardness Test									■	■	■				
Wear Simulation										■	■	■			
Progress Report										X					
Poster											X				
Draft Report												X			
Dissertation (soft bound)													X		
Technical Paper													X		
Oral Presentation														X	
Project Dissertation (Hard Bound)															X

■ Finish

X Submission

CHAPTER 4

RESULT AND DISCUSSION

Results of the experiment were depending on the methodology which had been specified earlier. Each methodology carried different result in order to verify the objectives of the research. From the pin flat test using TABER® Linear Abraser (Abrader) - Model 5750 with Modified Specimen Table, mass loss, coefficient of friction, and wear coefficient and wear depth of the pin specimen can be obtained. Based on the prediction, the wear rate will be higher when applied load been increased and number of cycles was added up. Then, the following result will be on the microscopic structure of the pin specimen worn surface area which merely focuses on the leading edge, center and trailing edge of surface contact. After that, hardness testing also had been performed to obtained result of hardness value due to wear. Lastly, the simulation of the surface contact between pin and flat specimen been performed. This applied to all specimens and results of pin specimens and squared specimens were being compared.

Note that all full experimental results, mathematical calculations and table results been attached in Appendix's section.

4.1 PIN ON FLAT TEST

Test had been carried on according to the parameters in Table 3.2. The categorizations of pin specimens were according to number of cycles as shown in Table 3.1. A comparison was made to study the effect of the increment of number of cycles and load to the wear's pattern of the surface contact between pin and flat specimen. Comparison of the wear mechanism between cylindrical pin specimen and squared specimen had been performed.

4.1.1 Worn Mass of Specimens

The magnitudes of wear which is the worn mass are shown in Figure 4.1 and Figure 4.2 corresponding to the number of load applied. Worn mass calculation which been calculated by:

$$Worn\ mass = \frac{Initial\ mass - Final\ mass}{1000}\ (mg)$$

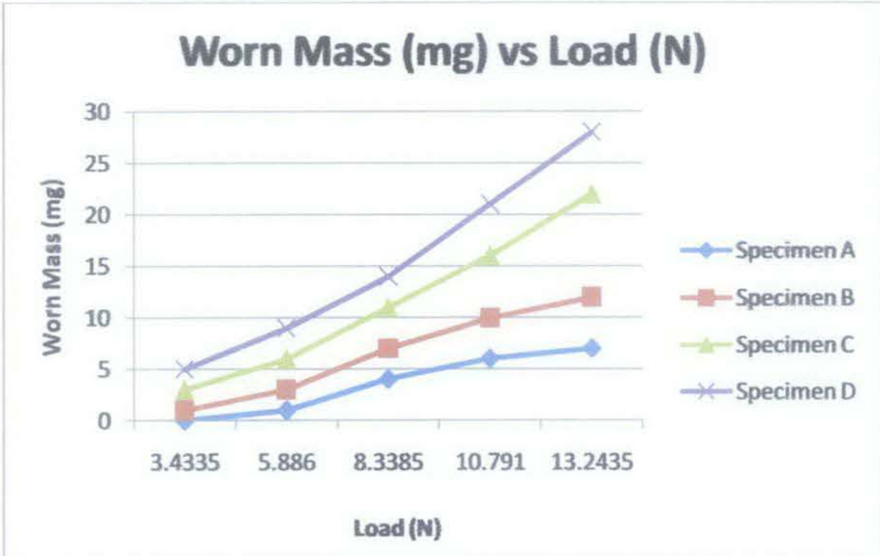

Figure 4.1: Worn mass of cylindrical pin specimens

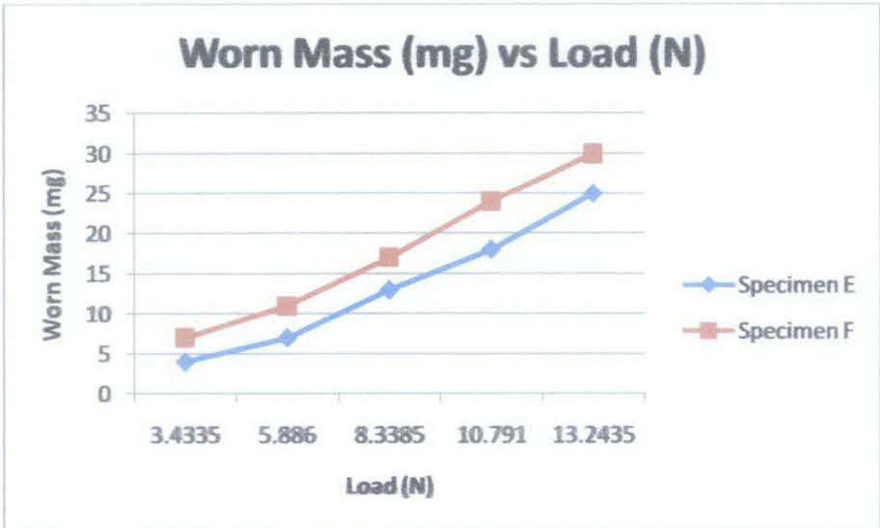

Figure 4.2: Worn mass of squared pin specimens

Figure 4.1 and Figure 4.2 shows the result of worn mass at the applied load for cylindrical and squared pin specimen at different number of cycles which specify in parameters which are 10 cycles, 20 cycles, 40 cycles, and 60 cycles. As shown in the pattern of the graph, as the loads were increasing, worn mass of the specimens were also relatively increasing. This means that the highest potential of wear to be happened when there were loads keep applied and increased on the material which was moving.

By comparing Specimen A at highest cycles of 60 cycles and Specimen D at lowest cycles of 10 cycles, the gradient of the slope of both line show the wear rate at highest cycle was much higher compared to the lowest cycle. Therefore, this can be defined that although sliding velocity was constant at 15 cycles/min and sliding of distance was constant at 4 inch, the increment of the cycles or repetition of the sliding increase the percentage rate of wear.

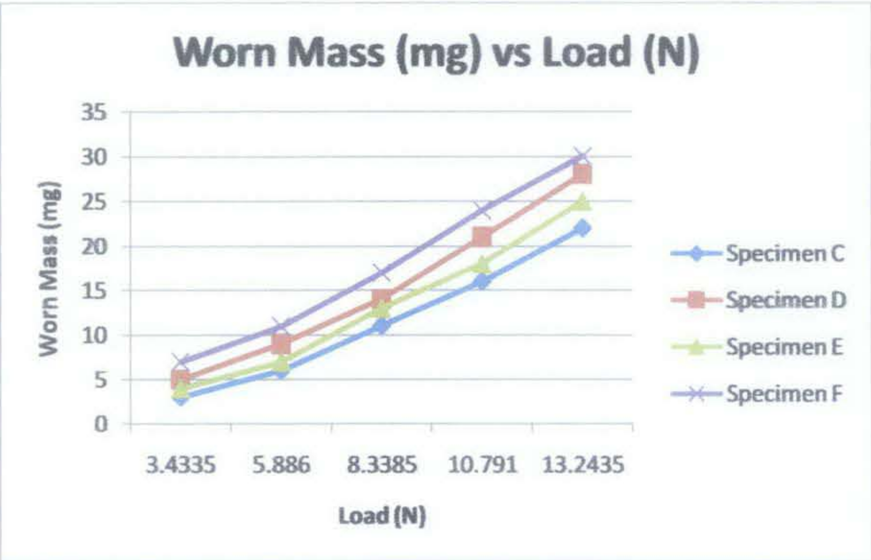

Figure 4.3: Worn mass comparison between cylindrical pin specimens and squared pin specimens

Comparison had been made between cylindrical and squared pin specimen to analyze the worn mass behavior between two different geometries as shown in Figure 4.3. The comparison been made by taking two highest number of cycles used in this experiment which are 40 cycles and 60 cycles as parameters with same increment of loads.

Result shows that worn mass of squared specimens for both cycles were higher than cylindrical specimens and defined that the wear rate of squared specimens were higher than cylindrical specimens. The result is caused by larger contact area of the squared specimens than cylindrical specimens, which resulted more contact occurred between two surface of squared specimens. Sharp edge of the squared specimens also has been a factor for wear to easily occur than cylindrical specimens although pressure on smaller contact area of cylindrical specimens higher than squared specimens.

4.1.2 Wear Coefficient

The effects of the applied normal load on the coefficient of wear for cylindrical and squared pin specimens are shown in Figure 4.4 and Figure 4.5 respectively. The worn mass is converted into the worn volume using the density. Then the coefficient of wear is obtained as the value of the worn volume per unit sliding distance and unit normal load. The calculation of the wear coefficient according to Archard's Wear Law where:

$$\frac{V}{s} = kFn$$

V is volume of wear, s = sliding distance, Fn = Normal Load, k = wear coefficient. Hardness is included as part of the wear coefficient. Therefore, sample calculation for Specimen A at 600g load was as follows:

Worn mass (m) = 1mg, density (ρ) of Aluminum Alloy as per specifications is $2700 kg/m^3$, thus

$V = m/\rho$

$V = (1 \times 10^{\wedge}6\ kg / 2700 kg/m^3) = 3.704E\text{-}10\ m^3$

$3.704E\text{-}10\ m^3 / 0.1016 m = k\ (5.886\ N)$

$\underline{k = 6.193E\text{-}10\ m^2/N}$

Calculations been applied to all specimens with same set of loads.

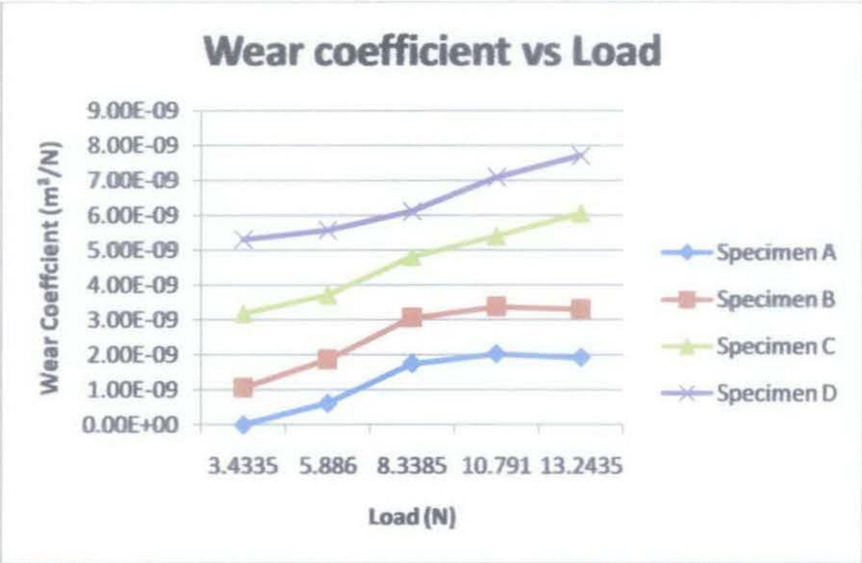

Figure 4.4: Wear coefficient of cylindrical pin specimens

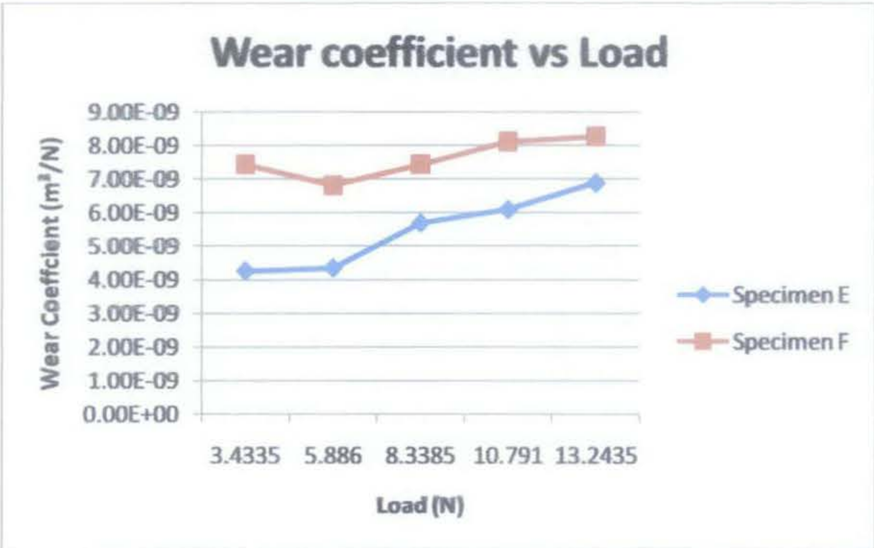

Figure 4.5: Wear coefficient of squared pin specimens

Based on Figure 4.4 and 4.5, the coefficient of wear of specimen D and specimen E are extremely large where the pin specimen were having 60 number of cycles. The contact between the specimens varies with the magnitude of the normal load and number of cycles. This contact is thought to have a strong influence on the wear.

Both figures shows that since the worn volume increase in proportion to the increase in the normal load and number of cycles, the coefficient of wear increases with the increase of the normal load and number of cycles.

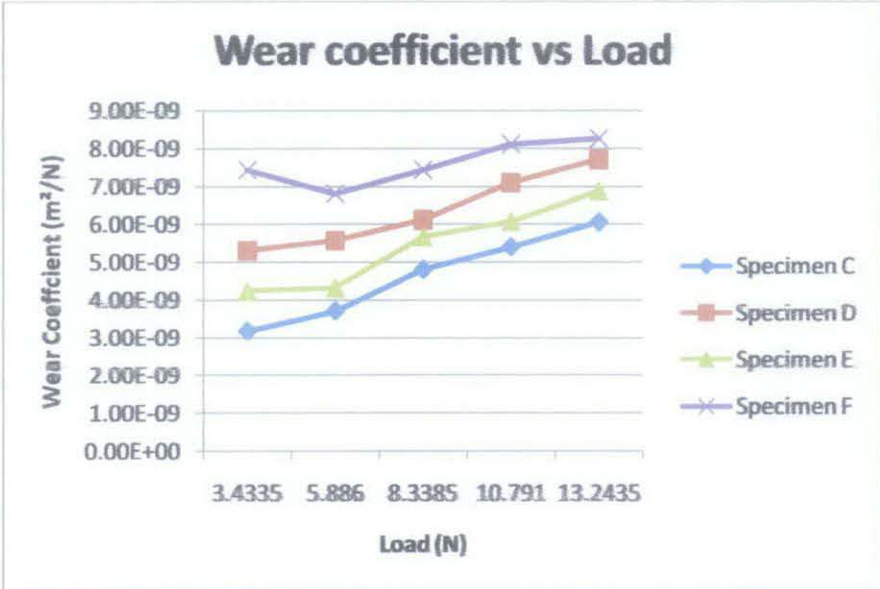

Figure 4.6: Comparison of wear coefficient between cylindrical pin specimens and squared pin specimens

In view of different geometries of the pin specimens, since worn volume of both squared specimens were greater than cylindrical specimen at respective number of cycles, wear coefficient of squared specimens are greater than cylindrical specimens as the load increases. This result shows that wear will be easily occurred when specimen geometry is squared shape at higher number of cycles.

4.1.3 Wear Depth of Specimens

Although worn volume of specimens have already specified earlier, wear depth of the specimens mostly need to be taken in considerations. This applicable to the industrial applications where wear depth was the main concern. Through Archard's Wear Law, wear depth can be calculated as follows:

$$\frac{V}{sA} = \frac{h}{s} = kP$$

Sample calculation using Specimen A with 600g load:

$h/(0.1016m) = (6.193E\text{-}10\ m^2/N) \times (5.886N / \pi(0.006\ m/2)^2)$

$\underline{h = 1.30992E\text{-}05\ m}$

This calculation applied for all specimens with same set of loads.

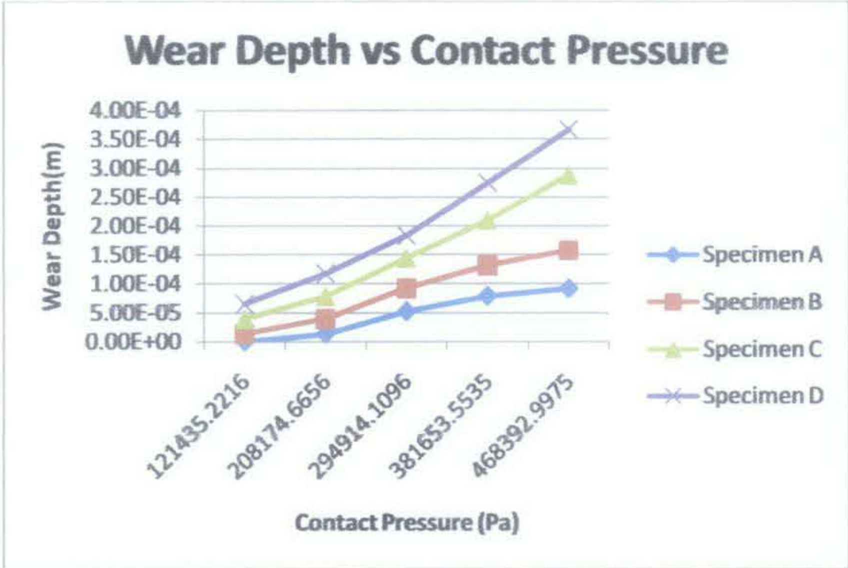

Figure 4.7: Wear depth of cylindrical pin specimens

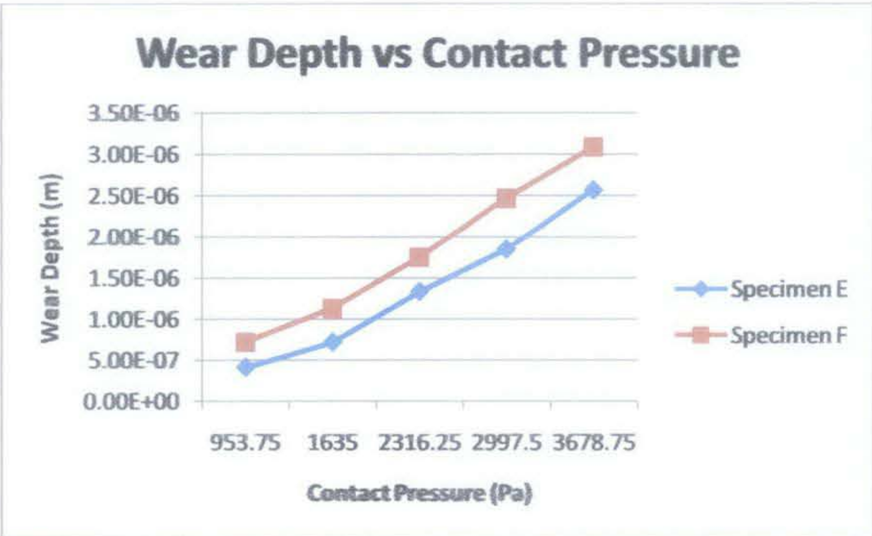

Figure 4.8: Wear depth of squared pin specimens

Based on Figure 4.7 and Figure 4.8, wear depth of the specimens are increasing as the pressure applied to the pin increase. Graph pattern of wear depth is same with worn mass graph pattern which shows the evidence that worn mass is linearly proportional to the wear depth of the pin. This result can be interpreted that when contact pressure is higher between two surfaces of pin and flat specimen resulted to larger surface contact area has been forced down to make contact. Therefore, with the increasing of number of cycles, more mass being worn away from the pin specimen.

However, by comparing Figure 4.7 and Figure 4.8, it shows that wear depth of squared pin specimens were smaller than cylindrical pin specimens. This is because the differential of contact area where the contact area of squared pin specimens were greater than cylindrical pin specimens whom resulted to pressure applied to cylindrical pin specimens was greater than squared pin specimens. This can be concluded that, the wear depth of squared pin specimens was lower but the worn volume was greater and the wear depth of cylindrical pin specimens was higher but the worn volume was lower.

4.2 MACROSCOPIC EXAMINATION

The pattern of wear been analyzed through the pattern of microstructure of the pin specimen's worn surface. As been specified in methodology, the microstructure at three point of locations been captured which at the leading edge, center and trailing edge and comparison can be made. Since there are six pin specimens involved, only cylindrical pin specimen and squared pin specimen which having 60 numbers of cycles (Specimen D and Specimen F) were selected where the wear rate of both of them based on previous result were the highest and will be analyzed for their microstructure of the worn surface. The rest of specimen's microstructure result will be attached in the Appendix's section.

4.2.1 Cylindrical Pin Specimen

(a) (b) (c)

Figure 4.9: Worn Surface Area of Cylindrical Pin Specimen (Specimen D) using 500x magnifications at (a) Trailing Edge (b) Center and (c) Leading Edge

Figure 4.9 shows the pattern of wear at three different locations on the cylindrical pin specimen's worn surface. At the leading edge, worn area was larger and clearly visible as shown by red circle. However, at the center and trailing edge, the worn area became smaller. The larger worn scar indicates that the worn volume at that area was greater which suggested that the contact pressure at that location was higher compared to center and trailing edge. This result also suggested that the wear depth at the leading edge was higher compared to other two locations.

Therefore, it can be proven that the worn surface was not totally even along the pin's surface and can be defined that as the pin specimen was moving along the surface contact area of the flat specimen, the pressure distribution was higher at the leading edge, decrease at the center, and the least at the trailing edge.

4.2.2 Squared Pin Specimen

(a) (b) (c)

Figure 4.10: Worn Surface Area of Squared Pin Specimen (Specimen F) using 500x magnifications at (a) Trailing Edge (b) Center and (c) Leading Edge

Compared to cylindrical pin specimen's microstructure, squared pin specimen's microstructure as shown in Figure 4.10 was having much clearer visibility of worn scar. However, the behavior of the wear mechanism was similar where worn area at leading edge was the largest compare with two other regions. It can be seen that the direction of the wear was linear and pointed into one direction. This had been supporting evidence that worn surface pattern satisfied to the modified linear wear tester which having one stroke of surface contact.

Worn scar of leading edge was larger compare to the center and trailing edge and also the leading edge of cylindrical pin specimen. This indicates that more worn volume occurred at the leading edge which should be resulted from higher contact stress at that area compared to other regions. In term of geometries, squared pin specimen was having tendency to wear quickly than cylindrical pin specimen based on the size of wear scar of these three regions.

4.3 HARDNESS TEST

Due to incapability of the TABER® Linear Abraser (Abrader) - Model 5750 to give the values of the coefficient of friction in order to simulate the tangential pressure distribution during the movement of the linear surface contact, the hardness measurements at leading edge, center and trailing edge have been taken as an alternative to illustrate the wear mechanism at those three locations.

According to the philosophy and basic understanding of wear properties, the surface area which encounter high wear rate will be having less hardness value while other part which having low wear rate will be having high hardness value. Therefore, based on this philosophy, the hardness values been measured at leading edge, center and trailing edge to investigate the wear behavior at those three locations and the relation with the mechanisms of the wear test. The hardness results were as shown as in Figure 4.11 and Figure 4.12.

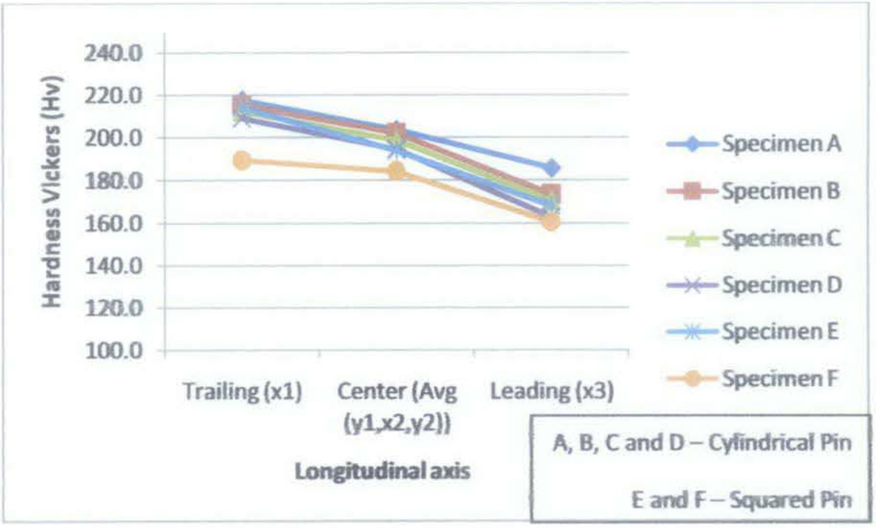

Figure 4.11: Hardness values at trailing, center and leading edge

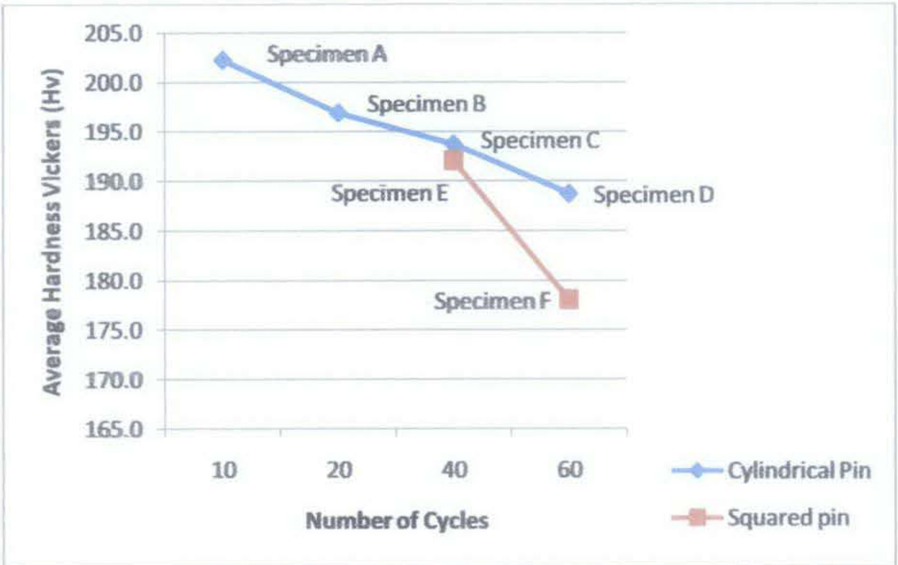

Figure 4.12: Average hardness values of all specimens

Figure 4.11 shows that the hardness values of all specimens decreased from trailing, center and leading edge of the specimens. These results show that the wear rate at the leading edge was greater, and then become much lesser at the center and the least at the trailing edge of the specimens. In relation with the pressure distribution, as pin specimens moved along the flat specimen, the frontal area of the pin were having greater worn surface compare at the back area of the pin specimens. These evidences satisfied with the philosophy that high wear rate will reduce the hardness value of the location of worn area.

On the other side, Figure 4.12 shows the average hardness values which have been obtained by calculation of the mean hardness values of leading edge, center and trailing edge. The pattern of result shows that as the number of cycles of surface contact between specimens increased, the hardness values of the surface material decreased. As known that the hardness values of the material is inversely proportional to the wear rate, this can be interpreted that the wear rate of specimen increased as the number of cycles increased. This theory contented with the result of the pin on flat test as mentioned earlier.

By comparison of geometrical factor of the pin specimen taken at two most highest number of cycles, 40 cycles and 60 cycles, squared pin specimens were having less hardness values than cylindrical specimens. The contact area of squared pin specimens was higher compared to cylindrical pin specimens. This shows that the larger worn area of squared pin specimen's surface where the resulted wear rate was high contributed to the more decrement of the hardness values compared to cylindrical pin specimens.

4.4 SIMULATION OF PRESSURE DISTRIBUTION

In this analysis, the pressure distribution illustrated using selected formula as specified in methodology section and been focused at the highest applied load of 13.2435N (1350g) for both specimens where the pressure is the highest. Since the previous results on pin on flat test shows that the wear rate was the highest and the worn surface area was obvious only when higher load been applied, therefore, the pressure distribution will illustrate the characterizations of the pressure applied around the surface of contact area of those pin specimens. The solution of the simulation only focused at normal load analysis since the incapability of the wear tester to obtain the coefficient of friction for simulation of tangential load analysis.

4.4.1 Normal Load Analysis

The assumption has been made that the normal load influence along the contact area only. There is not normal load influenced outside the contact area. It has been understandable that the maximum pressure applied could be at the center of the contact patch of the pin specimens and been distributed to the minimum pressure at the circumference of pin specimens. The contact pressure distribution is shown in Figure 4.13 and Figure 4.14.

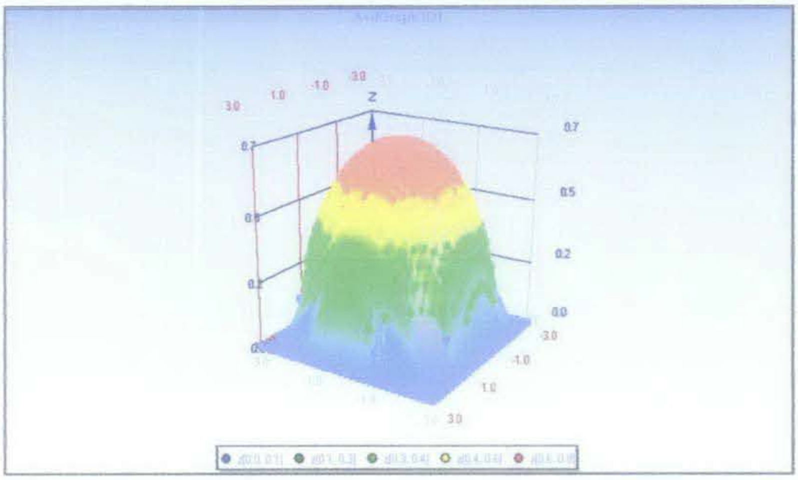

Figure 4.13: Normal pressure distribution of cylindrical pin specimen at 13.2435N (1350g) applied load

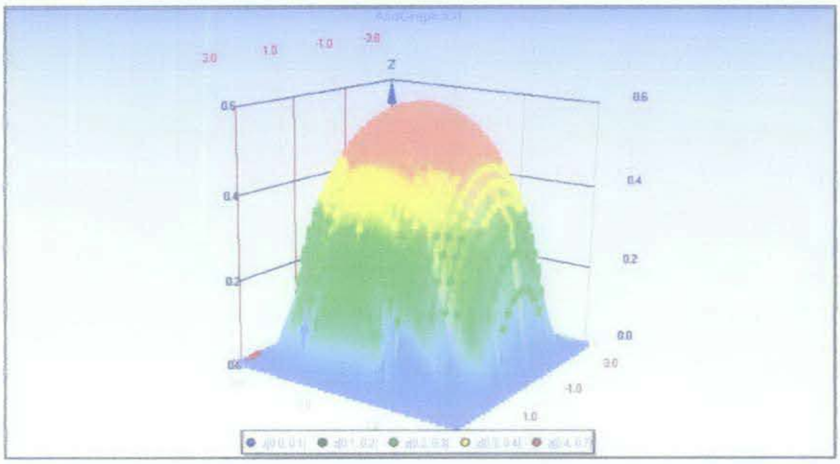

Figure 4.14: Normal pressure distribution of squared pin specimen at 13.2435N (1350g) applied load

Both Figure 4.13 and Figure 4.14 show that the pressure distribution curve is parabolic. The maximum pressures are 0.703 MPa and 0.5520 MPa for cylindrical pin specimen and squared pin specimen respectively at maximum 13.2435N (1350g) applied load. The comparison between both simulation shows that the maximum pressure and its distribution for squared pin specimen lesser than cylindrical pin specimen because the larger contact patch area of its geometrical factor. However, in term of wear rate obtained shows that the wear rate was higher for squared specimen due to more contact surface along its longitudinal and latitudinal distance.

The comparison between the maximum pressure distribution of loads applied for cylindrical and squared pin specimens at 3.43N (350g), 5.89N (600g), 8.34N (850g), 10.79N (1100g) and 13.24N (1350g) as shown in Figure 4.15 and Figure 4.16 respectively.

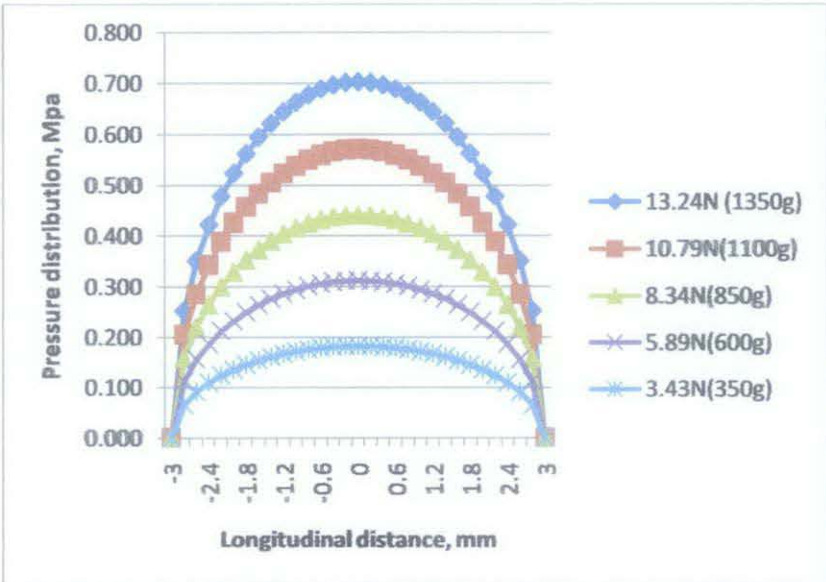

Figure 4.15: Maximum pressure distribution of all applied load for cylindrical specimen

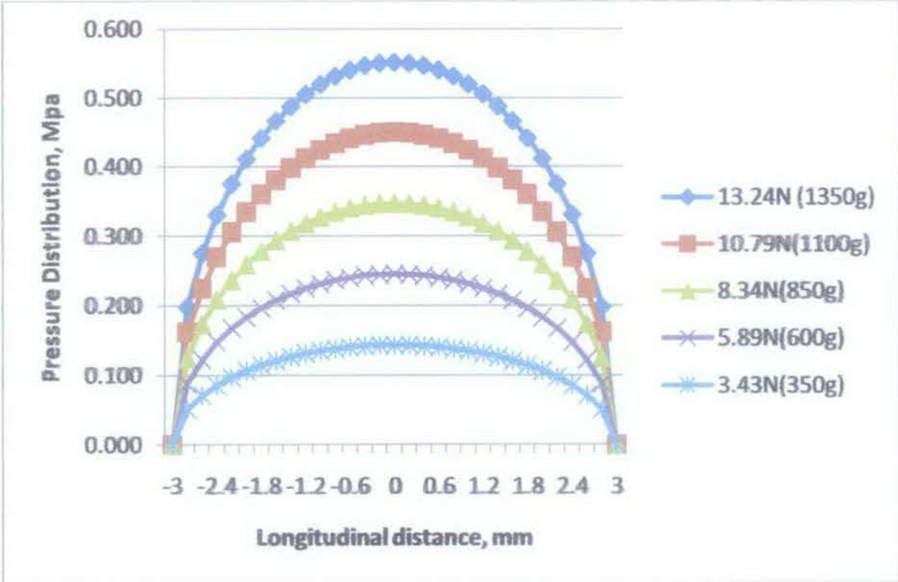

Figure 4.16: Maximum pressure distribution of all applied load for squared specimen

4.4.2 Prediction of tangential load analysis

The tangential contact problem is usually connected with friction and a solution is needed or surface shear stress distributions and related area of adhesion and slip in the contact patch. The slip stick area distributions in contact patch can be obtained if the value of coefficient of friction can be determined. However, due to incapability of machine wear tester to provide the value of coefficient of friction, the slip stick area distributions only can be predicted using the hardness value and macroscopic examination's results.

From this experiment, it is understandable that in this research, the adhesion area is located at the leading edge of contact area as proven in the measurement of lowest hardness value and obvious worn scar by macroscopic examination at this area and decreases at the trailing edge. Therefore, it can be concluded that the slip zone could be at the leading edge of the specimen where the surface shear stress is high and stick zone could be at the trailing edge where the surface shear stress is minimal.

4.4.3 Comparison on experimental and prediction of depth of wear

The comparison been focused on Specimen D of cylindrical pin specimen and Specimen F of squared pin specimen since these two specimens encountered surface contact at the highest number of cycles. The results have been shown in Figure 4.17 and Figure 4.18 respectively. The rest of the results will be as per attachments in appendices section.

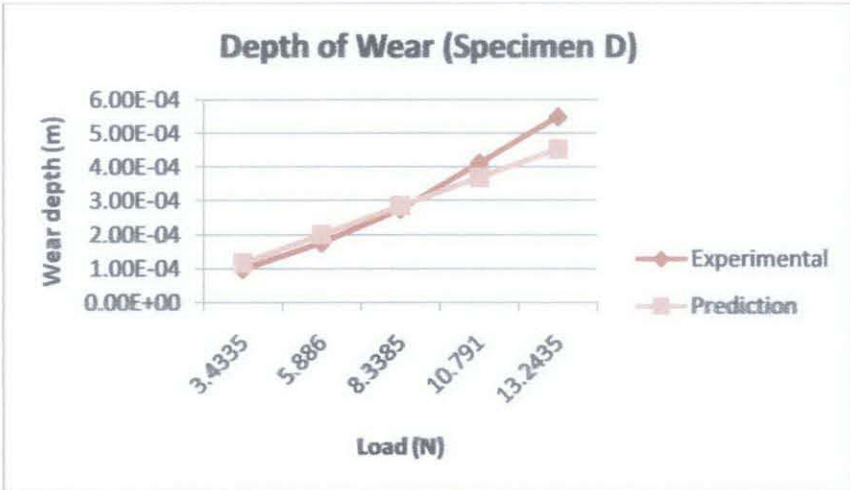

Figure 4.17: Comparison of cylindrical specimen's depth of wear between experimental and prediction

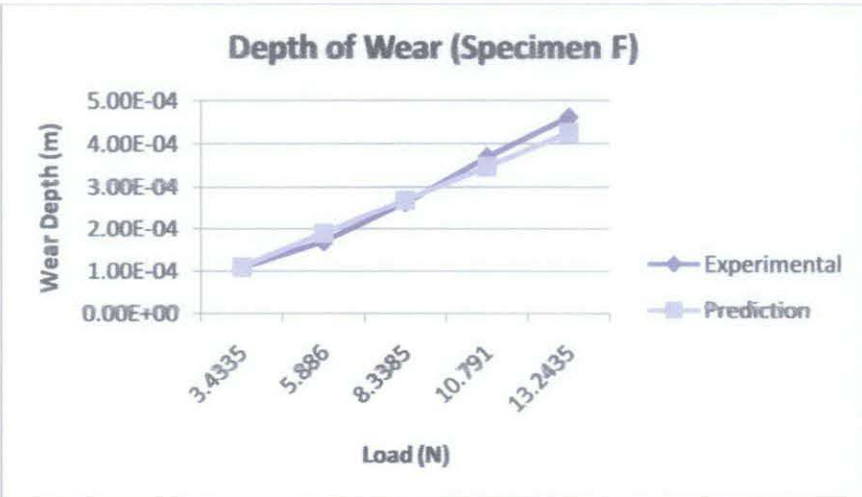

Figure 4.18: Comparison of squared specimen's depth of wear between experimental and prediction

Based on these two results, the prediction was used to fit the results of the experiment. The value of wear of coefficient was obtained from the experiment. It can be seen from the both of Figure 4.17 and Figure 4.18 that predictions have a good agreement with the experimental results. There were errors that occurred during the experiment which could not lead and satisfied with the prediction that have been calculated. For example the surface roughness of flat specimens may be varied from each other and the modified specimen table which controlled manually could lead to the errors.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The objectives of the investigation which to analyze wear mechanisms, behaviors, and characteristics of the laboratory wear testing result, to predict the wear rate of pin on flat contacts and the effect of leading and trailing edge and to simulate the pressure distribution at contact area was successfully achieved. The pin on flat wear test in linearly reciprocating motion has been investigated using pressure distribution study the wear rate have been obtained been successfully compared to the prediction result.

The results showed pressure distribution can be used to determine the depth of wear experimentally in pin on flat wear test and can be used also for the prediction at highest number of applied load. The pressure distribution indicated a parabolic curve with maximum pressure of 0.7030 MPa, 0.5720 MPa, 0.4420 Mpa, 0.3120 MPa and 1820 MPa for 13.24N (1350g), 10.79N (1100g), 8.34N (850g), 5.89N (600g) and 3.43N (350g) applied load respectively of cylindrical pin specimens and 0.5520 MPa, 0.4500 MPa, 0.3475 MPa, 0.2454 MPa and 0.1429 MPa for 13.24N (1350g), 10.79N (1100g), 8.34N (850g), 5.89N (600g) and 3.43N (350g) applied load respectively of squared pin specimens. The depth of wear can be predicted from these pressure distributions and the experimental results have a good agreement with the predictions.

Although the incapability of the wear tester machine to produce the value of coefficient of friction in order to perform tangential load analysis, the effect of leading edge and trailing edge of pin specimens have been successfully determined using the hardness values and macroscopic examination of the worn surface. The results indicate the evidences for all specimens that the hardness values were the lowest at the leading edge area and the highest at the trailing edge area while supported by the results of macroscopic examinations where the worn scar was most obvious at the leading edge and less obvious at the trailing edge. These evidences concluded that the wear rate was the highest at the leading and the lowest at the trailing edge of pin specimens.

The recommendations to improve these researches by obtaining the value of coefficient of friction of surface contact. This can be done by using pin on disc wear tester to obtain the values by using same materials of aluminum tested in this research. Therefore, the tangential load analysis can be done to analyze the slip-stick area distribution and surface shear stress. The research work could be expanded by using the specimens consist of two different materials where the properties of both materials should be varied thus the wear behavior and mechanisms should be different.

In addition to that, further research can be implemented where the experiment can be planned to be carried out with the lubrication effect. The behavior of the result of wear mechanisms could be different as this research was dry sliding type where there were non-lubrication effects. Same goes to other varied parameters, such operating the experiment in high temperature with low humidity or the experiment been carried out with the effect of acidic additives to the test, as relation to the industrial application, where high acidity of environment always been a concern.

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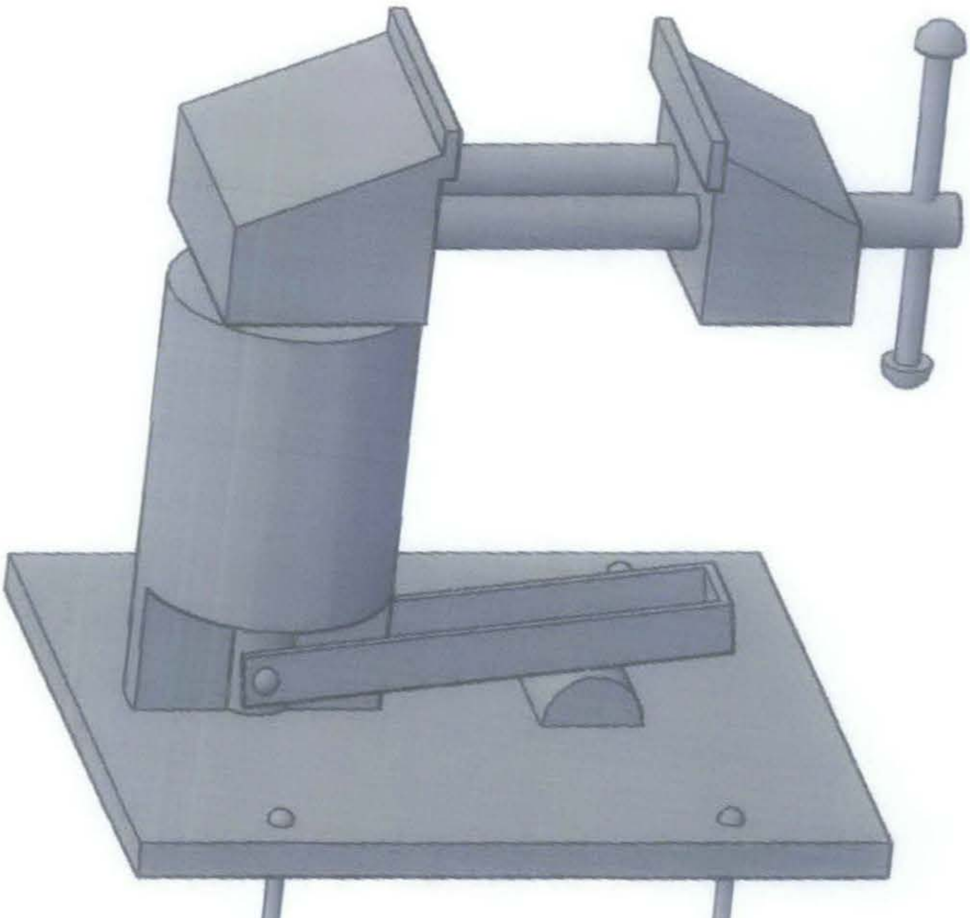
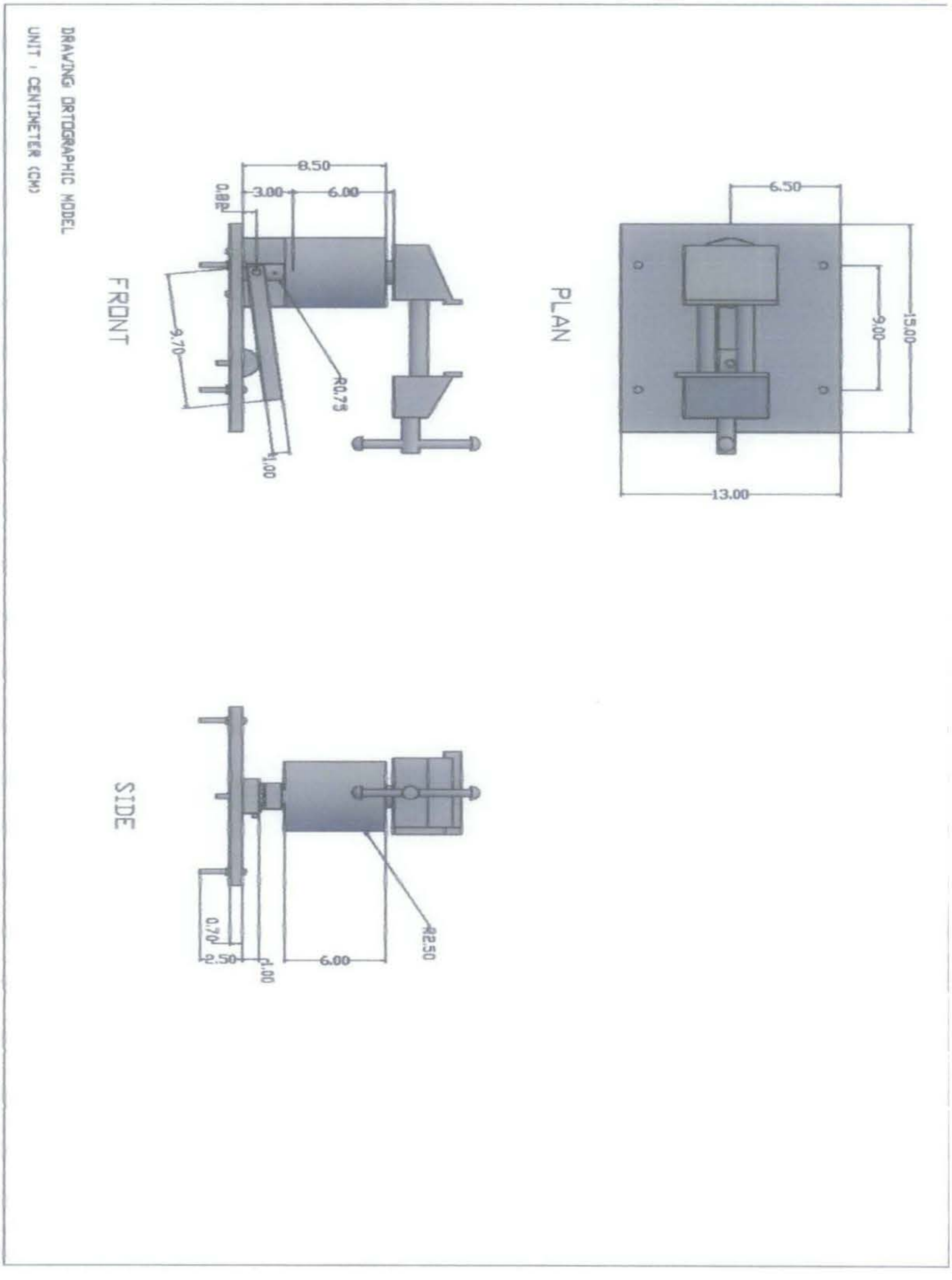
APPENDICES

APPENDIX I



APPENDIX II


DRAWING ORTOGRAPHIC MODEL
UNIT : CENTIMETER (CM)
FRONT
PLAN
SIDE
8.50
3.00
6.00
0.82
9.70
R0.75
1.00
6.50
9.00
15.00
13.00
0.70
2.50
1.00
6.00
R2.50

APPENDIX III

APPENDIX IV

erview of materials for Aluminum Alloy

egories: Metal; Nonferrous Metal; Aluminum Alloy

terial es: This property data is a summary of similar materials in the MatWeb database for the category "Aluminum Alloy". Each property range of values reported is minimum and maximum values of appropriate MatWeb entries. The comments report the average value, and number of data points used to calculate the average. The values are not necessarily typical of any specific grade, especially less common values and those that can be most affected by additives or processing methods.

idors: **Click here to view all available suppliers for this material.**

Please click here if you are a supplier and would like information on how to add your listing to this material.

sical Properties	Metric	English	Comments
isity	0.0160 - 3.50 g/cc	0.000579 - 0.126 lb/in³	Average value: 2.48 g/cc Grade Count:1099
Length	3.00 - 7.00 mm	0.118 - 0.276 in	Average value: 4.67 mm Grade Count:3

chanical Properties	Metric	English	Comments
dness, Brinell	12.0 - 210	12.0 - 210	Average value: 87.7 Grade Count:472
dness, Knoop	67.0 - 232	67.0 - 232	Average value: 122 Grade Count:324
dness, Rockwell A	35.4 - 60.0	35.4 - 60.0	Average value: 44.6 Grade Count:196
dness, Rockwell B	45.0 - 96.0	45.0 - 96.0	Average value: 68.1 Grade Count:217
dness, Vickers	15.0 - 217	15.0 - 217	Average value: 112 Grade Count:309
sile Strength, Ultimate	0.700 - 1600 MPa	102 - 232000 psi	Average value: 330 MPa Grade Count:637
sile Strength, Yield	1.24 - 750 MPa	180 - 109000 psi	Average value: 262 MPa Grade Count:577
igation at Break	0.150 - 50.0 %	0.150 - 50.0 %	Average value: 10.6 % Grade Count:579
igation at Yield	1.00 - 10.0 %	1.00 - 10.0 %	Average value: 4.69 % Grade Count:13
luction of Area	9.00 - 26.0 %	9.00 - 26.0 %	Average value: 17.8 % Grade Count:3
ep Strength	315 - 538 MPa	45700 - 78000 psi	Average value: 435 MPa Grade Count:6
iture Strength	420 - 552 MPa	60900 - 80100 psi	Average value: 482 MPa Grade Count:6
lulus of Elasticity	0.0480 - 342 GPa	6.96 - 49600 ksi	Average value: 75.4 GPa Grade Count:579
cural Yield Strength	172 - 330 MPa	24900 - 47900 psi	Average value: 260 MPa Grade Count:8
npressive Yield Strength	0.138 - 3400 MPa	20.0 - 493000 psi	Average value: 60.5 MPa Grade Count:180
npressive Modulus	0.0689 - 82.8 GPa	10.0 - 12000 ksi	Average value: 22.3 GPa Grade Count:163
ched Tensile Strength	90.0 - 414 MPa	13100 - 60000 psi	Average value: 258 MPa Grade Count:21
nate Bearing Strength	117 - 1090 MPa	17000 - 158000 psi	Average value: 496 MPa Grade Count:41
ring Yield Strength	41.0 - 910 MPa	5950 - 132000 psi	Average value: 436 MPa Grade Count:44
ssons Ratio	0.230 - 0.360	0.230 - 0.360	Average value: 0.329 Grade Count:439
irpy Impact	3.30 - 21.7 J	2.43 - 16.0 ft-lb	Average value: 8.33 J Grade Count:17
irpy Impact, Unnotched	16.3 - 77.0 J	12.0 - 56.8 ft-lb	Average value: 55.8 J Grade Count:7
gue Strength	20.7 - 469 MPa	3000 - 68000 psi	Average value: 134 MPa Grade Count:213
cture Toughness	10.0 - 165 MPa-m½	9.10 - 150 ksi-in½	Average value: 37.4 MPa-m½ Grade Count:42
chinability	10.0 - 90.0 %	10.0 - 90.0 %	Average value: 54.8 % Grade Count:250
iar Modulus	0.0469 - 72.4 GPa	6.80 - 10500 ksi	Average value: 17.8 GPa Grade Count:523
iar Strength	0.138 - 420 MPa	20.0 - 60900 psi	Average value: 101 MPa Grade Count:617

ctrical Properties	Metric	English	Comments
ctrical Resistivity	0.00000260 - 250000 ohm-cm	0.00000260 - 250000 ohm-cm	Average value: 436 ohm-cm Grade Count:516
gnetic Susceptibility	6.00e-7 - 8.00e-7	6.00e-7 - 8.00e-7	Average value: 7.61e-7 Grade Count:18

irmal Properties	Metric	English	Comments
it of Fusion	387 - 390 J/g	166 - 168 BTU/lb	Average value: 389 J/g Grade Count:182
E, linear	7.00 - 29.2 µm/m-°C	3.89 - 16.2 µin/in-°F	Average value: 23.5 µm/m-°C Grade Count:516
cific Heat Capacity	0.690 - 1.01 J/g-°C	0.165 - 0.241 BTU/lb-°F	Average value: 0.911 J/g-°C Grade Count:467
irmal Conductivity	1.48 - 255 W/m-K	10.3 - 1770 BTU-in/hr-ft²-°F	Average value: 151 W/m-K Grade Count:557
ting Point	204 - 1350 °C	400 - 2460 °F	Average value: 607 °C Grade Count:489
dus	204 - 660 °C	400 - 1220 °F	Average value: 567 °C Grade Count:471
idus	543 - 674 °C	1010 - 1250 °F	Average value: 639 °C Grade Count:477
imum Service Temperature, Air	60.0 - 371 °C	140 - 700 °F	Average value: 239 °C Grade Count:6
imum Service Temperature, Air	-80.0 °C	-112 °F	Average value: -80.0 °C Grade Count:3

ical Properties	Metric	English	Comments
issivity (0-1)	0.0400 - 0.300	0.0400 - 0.300	Average value: 0.0655 Grade Count:10
lection Coefficient, Visible (0-1)	0.860 - 0.960	0.860 - 0.960	Average value: 0.890 Grade Count:12

cessing Properties	Metric	English	Comments
cessing Temperature	505 - 816 °C	941 - 1500 °F	Average value: 723 °C Grade Count:75
iealing Temperature	177 - 546 °C	350 - 1020 °F	Average value: 376 °C Grade Count:274

ıtion Temperature	399 - 566 °C	750 - 1050 °F	Average value: 512 °C Grade Count:218
ıg Temperature	22.2 - 346 °C	72.0 - 655 °F	Average value: 169 °C Grade Count:158
Working Temperature	260 - 510 °C	500 - 950 °F	Average value: 386 °C Grade Count:95
ting Temperature	616 - 816 °C	1140 - 1500 °F	Average value: 720 °C Grade Count:70

nponent Elements Properties	Metric	English	Comments
ninum, Al	30.0 - 100 %	30.0 - 100 %	Average value: 92.4 % Grade Count:1252
mony, Sb	0.150 - 0.300 %	0.150 - 0.300 %	Average value: 0.200 % Grade Count:4
um, Ba	0.0100 - 0.100 %	0.0100 - 0.100 %	Average value: 0.0650 % Grade Count:4
/llium, Be	0.000100 - 6.00 %	0.000100 - 6.00 %	Average value: 0.135 % Grade Count:73
nuth, Bi	0.0100 - 11.0 %	0.0100 - 11.0 %	Average value: 1.08 % Grade Count:34
on, B	0.00100 - 11.0 %	0.00100 - 11.0 %	Average value: 0.605 % Grade Count:62
mium, Cd	0.00200 - 0.200 %	0.00200 - 0.200 %	Average value: 0.0321 % Grade Count:6
ium, Ca	0.00200 - 22.0 %	0.00200 - 22.0 %	Average value: 2.33 % Grade Count:13
oon, C	0.0300 - 0.350 %	0.0300 - 0.350 %	Average value: 0.168 % Grade Count:4
omium, Cr	0.0100 - 21.0 %	0.0100 - 21.0 %	Average value: 0.192 % Grade Count:560
alt, Co	0.00100 - 10.0 %	0.00100 - 10.0 %	Average value: 1.55 % Grade Count:8
per, Cu	0.00300 - 52.0 %	0.00300 - 52.0 %	Average value: 1.45 % Grade Count:1155
Mn	0.100 - 0.800 %	0.100 - 0.800 %	Average value: 0.439 % Grade Count:10
Mn + Ti + V	0.0250 - 0.0300 %	0.0250 - 0.0300 %	Average value: 0.0258 % Grade Count:6
ium, Ga	0.00500 - 0.0500 %	0.00500 - 0.0500 %	Average value: 0.0294 % Grade Count:43
, Fe	0.00600 - 50.0 %	0.00600 - 50.0 %	Average value: 0.646 % Grade Count:1147
d, Pb	0.00300 - 9.00 %	0.00300 - 9.00 %	Average value: 0.401 % Grade Count:60
um, Li	0.00300 - 4.20 %	0.00300 - 4.20 %	Average value: 1.61 % Grade Count:38
nesium, Mg	0.00500 - 52.0 %	0.00500 - 52.0 %	Average value: 1.25 % Grade Count:1092
ganese, Mn	0.00200 - 26.0 %	0.00200 - 26.0 %	Average value: 0.342 % Grade Count:1086
el, Ni	0.0100 - 50.0 %	0.0100 - 50.0 %	Average value: 0.895 % Grade Count:236
er, each	0.00200 - 0.200 %	0.00200 - 0.200 %	Average value: 0.0481 % Grade Count:1045
er, total	0.0100 - 0.800 %	0.0100 - 0.800 %	Average value: 0.171 % Grade Count:1085
gen, O	0.0500 - 0.600 %	0.0500 - 0.600 %	Average value: 0.291 % Grade Count:11
sphorous, P	0.00100 - 0.0100 %	0.00100 - 0.0100 %	Average value: 0.00800 % Grade Count:9
ıssium, K	1.00 %	1.00 %	Average value: 1.00 % Grade Count:5
Fe	0.0200 - 1.00 %	0.0200 - 1.00 %	Average value: 0.628 % Grade Count:59
on, Si	0.000 - 70.0 %	0.000 - 70.0 %	Average value: 2.95 % Grade Count:1162
er, Ag	0.0500 - 1.00 %	0.0500 - 1.00 %	Average value: 0.513 % Grade Count:21
ium, Na	0.00100 - 0.500 %	0.00100 - 0.500 %	Average value: 0.360 % Grade Count:7
ntium, Sr	0.00500 - 16.0 %	0.00500 - 16.0 %	Average value: 2.16 % Grade Count:26
Sn	0.0200 - 22.0 %	0.0200 - 22.0 %	Average value: 1.31 % Grade Count:116
nium, Ti	0.00200 - 11.0 %	0.00200 - 11.0 %	Average value: 0.226 % Grade Count:878
i	0.0100 - 0.0300 %	0.0100 - 0.0300 %	Average value: 0.0208 % Grade Count:13
adium, V	0.00500 - 11.0 %	0.00500 - 11.0 %	Average value: 0.286 % Grade Count:133
, Zn	0.000 - 50.0 %	0.000 - 50.0 %	Average value: 1.12 % Grade Count:1093
onium, Zr	0.0100 - 16.0 %	0.0100 - 16.0 %	Average value: 0.427 % Grade Count:138
i	0.0800 - 0.500 %	0.0800 - 0.500 %	Average value: 0.236 % Grade Count:16

e of the values displayed above may have been converted from their original units and/or rounded in order to display the information in a consistent format. Users requiring more precise data for scientific or neering calculations can click on the property value to see the original value as well as raw conversions to equivalent units. We advise that you only use the original value or one of its raw conversions in your lations to minimize rounding error. We also ask that you refer to MatWeb's terms of use regarding this information. Click here to view all the property values for this datasheet as they were originally entered into Veb.

APPENDIX V

Specimen A

Distance (m)	0.1016	0.1016	0.1016	0.1016	0.101(
Load (g)	350	600	850	1100	135(
Load (N)	3.4335	5.886	8.3385	10.791	13.243!
V (m^3)	*0.000E+00*	*3.704E-10*	*1.481E-09*	*2.222E-09*	*2.593E-0!*
Worn Mass (mg)	0	1	4	6	[illegible]
Wear coefficient (k)(m^2/N)	0	6.193E-10	1.749E-09	2.027E-09	1.9268E-0!
Contact area(m^2)	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-0!
Contact Pressure (Pa)	121435.2216	208174.6656	294914.1096	381653.5535	468392.997!
Wear depth (m)	0	1.30992E-05	5.23967E-05	7.8595E-05	9.16942E-0!

Final mass (mg)	Initial mass (mg)	Worn mass (mg)
753	753	0
752	753	1
748	752	4
742	748	6
735	742	7

Specimen B

Distance (m)	0.1016	0.1016	0.1016	0.1016	0.101(
Load (g)	350	600	850	1100	135(
Load (N)	3.4335	5.886	8.3385	10.791	13.243!
V (m^3)	3.704E-10	1.111E-09	2.593E-09	3.704E-09	4.444E-0!
Worn Mass (mg)	1	3	7	10	1!
Wear coefficient (k)(m^2/N)	*1.06171E-09*	*1.858E-09*	*3.060E-09*	*3.378E-09*	*3.3031E-0!*
Contact area(m^2)	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-0!
Contact Pressure (Pa)	121435.2216	208174.6656	294914.1096	381653.5535	468392.997!
Wear depth (m)	1.30992E-05	3.92975E-05	9.16942E-05	0.000130992	0.00015715

Final mass (mg)	*Initial mass (mg)*	*Worn mass (mg)*
752	753	1
749	752	3
742	749	7
732	742	10
720	*732*	*12*

Specimen C

Distance (m)	0.1016	0.1016	0.1016	0.1016	0.101
Load (g)	350	600	850	1100	135
Load (N)	3.4335	5.886	8.3385	10.791	13.243
V (m^3)	1.111E-09	2.222E-09	4.074E-09	5.926E-09	8.148E-0
Worn Mass (mg)	3	6	11	16	2
Wear coefficient (k)(m^2/N)	*3.18513E-09*	*3.716E-09*	*4.809E-09*	*5.405E-09*	*6.0557E-0*
Contact area(m^2)	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-0
Contact Pressure (Pa)	121435.2216	208174.6656	294914.1096	381653.5535	468392.997
Wear depth (m)	3.92975E-05	7.8595E-05	0.000144091	0.000209587	0.00028818

Final mass (mg)	Initial mass (mg)	Worn mass (mg)
750	753	3
744	750	6
733	744	11
717	733	16
695	717	22

Specimen D

Distance (m)	0.1016	0.1016	0.1016	0.1016	0.101
Load (g)	350	600	850	1100	135
Load (N)	3.4335	5.886	8.3385	10.791	13.243
V (m^3)	1.852E-09	3.333E-09	5.185E-09	7.778E-09	1.037E-0
Worn Mass (mg)	5	9	14	21	2
Wear coefficient (k)(m^2/N)	5.30854E-09	5.574E-09	6.120E-09	7.094E-09	7.7072E-0
Contact area(m^2)	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-05	2.82743E-0
Contact Pressure (Pa)	121435.2216	208174.6656	294914.1096	381653.5535	468392.997
Wear depth (m)	6.54959E-05	0.000117893	0.000183388	0.000275083	0.00036677

Final mass (mg)	Initial mass (mg)	Worn mass (mg)
748	753	5
739	748	9
725	739	14
704	725	21
676	704	28

Specimen E

Distance (m)	0.1016	0.1016	0.1016	0.1016	0.101
Load (g)	350	600	850	1100	135
Load (N)	3.4335	5.886	8.3385	10.791	13.243
V (m^3)	1.481E-09	2.593E-09	4.815E-09	6.667E-09	9.259E-0
Worn Mass (mg)	4	7	13	18	2
Wear coefficient (k)(m^2/N)	4.24684E-09	4.335E-09	5.683E-09	6.081E-09	6.8814E-0
Contact area(m^2)	0.0036	0.0036	0.0036	0.0036	0.003
Contact Pressure (Pa)	953.75	1635	2316.25	2997.5	3678.7
Wear depth (m)	4.11523E-07	7.20165E-07	1.33745E-06	1.85185E-06	2.57202E-0

Final mass (mg)	Initial mass (mg)	Worn mass (mg)
879	883	4
872	879	7
859	872	13
841	859	18
816	841	25

Specimen F

Distance (m)	0.1016	0.1016	0.1016	0.1016	0.101
Load (g)	350	600	850	1100	13
Load (N)	3.4335	5.886	8.3385	10.791	13.24
V (m^3)	2.593E-09	4.074E-09	6.296E-09	8.889E-09	1.111E-
Worn Mass (mg)	7	11	17	24	[illegible]
Wear coefficient (k)(m^2/N)	7.43196E-09	6.813E-09	7.432E-09	8.108E-09	8.2577E-
Contact area	0.0036	0.0036	0.0036	0.0036	0.00
Contact Pressure (Pa)	953.75	1635	2316.25	2997.5	3678.
Wear depth (m)	7.20165E-07	1.13169E-06	1.74897E-06	2.46914E-06	3.08642E-

Final mass (mg)	Initial mass (mg)	Worn mass (mg)
876	883	7
865	876	11
848	865	17
824	848	24
794	824	30

APPENDIX VI

(a) Trailing Edge

(b)Center

(c) Leading Edge

Specimen A

(a)

(b)

(c)

Specimen B

(a)

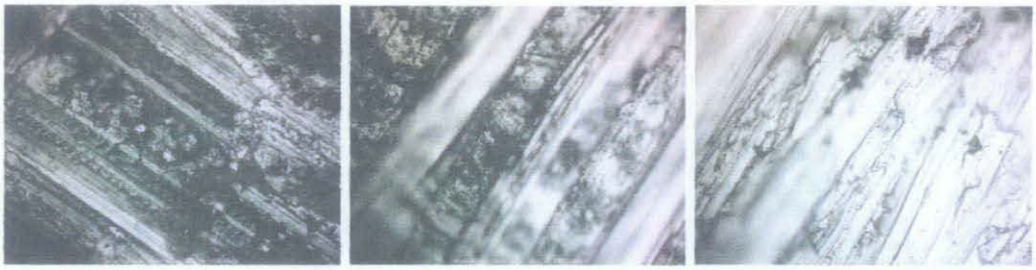
(b)

(c)

Specimen C

(a) (b) (c)

Specimen E



(a) (b) (c)

APPENDIX VII

Longitudinal

	-3.0	-2.8	-2.6	-2.4	-2.2	-2.0	-1.8	-1.6	-1.4	-1.2	-1.0	-0.8	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.8	0	0	0	0	0	0	0	0	0	0	0.093733	0.16898	0.209594	0.234333	0.247995	0.252385	0.247995	0.234333	0.209594	0.16898	0.093733	0	0	0	0	0	0	0	0	0	0
-2.6	0	0	0	0	0	0	0	0	0.123998	0.209594	0.260943	0.296411	0.321302	0.33796	0.347573	0.350718	0.347573	0.33796	0.321302	0.296411	0.260943	0.209594	0.123998	0	0	0	0	0	0	0	0
-2.4	0	0	0	0	0	0	7.40731E-09	0.193236	0.265118	0.314391	0.350718	0.377851	0.397677	0.411253	0.419188	0.4218	0.419188	0.411253	0.397677	0.377851	0.350718	0.314391	0.265118	0.193236	7.41E-09	0	0	0	0	0	0
-2.2	0	0	0	0	0	0.093733	0.224764637	0.296411	0.347573	0.386471	0.41656	0.439648	0.4568	0.468667	0.475645	0.477948	0.475645	0.468667	0.4568	0.439648	0.41656	0.386472	0.347573	0.296411	0.224765	0.093733	0	0	0	0	0
-2.0	0	0	0	0	0.093733	0.234333	0.310878297	0.36604	0.408574	0.442139	0.468667	0.489302	0.504769	0.515533	0.521885	0.523985	0.521885	0.515533	0.504769	0.489302	0.468667	0.442139	0.408574	0.36604	0.310878	0.234333	0.093733	0	0	0	0
-1.8	0	0	0	7.40731E-09	0.224765	0.310878	0.371992634	0.419188	0.4568	0.487053	0.511255	0.530236	0.544541	0.554534	0.560444	0.5624	0.560444	0.554534	0.544541	0.530236	0.511255	0.487053	0.4568	0.419188	0.371993	0.310878	0.224765	7.41E-09	0	0	0
-1.6	0	0	0.132559	0.193236217	0.296411	0.36604	0.41918821	0.461583	0.49599	0.523985	0.546555	0.564349	0.577811	0.587238	0.592822	0.594671	0.592822	0.587238	0.577811	0.564349	0.546555	0.523985	0.49599	0.461583	0.419188	0.36604	0.296411	0.193236	0.132559	0	0
-1.4	0	0	0.123998	0.265117902	0.347573	0.408574	0.456799762	0.49599	0.528161	0.554534	0.575907	0.592822	0.605651	0.614651	0.619988	0.621757	0.619988	0.614651	0.605651	0.592822	0.575907	0.554534	0.528161	0.49599	0.4568	0.408574	0.347573	0.265118	0.123998	0	0
-1.2	0	0	0.209594	0.314391158	0.386472	0.442139	0.487052687	0.523985	0.554534	0.579709	0.600186	0.616435	0.628782	0.637456	0.642603	0.64431	0.642603	0.637456	0.628782	0.616435	0.600186	0.579709	0.554534	0.523985	0.487053	0.442139	0.386472	0.314391	0.209594	0	0
-1.0	0	0.0937333	0.260943	0.350718019	0.41656	0.468667	0.511254974	0.546555	0.575907	0.600186	0.619988	0.63573	0.64771	0.656133	0.661136	0.662795	0.661136	0.656133	0.64771	0.63573	0.619988	0.600186	0.575907	0.546555	0.511255	0.468667	0.41656	0.350718	0.260943	0.093733	0
-0.8	0	0.1689802	0.296411	0.377851146	0.439648	0.489302	0.530235805	0.564349	0.592822	0.616435	0.63573	0.651093	0.662795	0.671029	0.675921	0.677544	0.675921	0.671029	0.662795	0.651093	0.63573	0.616435	0.592822	0.564349	0.530236	0.489302	0.439648	0.377851	0.296411	0.16898	0
-0.6	0	0.2095941	0.321302	0.397676854	0.4568	0.504769	0.544541458	0.577811	0.605651	0.628782	0.64771	0.662795	0.674294	0.682389	0.6872	0.688797	0.6872	0.682389	0.674294	0.662795	0.64771	0.628782	0.605651	0.577811	0.544541	0.504769	0.4568	0.397677	0.321302	0.209594	0
-0.4	0	0.2343333	0.33796	0.411253331	0.468667	0.515533	0.554533878	0.587238	0.614651	0.637456	0.656133	0.671029	0.682389	0.690389	0.695145	0.696723	0.695145	0.690389	0.682389	0.671029	0.656133	0.637456	0.614651	0.587238	0.554534	0.515533	0.468667	0.411253	0.33796	0.234333	0
-0.2	0	0.2479951	0.347573	0.41918821	0.475645	0.521885	0.56044382	0.592822	0.619988	0.642603	0.661136	0.675921	0.6872	0.695145	0.699869	0.701436	0.699869	0.695145	0.6872	0.675921	0.661136	0.642603	0.619988	0.592822	0.560444	0.521885	0.475645	0.419188	0.347573	0.247995	0
0.0	0	0.2523847	0.350718	0.4218	0.477948	0.523985	0.5624	0.594671	0.621757	0.64431	0.662795	0.677544	0.688797	0.696723	0.701436	0.703	0.701436	0.696723	0.688797	0.677544	0.662795	0.64431	0.621757	0.594671	0.5624	0.523985	0.477948	0.4218	0.350718	0.252385	0
0.2	0	0.2479951	0.347573	0.41918821	0.475645	0.521885	0.56044382	0.592822	0.619988	0.642603	0.661136	0.675921	0.6872	0.695145	0.699869	0.701436	0.699869	0.695145	0.6872	0.675921	0.661136	0.642603	0.619988	0.592822	0.560444	0.521885	0.475645	0.419188	0.347573	0.247995	0
0.4	0	0.2343333	0.33796	0.411253331	0.468667	0.515533	0.554533878	0.587238	0.614651	0.637456	0.656133	0.671029	0.682389	0.690389	0.695145	0.696723	0.695145	0.690389	0.682389	0.671029	0.656133	0.637456	0.614651	0.587238	0.554534	0.515533	0.468667	0.411253	0.33796	0.234333	0
0.6	0	0.2095941	0.321302	0.397676854	0.4568	0.504769	0.544541458	0.577811	0.605651	0.628782	0.64771	0.662795	0.674294	0.682389	0.6872	0.688797	0.6872	0.682389	0.674294	0.662795	0.64771	0.628782	0.605651	0.577811	0.544541	0.504769	0.4568	0.397677	0.321302	0.209594	0
0.8	0	0.1689802	0.296411	0.377851146	0.439648	0.489302	0.530235805	0.564349	0.592822	0.616435	0.63573	0.651093	0.662795	0.671029	0.675921	0.677544	0.675921	0.671029	0.662795	0.651093	0.63573	0.616435	0.592822	0.564349	0.530236	0.489302	0.439648	0.377851	0.296411	0.16898	0
1.0	0	0.0937333	0.260943	0.350718019	0.41656	0.468667	0.511254974	0.546555	0.575907	0.600186	0.619988	0.63573	0.64771	0.656133	0.661136	0.662795	0.661136	0.656133	0.64771	0.63573	0.619988	0.600186	0.575907	0.546555	0.511255	0.468667	0.41656	0.350718	0.260943	0.093733	0
1.2	0	0	0.209594	0.314391158	0.386472	0.442139	0.487052687	0.523985	0.554534	0.579709	0.600186	0.616435	0.628782	0.637456	0.642603	0.64431	0.642603	0.637456	0.628782	0.616435	0.600186	0.579709	0.554534	0.523985	0.487053	0.442139	0.386472	0.314391	0.209594	0	0
1.4	0	0	0.123998	0.265117902	0.347573	0.408574	0.456799762	0.49599	0.528161	0.554534	0.575907	0.592822	0.605651	0.614651	0.619988	0.621757	0.619988	0.614651	0.605651	0.592822	0.575907	0.554534	0.528161	0.49599	0.4568	0.408574	0.347573	0.265118	0.123998	0	0
1.6	0	0	0.132559	0.193236217	0.296411	0.36604	0.41918821	0.461583	0.49599	0.523985	0.546555	0.564349	0.577811	0.587238	0.592822	0.594671	0.592822	0.587238	0.577811	0.564349	0.546555	0.523985	0.49599	0.461583	0.419188	0.36604	0.296411	0.193236	0.132559	0	0
1.8	0	0	0	7.40731E-09	0.224765	0.310878	0.371992634	0.419188	0.4568	0.487053	0.511255	0.530236	0.544541	0.554534	0.560444	0.5624	0.560444	0.554534	0.544541	0.530236	0.511255	0.487053	0.4568	0.419188	0.371993	0.310878	0.224765	7.41E-09	0	0	0
2.0	0	0	0	0	0.093733	0.234333	0.310878297	0.36604	0.408574	0.442139	0.468667	0.489302	0.504769	0.515533	0.521885	0.523985	0.521885	0.515533	0.504769	0.489302	0.468667	0.442139	0.408574	0.36604	0.310878	0.234333	0.093733	0	0	0	0
2.2	0	0	0	0	0	0.093733	0.224764637	0.296411	0.347573	0.386472	0.41656	0.439648	0.4568	0.468667	0.475645	0.477948	0.475645	0.468667	0.4568	0.439648	0.41656	0.386472	0.347573	0.296411	0.224765	0.093733	0	0	0	0	0
2.4	0	0	0	0	0	0	7.40731E-09	0.193236	0.265118	0.314391	0.350718	0.377851	0.397677	0.411253	0.419188	0.4218	0.419188	0.411253	0.397677	0.377851	0.350718	0.314391	0.265118	0.193236	7.41E-09	0	0	0	0	0	0
2.6	0	0	0	0	0	0	0	0	0.123998	0.209594	0.260943	0.296411	0.321302	0.33796	0.347573	0.350718	0.347573	0.33796	0.321302	0.296411	0.260943	0.209594	0.123998	0	0	0	0	0	0	0	0
2.8	0	0	0	0	0	0	0	0	0	0	0.093733	0.16898	0.209594	0.234333	0.247995	0.252385	0.247995	0.234333	0.209594	0.16898	0.093733	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Latitudinal

	-3	-2.8	-2.6	-2.4	-2.2	-2	-1.8	-1.6	-1.4	-1.2	-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.8	3
-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.8	0	0	0	0	0	0	0	0	0	0	0.093733	0.16898	0.209594	0.234333	0.247995	0.252385	0.247995	0.234333	0.209594	0.16898	0.093733	0	0	0	0	0	0	0	0	0	0
-2.6	0	0	0	0	0	0	0	0.132559	0.123998	0.209594	0.260943	0.296411	0.321302	0.33796	0.347573	0.350718	0.347573	0.33796	0.321302	0.296411	0.260943	0.209594	0.123998	0.132559	0	0	0	0	0	0	0
-2.4	0	0	0	0	0	0	7.41E-09	0.193236	0.265118	0.314391	0.350718	0.377851	0.397677	0.411253	0.419188	0.4218	0.419188	0.411253	0.397677	0.377851	0.350718	0.314391	0.265118	0.193236	7.41E-09	0	0	0	0	0	0
-2.2	0	0	0	0	0	0.093733	0.224765	0.296411	0.347573	0.386472	0.41656	0.439648	0.4568	0.468667	0.475645	0.477948	0.475645	0.468667	0.4568	0.439648	0.41656	0.386472	0.347573	0.296411	0.224765	0.093733	0	0	0	0	0
-2.0	0	0	0	0	0.093733	0.234333	0.310878	0.36604	0.408574	0.442139	0.468667	0.489302	0.504769	0.515533	0.521885	0.523985	0.521885	0.515533	0.504769	0.489302	0.468667	0.442139	0.408574	0.36604	0.310878	0.234333	0.093733	0	0	0	0
-1.8	0	0	0	7.41E-09	0.224765	0.310878	0.371993	0.419188	0.4568	0.487053	0.511255	0.530236	0.544541	0.554534	0.560444	0.5624	0.560444	0.554534	0.544541	0.530236	0.511255	0.487053	0.4568	0.419188	0.371993	0.310878	0.224765	7.41E-09	0	0	0
-1.6	0	0	0	0.193236	0.296411	0.36604	0.419188	0.461583	0.49599	0.523985	0.546555	0.564349	0.577811	0.587238	0.592822	0.594671	0.592822	0.587238	0.577811	0.564349	0.546555	0.523985	0.49599	0.461583	0.419188	0.36604	0.296411	0.193236	0	0	0
-1.4	0	0	0.123998	0.265118	0.347573	0.408574	0.4568	0.49599	0.528161	0.554534	0.575907	0.592822	0.605651	0.614651	0.619988	0.621757	0.619988	0.614651	0.605651	0.592822	0.575907	0.554534	0.528161	0.49599	0.4568	0.408574	0.347573	0.265118	0.123998	0	0
-1.2	0	0	0.209594	0.314391	0.386472	0.442139	0.487053	0.523985	0.554534	0.579709	0.600186	0.616435	0.628782	0.637456	0.642603	0.64431	0.642603	0.637456	0.628782	0.616435	0.600186	0.579709	0.554534	0.523985	0.487053	0.442139	0.386472	0.314391	0.209594	0	0
-1.0	0	0.093733	0.260943	0.350718	0.41656	0.468667	0.511255	0.546555	0.575907	0.600186	0.619988	0.63573	0.64771	0.656133	0.661136	0.662795	0.661136	0.656133	0.64771	0.63573	0.619988	0.600186	0.575907	0.546555	0.511255	0.468667	0.41656	0.350718	0.260943	0.093733	0
-0.8	0	0.16898	0.296411	0.377851	0.439648	0.489302	0.530236	0.564349	0.592822	0.616435	0.63573	0.651093	0.662795	0.671029	0.675921	0.677544	0.675921	0.671029	0.662795	0.651093	0.63573	0.616435	0.592822	0.564349	0.530236	0.489302	0.439648	0.377851	0.296411	0.16898	0
-0.6	0	0.209594	0.321302	0.397677	0.4568	0.504769	0.544541	0.577811	0.605651	0.628782	0.64771	0.662795	0.674294	0.682389	0.6872	0.688797	0.6872	0.682389	0.674294	0.662795	0.64771	0.628782	0.605651	0.577811	0.544541	0.504769	0.4568	0.397677	0.321302	0.209594	0
-0.4	0	0.234333	0.33796	0.411253	0.468667	0.515533	0.554534	0.587238	0.614651	0.637456	0.656133	0.671029	0.682389	0.690389	0.695145	0.696723	0.695145	0.690389	0.682389	0.671029	0.656133	0.637456	0.614651	0.587238	0.554534	0.515533	0.468667	0.411253	0.33796	0.234333	0
-0.2	0	0.247995	0.347573	0.419188	0.475645	0.521885	0.560444	0.592822	0.619988	0.642603	0.661136	0.675921	0.6872	0.695145	0.699869	0.701436	0.699869	0.695145	0.6872	0.675921	0.661136	0.642603	0.619988	0.592822	0.560444	0.521885	0.475645	0.419188	0.347573	0.247995	0
0.0	0	0.252385	0.350718	0.4218	0.477948	0.523985	0.5624	0.594671	0.621757	0.64431	0.662795	0.677544	0.688797	0.696723	0.701436	0.703	0.701436	0.696723	0.688797	0.677544	0.662795	0.64431	0.621757	0.594671	0.5624	0.523985	0.477948	0.4218	0.350718	0.252385	0
0.2	0	0.247995	0.347573	0.419188	0.475645	0.521885	0.560444	0.592822	0.619988	0.642603	0.661136	0.675921	0.6872	0.695145	0.699869	0.701436	0.699869	0.695145	0.6872	0.675921	0.661136	0.642603	0.619988	0.592822	0.560444	0.521885	0.475645	0.419188	0.347573	0.247995	0
0.4	0	0.234333	0.33796	0.411253	0.468667	0.515533	0.554534	0.587238	0.614651	0.637456	0.656133	0.671029	0.682389	0.690389	0.695145	0.696723	0.695145	0.690389	0.682389	0.671029	0.656133	0.637456	0.614651	0.587238	0.554534	0.515533	0.468667	0.411253	0.33796	0.234333	0
0.6	0	0.209594	0.321302	0.397677	0.4568	0.504769	0.544541	0.577811	0.605651	0.628782	0.64771	0.662795	0.674294	0.682389	0.6872	0.688797	0.6872	0.682389	0.674294	0.662795	0.64771	0.628782	0.605651	0.577811	0.544541	0.504769	0.4568	0.397677	0.321302	0.209594	0
0.8	0	0.16898	0.296411	0.377851	0.439648	0.489302	0.530236	0.564349	0.592822	0.616435	0.63573	0.651093	0.662795	0.671029	0.675921	0.677544	0.675921	0.671029	0.662795	0.651093	0.63573	0.616435	0.592822	0.564349	0.530236	0.489302	0.439648	0.377851	0.296411	0.16898	0
1.0	0	0.093733	0.260943	0.350718	0.41656	0.468667	0.511255	0.546555	0.575907	0.600186	0.619988	0.63573	0.64771	0.656133	0.661136	0.662795	0.661136	0.656133	0.64771	0.63573	0.619988	0.600186	0.575907	0.546555	0.511255	0.468667	0.41656	0.350718	0.260943	0.093733	0
1.2	0	0	0.209594	0.314391	0.386472	0.442139	0.487053	0.523985	0.554534	0.579709	0.600186	0.616435	0.628782	0.637456	0.642603	0.64431	0.642603	0.637456	0.628782	0.616435	0.600186	0.579709	0.554534	0.523985	0.487053	0.442139	0.386472	0.314391	0.209594	0	0
1.4	0	0	0.123998	0.265118	0.347573	0.408574	0.4568	0.49599	0.528161	0.554534	0.575907	0.592822	0.605651	0.614651	0.619988	0.621757	0.619988	0.614651	0.605651	0.592822	0.575907	0.554534	0.528161	0.49599	0.4568	0.408574	0.347573	0.265118	0.123998	0	0
1.6	0	0	0	0.193236	0.296411	0.36604	0.419188	0.461583	0.49599	0.523985	0.546555	0.564349	0.577811	0.587238	0.592822	0.594671	0.592822	0.587238	0.577811	0.564349	0.546555	0.523985	0.49599	0.461583	0.419188	0.36604	0.296411	0.193236	0	0	0
1.8	0	0	0	7.41E-09	0.224765	0.310878	0.371993	0.419188	0.4568	0.487053	0.511255	0.530236	0.544541	0.554534	0.560444	0.5624	0.560444	0.554534	0.544541	0.530236	0.511255	0.487053	0.4568	0.419188	0.371993	0.310878	0.224765	7.41E-09	0	0	0
2.0	0	0	0	0	0.093733	0.234333	0.310878	0.36604	0.408574	0.442139	0.468667	0.489302	0.504769	0.515533	0.521885	0.523985	0.521885	0.515533	0.504769	0.489302	0.468667	0.442139	0.408574	0.36604	0.310878	0.234333	0.093733	0	0	0	0
2.2	0	0	0	0	0	0.093733	0.224765	0.296411	0.347573	0.386472	0.41656	0.439648	0.4568	0.468667	0.475645	0.477948	0.475645	0.468667	0.4568	0.439648	0.41656	0.386472	0.347573	0.296411	0.224765	0.093733	0	0	0	0	0
2.4	0	0	0	0	0	0	7.41E-09	0.193236	0.265118	0.314391	0.350718	0.377851	0.397677	0.411253	0.419188	0.4218	0.419188	0.411253	0.397677	0.377851	0.350718	0.314391	0.265118	0.193236	7.41E-09	0	0	0	0	0	0
2.6	0	0	0	0	0	0	0	0.132559	0.123998	0.209594	0.260943	0.296411	0.321302	0.33796	0.347573	0.350718	0.347573	0.33796	0.321302	0.296411	0.260943	0.209594	0.123998	0.132559	0	0	0	0	0	0	0
2.8	0	0	0	0	0	0	0	0	0	0	0.093733	0.16898	0.209594	0.234333	0.247995	0.252385	0.247995	0.234333	0.209594	0.16898	0.093733	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX VIII

Longitudinal

	-3.0	-2.8	-2.6	-2.4	-2.2	-2.0	-1.8	-1.6	-1.4	-1.2	-1.0	-0.8	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.8	0	0	0	0	0	0	0	0	0	0	0.0736	0.132684	0.164575	0.184	0.194727	0.198174	0.194727	0.184	0.164575	0.132684	0.0736	0	0	0	0	0	0	0	0	0	0
-2.6	0	0	0	0	0	0	0	0	0.097364	0.164575	0.204894	0.232744	0.252288	0.265369	0.272916	0.275386	0.272916	0.265369	0.252288	0.232744	0.204894	0.164575	0.097364	0	0	0	0	0	0	0	0
-2.4	0	0	0	0	0	0	5.82E-09	0.15173	0.208172	0.246862	0.275386	0.296691	0.312258	0.322919	0.329149	0.3312	0.329149	0.322919	0.312258	0.296691	0.275386	0.246862	0.208172	0.15173	5.82E-09	0	0	0	0	0	0
-2.2	0	0	0	0	0	0.0736	0.176487	0.232744	0.272916	0.303461	0.327086	0.345215	0.358682	0.368	0.373479	0.375288	0.373479	0.368	0.358682	0.345215	0.327086	0.303461	0.272916	0.232744	0.176487	0.0736	0	0	0	0	0
-2.0	0	0	0	0	0.0736	0.184	0.244104	0.287417	0.320815	0.347171	0.368	0.384203	0.396348	0.4048	0.409787	0.411437	0.409787	0.4048	0.396348	0.384203	0.368	0.347171	0.320815	0.287417	0.244104	0.184	0.0736	0	0	0	0
-1.8	0	0	0	5.82E-09	0.176487	0.244104	0.292091	0.329149	0.358682	0.382437	0.401441	0.416344	0.427577	0.435423	0.440064	0.4416	0.440064	0.435423	0.427577	0.416344	0.401441	0.382437	0.358682	0.329149	0.292091	0.244104	0.176487	5.82E-09	0	0	0
-1.6	0	0	0	0.15173	0.232744	0.287417	0.329149	0.362438	0.389455	0.411437	0.429158	0.443131	0.453701	0.461103	0.465487	0.46694	0.465487	0.461103	0.453701	0.443131	0.429158	0.411437	0.389455	0.362438	0.329149	0.287417	0.232744	0.15173	0	0	0
-1.4	0	0	0.097364	0.208172	0.272916	0.320815	0.358682	0.389455	0.414715	0.435423	0.452206	0.465487	0.475561	0.482627	0.486818	0.488207	0.486818	0.482627	0.475561	0.465487	0.452206	0.435423	0.414715	0.389455	0.358682	0.320815	0.272916	0.208172	0.097364	0	0
-1.2	0	0	0.164575	0.246862	0.303461	0.347171	0.382437	0.411437	0.435423	0.455191	0.47127	0.484028	0.493724	0.500534	0.504576	0.509916	0.504576	0.500534	0.493724	0.484028	0.47127	0.455191	0.435423	0.411437	0.382437	0.347171	0.303461	0.246862	0.164575	0	0
-1.0	0	0.0736	0.204894	0.275386	0.327086	0.368	0.401441	0.429158	0.452206	0.47127	0.486818	0.499179	0.508586	0.5152	0.519128	0.520431	0.519128	0.5152	0.508586	0.499179	0.486818	0.47127	0.452206	0.429158	0.401441	0.368	0.327086	0.275386	0.204894	0.0736	0
-0.8	0	0.132684	0.232744	0.296691	0.345215	0.384203	0.416344	0.443131	0.465487	0.484028	0.499179	0.511242	0.520431	0.526896	0.530737	0.532011	0.530737	0.526896	0.520431	0.511242	0.499179	0.484028	0.465487	0.443131	0.416344	0.384203	0.345215	0.296691	0.232744	0.132684	0
-0.6	0	0.164575	0.252288	0.312258	0.358682	0.396348	0.427577	0.453701	0.475561	0.493724	0.508586	0.520431	0.52946	0.535816	0.539594	0.540847	0.539594	0.535816	0.52946	0.520431	0.508586	0.493724	0.475561	0.453701	0.427577	0.396348	0.358682	0.312258	0.252288	0.164575	0
-0.4	0	0.184	0.265369	0.322919	0.368	0.4048	0.435423	0.461103	0.482627	0.500534	0.5152	0.526896	0.535816	0.542098	0.545832	0.547071	0.545832	0.542098	0.535816	0.526896	0.5152	0.500534	0.482627	0.461103	0.435423	0.4048	0.368	0.322919	0.265369	0.184	0
-0.2	0	0.194727	0.272916	0.329149	0.373479	0.409787	0.440064	0.465487	0.486818	0.504576	0.519128	0.530737	0.539594	0.545832	0.549541	0.550772	0.549541	0.545832	0.539594	0.530737	0.519128	0.504576	0.486818	0.465487	0.440064	0.409787	0.373479	0.329149	0.272916	0.194727	0
0.0	0	0.198174	0.275386	0.3312	0.375288	0.411437	0.4416	0.46694	0.488207	0.509916	0.520431	0.532011	0.540847	0.547071	0.550772	0.552	0.550772	0.547071	0.540847	0.532011	0.520431	0.509916	0.488207	0.46694	0.4416	0.411437	0.375288	0.3312	0.275386	0.198174	0
0.2	0	0.194727	0.272916	0.329149	0.373479	0.409787	0.440064	0.465487	0.486818	0.504576	0.519128	0.530737	0.539594	0.545832	0.549541	0.550772	0.549541	0.545832	0.539594	0.530737	0.519128	0.504576	0.486818	0.465487	0.440064	0.409787	0.373479	0.329149	0.272916	0.194727	0
0.4	0	0.184	0.265369	0.322919	0.368	0.4048	0.435423	0.461103	0.482627	0.500534	0.5152	0.526896	0.535816	0.542098	0.545832	0.547071	0.545832	0.542098	0.535816	0.526896	0.5152	0.500534	0.482627	0.461103	0.435423	0.4048	0.368	0.322919	0.265369	0.184	0
0.6	0	0.164575	0.252288	0.312258	0.358682	0.396348	0.427577	0.453701	0.475561	0.493724	0.508586	0.520431	0.52946	0.535816	0.539594	0.540847	0.539594	0.535816	0.52946	0.520431	0.508586	0.493724	0.475561	0.453701	0.427577	0.396348	0.358682	0.312258	0.252288	0.164575	0
0.8	0	0.132684	0.232744	0.296691	0.345215	0.384203	0.416344	0.443131	0.465487	0.484028	0.499179	0.511242	0.520431	0.526896	0.530737	0.532011	0.530737	0.526896	0.520431	0.511242	0.499179	0.484028	0.465487	0.443131	0.416344	0.384203	0.345215	0.296691	0.232744	0.132684	0
1.0	0	0.0736	0.204894	0.275386	0.327086	0.368	0.401441	0.429158	0.452206	0.47127	0.486818	0.499179	0.508586	0.5152	0.519128	0.520431	0.519128	0.5152	0.508586	0.499179	0.486818	0.47127	0.452206	0.429158	0.401441	0.368	0.327086	0.275386	0.204894	0.0736	0
1.2	0	0	0.164575	0.246862	0.303461	0.347171	0.382437	0.411437	0.435423	0.455191	0.47127	0.484028	0.493724	0.500534	0.504576	0.509916	0.504576	0.500534	0.493724	0.484028	0.47127	0.455191	0.435423	0.411437	0.382437	0.347171	0.303461	0.246862	0.164575	0	0
1.4	0	0	0.097364	0.208172	0.272916	0.320815	0.358682	0.389455	0.414715	0.435423	0.452206	0.465487	0.475561	0.482627	0.486818	0.488207	0.486818	0.482627	0.475561	0.465487	0.452206	0.435423	0.414715	0.389455	0.358682	0.320815	0.272916	0.208172	0.097364	0	0
1.6	0	0	0	0.15173	0.232744	0.287417	0.329149	0.362438	0.389455	0.411437	0.429158	0.443131	0.453701	0.461103	0.465487	0.46694	0.465487	0.461103	0.453701	0.443131	0.429158	0.411437	0.389455	0.362438	0.329149	0.287417	0.232744	0.15173	0	0	0
1.8	0	0	0	5.82E-09	0.176487	0.244104	0.292091	0.329149	0.358682	0.382437	0.401441	0.416344	0.427577	0.435423	0.440064	0.4416	0.440064	0.435423	0.427577	0.416344	0.401441	0.382437	0.358682	0.329149	0.292091	0.244104	0.176487	5.82E-09	0	0	0
2.0	0	0	0	0	0.0736	0.184	0.244104	0.287417	0.320815	0.347171	0.368	0.384203	0.396348	0.4048	0.409787	0.411437	0.409787	0.4048	0.396348	0.384203	0.368	0.347171	0.320815	0.287417	0.244104	0.184	0.0736	0	0	0	0
2.2	0	0	0	0	0	0.0736	0.176487	0.232744	0.272916	0.303461	0.327086	0.345215	0.358682	0.368	0.373479	0.375288	0.373479	0.368	0.358682	0.345215	0.327086	0.303461	0.272916	0.232744	0.176487	0.0736	0	0	0	0	0
2.4	0	0	0	0	0	0	5.82E-09	0.15173	0.208172	0.246862	0.275386	0.296691	0.312258	0.322919	0.329149	0.3312	0.329149	0.322919	0.312258	0.296691	0.275386	0.246862	0.208172	0.15173	5.82E-09	0	0	0	0	0	0
2.6	0	0	0	0	0	0	0	0	0.097364	0.164575	0.204894	0.232744	0.252288	0.265369	0.272916	0.275386	0.272916	0.265369	0.252288	0.232744	0.204894	0.164575	0.097364	0	0	0	0	0	0	0	0
2.8	0	0	0	0	0	0	0	0	0	0	0.0736	0.132684	0.164575	0.184	0.194727	0.198174	0.194727	0.184	0.164575	0.132684	0.0736	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Latitudinal

	-3.0	-2.8	-2.6	-2.4	-2.2	-2.0	-1.8	-1.6	-1.4	-1.2	-1.0	-0.8	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0
-3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-2.8	0	0	0	0	0	0	0	0	0	0	0.0736	0.132684	0.164575	0.184	0.194727	0.198174	0.194727	0.184	0.164575	0.132684	0.0736	0	0	0	0	0	0	0	0	0	0
-2.6	0	0	0	0	0	0	0	0	0.097364	0.164575	0.204894	0.232744	0.252288	0.265369	0.272916	0.275386	0.272916	0.265369	0.252288	0.232744	0.204894	0.164575	0.097364	0	0	0	0	0	0	0	0
-2.4	0	0	0	0	0	0	5.82E-09	0.15173	0.208172	0.246862	0.275386	0.296691	0.312258	0.322919	0.329149	0.3312	0.329149	0.322919	0.312258	0.296691	0.275386	0.246862	0.208172	0.15173	5.82E-09	0	0	0	0	0	0
-2.2	0	0	0	0	0	0.0736	0.176487	0.232744	0.272916	0.303461	0.327086	0.345215	0.358682	0.368	0.373479	0.375288	0.373479	0.368	0.358682	0.345215	0.327086	0.303461	0.272916	0.232744	0.176487	0.0736	0	0	0	0	0
-2.0	0	0	0	0	0.0736	0.184	0.244104	0.287417	0.320815	0.347171	0.368	0.384203	0.396348	0.4048	0.409787	0.411437	0.409787	0.4048	0.396348	0.384203	0.368	0.347171	0.320815	0.287417	0.244104	0.184	0.0736	0	0	0	0
-1.8	0	0	0	5.82E-09	0.176487	0.244104	0.292091	0.329149	0.358682	0.382437	0.401441	0.416344	0.427577	0.435423	0.440064	0.4416	0.440064	0.435423	0.427577	0.416344	0.401441	0.382437	0.358682	0.329149	0.292091	0.244104	0.176487	5.82E-09	0	0	0
-1.6	0	0	0	0.15173	0.232744	0.287417	0.329149	0.362438	0.389455	0.411437	0.429158	0.443131	0.453701	0.461103	0.465487	0.46694	0.465487	0.461103	0.453701	0.443131	0.429158	0.411437	0.389455	0.362438	0.329149	0.287417	0.232744	0.15173	0	0	0
-1.4	0	0	0.097364	0.208172	0.272916	0.320815	0.358682	0.389455	0.414715	0.435423	0.452206	0.465487	0.475561	0.482627	0.486818	0.488207	0.486818	0.482627	0.475561	0.465487	0.452206	0.435423	0.414715	0.389455	0.358682	0.320815	0.272916	0.208172	0.097364	0	0
-1.2	0	0	0.164575	0.246862	0.303461	0.347171	0.382437	0.411437	0.435423	0.455191	0.47127	0.484028	0.493724	0.500534	0.504576	0.505916	0.504576	0.500534	0.493724	0.484028	0.47127	0.455191	0.435423	0.411437	0.382437	0.347171	0.303461	0.246862	0.164575	0	0
-1.0	0	0.0736	0.204894	0.275386	0.327086	0.368	0.401441	0.429158	0.452206	0.47127	0.486818	0.499179	0.508586	0.5152	0.519128	0.520431	0.519128	0.5152	0.508586	0.499179	0.486818	0.47127	0.452206	0.429158	0.401441	0.368	0.327086	0.275386	0.204894	0.0736	0
-0.8	0	0.132684	0.232744	0.296691	0.345215	0.384203	0.416344	0.443131	0.465487	0.484028	0.499179	0.511242	0.520431	0.526896	0.530737	0.532011	0.530737	0.526896	0.520431	0.511242	0.499179	0.484028	0.465487	0.443131	0.416344	0.384203	0.345215	0.296691	0.232744	0.132684	0
-0.6	0	0.164575	0.252288	0.312258	0.358682	0.396348	0.427577	0.453701	0.475561	0.493724	0.508586	0.520431	0.52946	0.535816	0.539594	0.540847	0.539594	0.535816	0.52946	0.520431	0.508586	0.493724	0.475561	0.453701	0.427577	0.396348	0.358682	0.312258	0.252288	0.164575	0
-0.4	0	0.184	0.265369	0.322919	0.368	0.4048	0.435423	0.461103	0.482627	0.500534	0.5152	0.526896	0.535816	0.542098	0.545832	0.547071	0.545832	0.542098	0.535816	0.526896	0.5152	0.500534	0.482627	0.461103	0.435423	0.4048	0.368	0.322919	0.265369	0.184	0
-0.2	0	0.194727	0.272916	0.329149	0.373479	0.409787	0.440064	0.465487	0.486818	0.504576	0.519128	0.530737	0.539594	0.545832	0.549541	0.550771	0.549541	0.545832	0.539594	0.530737	0.519128	0.504576	0.486818	0.465487	0.440064	0.409787	0.373479	0.329149	0.272916	0.194727	0
0.0	0	0.198174	0.275386	0.3312	0.375288	0.411437	0.4416	0.46694	0.488207	0.505916	0.520431	0.532011	0.540847	0.547071	0.550772	0.552	0.550772	0.547071	0.540847	0.532011	0.520431	0.505916	0.488207	0.46694	0.4416	0.411437	0.375288	0.3312	0.275386	0.198174	0
0.2	0	0.194727	0.272916	0.329149	0.373479	0.409787	0.440064	0.465487	0.486818	0.504576	0.519128	0.530737	0.539594	0.545832	0.549541	0.550772	0.549541	0.545832	0.539594	0.530737	0.519128	0.504576	0.486818	0.465487	0.440064	0.409787	0.373479	0.329149	0.272916	0.194727	0
0.4	0	0.184	0.265369	0.322919	0.368	0.4048	0.435423	0.461103	0.482627	0.500534	0.5152	0.526896	0.535816	0.542098	0.545832	0.547071	0.545832	0.542098	0.535816	0.526896	0.5152	0.500534	0.482627	0.461103	0.435423	0.4048	0.368	0.322919	0.265369	0.184	0
0.6	0	0.164575	0.252288	0.312258	0.358682	0.396348	0.427577	0.453701	0.475561	0.493724	0.508586	0.520431	0.52946	0.535816	0.539594	0.540847	0.539594	0.535816	0.52946	0.520431	0.508586	0.493724	0.475561	0.453701	0.427577	0.396348	0.358682	0.312258	0.252288	0.164575	0
0.8	0	0.132684	0.232744	0.296691	0.345215	0.384203	0.416344	0.443131	0.465487	0.484028	0.499179	0.511242	0.520431	0.526896	0.530737	0.532011	0.530737	0.526896	0.520431	0.511242	0.499179	0.484028	0.465487	0.443131	0.416344	0.384203	0.345215	0.296691	0.232744	0.132684	0
1.0	0	0.0736	0.204894	0.275386	0.327086	0.368	0.401441	0.429158	0.452206	0.47127	0.486818	0.499179	0.508586	0.5152	0.519128	0.520431	0.519128	0.5152	0.508586	0.499179	0.486818	0.47127	0.452206	0.429158	0.401441	0.368	0.327086	0.275386	0.204894	0.0736	0
1.2	0	0	0.164575	0.246862	0.303461	0.347171	0.382437	0.411437	0.435423	0.455191	0.47127	0.484028	0.493724	0.500534	0.504576	0.505916	0.504576	0.500534	0.493724	0.484028	0.47127	0.455191	0.435423	0.411437	0.382437	0.347171	0.303461	0.246862	0.164575	0	0
1.4	0	0	0.097364	0.208172	0.272916	0.320815	0.358682	0.389455	0.414715	0.435423	0.452206	0.465487	0.475561	0.482627	0.486818	0.488207	0.486818	0.482627	0.475561	0.465487	0.452206	0.435423	0.414715	0.389455	0.358682	0.320815	0.272916	0.208172	0.097364	0	0
1.6	0	0	0	0.15173	0.232744	0.287417	0.329149	0.362438	0.389455	0.411437	0.429158	0.443131	0.453701	0.461103	0.465487	0.46694	0.465487	0.461103	0.453701	0.443131	0.429158	0.411437	0.389455	0.362438	0.329149	0.287417	0.232744	0.15173	0	0	0
1.8	0	0	0	5.82E-09	0.176487	0.244104	0.292091	0.329149	0.358682	0.382437	0.401441	0.416344	0.427577	0.435423	0.440064	0.4416	0.440064	0.435423	0.427577	0.416344	0.401441	0.382437	0.358682	0.329149	0.292091	0.244104	0.176487	5.82E-09	0	0	0
2.0	0	0	0	0	0.0736	0.184	0.244104	0.287417	0.320815	0.347171	0.368	0.384203	0.396348	0.4048	0.409787	0.411437	0.409787	0.4048	0.396348	0.384203	0.368	0.347171	0.320815	0.287417	0.244104	0.184	0.0736	0	0	0	0
2.2	0	0	0	0	0	0.0736	0.176487	0.232744	0.272916	0.303461	0.327086	0.345215	0.358682	0.368	0.373479	0.375288	0.373479	0.368	0.358682	0.345215	0.327086	0.303461	0.272916	0.232744	0.176487	0.0736	0	0	0	0	0
2.4	0	0	0	0	0	0	5.82E-09	0.15173	0.208172	0.246862	0.275386	0.296691	0.312258	0.322919	0.329149	0.3312	0.329149	0.322919	0.312258	0.296691	0.275386	0.246862	0.208172	0.15173	5.82E-09	0	0	0	0	0	0
2.6	0	0	0	0	0	0	0	0	0.097364	0.164575	0.204894	0.232744	0.252288	0.265369	0.272916	0.275386	0.272916	0.265369	0.252288	0.232744	0.204894	0.164575	0.097364	0	0	0	0	0	0	0	0
2.8	0	0	0	0	0	0	0	0	0	0	0.0736	0.132684	0.164575	0.184	0.194727	0.198174	0.194727	0.184	0.164575	0.132684	0.0736	0	0	0	0	0	0	0	0	0	0
3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX IX

	Cylindrical Specimen					Squared Specimen				
Distance/Load	13.24N (1350g)	10.79N(1100g)	8.34N(850g)	5.89N(600g)	3.43N(350g)	13.24N (1350g)	10.79N(1100g)	8.34N(850g)	5.89N(600g)	3.43N(350g)
-3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-2.8	0.2524	0.2054	0.1587	0.1120	0.0653	0.1982	0.1616	0.1248	0.0881	0.0513
-2.6	0.3507	0.2854	0.2205	0.1557	0.0908	0.2754	0.2245	0.1734	0.1224	0.0713
-2.4	0.4218	0.3432	0.2652	0.1872	0.1092	0.3312	0.2700	0.2085	0.1472	0.0857
-2.2	0.4779	0.3889	0.3005	0.2121	0.1237	0.3753	0.3059	0.2363	0.1668	0.0972
-2	0.5240	0.4263	0.3294	0.2326	0.1357	0.4114	0.3354	0.2590	0.1829	0.1065
-1.8	0.5624	0.4576	0.3536	0.2496	0.1456	0.4416	0.3600	0.2780	0.1963	0.1143
-1.6	0.5947	0.4839	0.3739	0.2639	0.1540	0.4669	0.3807	0.2940	0.2076	0.1209
-1.4	0.6218	0.5059	0.3909	0.2759	0.1610	0.4882	0.3980	0.3073	0.2170	0.1264
-1.2	0.6443	0.5242	0.4051	0.2860	0.1668	0.5059	0.4124	0.3185	0.2249	0.1310
-1	0.6628	0.5393	0.4167	0.2942	0.1716	0.5204	0.4243	0.3276	0.2314	0.1347
-0.8	0.6775	0.5513	0.4260	0.3007	0.1754	0.5320	0.4337	0.3349	0.2365	0.1377
-0.6	0.6888	0.5604	0.4331	0.3057	0.1783	0.5408	0.4409	0.3405	0.2404	0.1400
-0.4	0.6967	0.5669	0.4381	0.3092	0.1804	0.5471	0.4460	0.3444	0.2432	0.1416
-0.2	0.7014	0.5707	0.4410	0.3113	0.1816	0.5508	0.4490	0.3467	0.2449	0.1426
0	0.7030	0.5720	0.4420	0.3120	0.1820	0.5520	0.4500	0.3475	0.2454	0.1429
0.2	0.7014	0.5707	0.4410	0.3113	0.1816	0.5508	0.4490	0.3467	0.2449	0.1426
0.4	0.6967	0.5669	0.4381	0.3092	0.1804	0.5471	0.4460	0.3444	0.2432	0.1416
0.6	0.6888	0.5604	0.4331	0.3057	0.1783	0.5408	0.4409	0.3405	0.2404	0.1400
0.8	0.6775	0.5513	0.4260	0.3007	0.1754	0.5320	0.4337	0.3349	0.2365	0.1377
1	0.6628	0.5393	0.4167	0.2942	0.1716	0.5204	0.4243	0.3276	0.2314	0.1347
1.2	0.6443	0.5242	0.4051	0.2860	0.1668	0.5059	0.4124	0.3185	0.2249	0.1310
1.4	0.6218	0.5059	0.3909	0.2759	0.1610	0.4882	0.3980	0.3073	0.2170	0.1264
1.6	0.5947	0.4839	0.3739	0.2639	0.1540	0.4669	0.3807	0.2940	0.2076	0.1209
1.8	0.5624	0.4576	0.3536	0.2496	0.1456	0.4416	0.3600	0.2780	0.1963	0.1143
2	0.5240	0.4263	0.3294	0.2326	0.1357	0.4114	0.3354	0.2590	0.1829	0.1065
2.2	0.4779	0.3889	0.3005	0.2121	0.1237	0.3753	0.3059	0.2363	0.1668	0.0972
2.4	0.4218	0.3432	0.2652	0.1872	0.1092	0.3312	0.2700	0.2085	0.1472	0.0857
2.6	0.3507	0.2854	0.2205	0.1557	0.0908	0.2754	0.2245	0.1734	0.1224	0.0713
2.8	0.2524	0.2054	0.1587	0.1120	0.0653	0.1982	0.1616	0.1248	0.0881	0.0513
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

APPENDIX X

Specimen D

Specimen D(exp)					
Distance (m)	0.1016				
Load (N)	3.4335	5.886	8.3385	10.791	13.2435
Wear coefficient (k)(m^2/N)	5.31E-09	5.57E-09	6.12E-09	7.09E-09	7.71E-09
Wear depth (m)	9.82E-05	0.000177	0.000275	0.000413	0.00055

Prediction					
Contact Pressure (Pa)	1.82E+05	3.12E+05	4.42E+05	5.72E+05	7.03E+05
Wear coefficient (k)(m^2/N)	6.36E-09	6.36E-09	6.36E-09	6.36E-09	6.36E-09
Wear depth (m)	1.18E-04	2.02E-04	2.86E-04	3.70E-04	4.54E-04

Specimen F

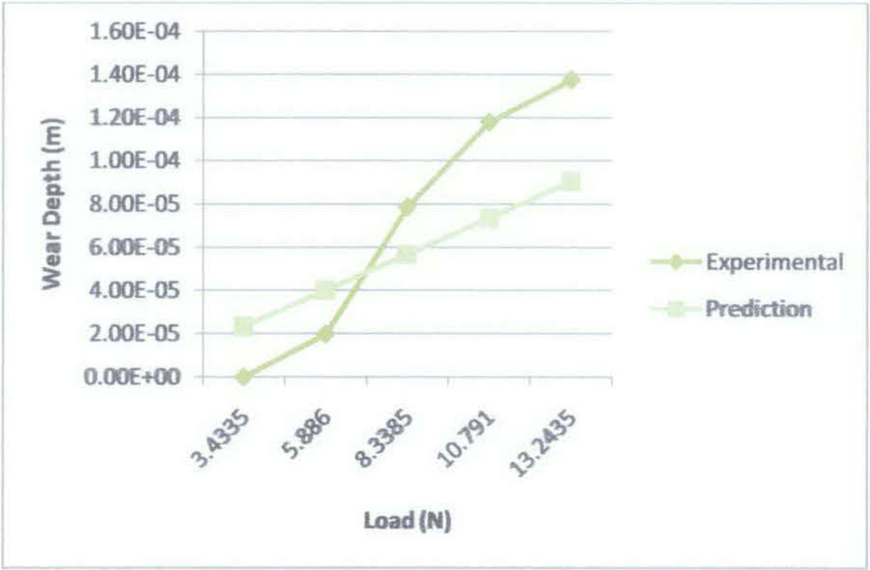
Specimen F(exp)					
Load (N)	3.4335	5.886	8.3385	10.791	13.2435
Wear coefficient (k)(m^2/N)	7.43E-09	6.81E-09	7.43E-09	8.11E-09	8.26E-09
Wear depth (m)	0.000108	0.00017	0.000262	0.00037	0.000463

Prediction					
Contact Pressure (Pa)	1.43E+05	2.45E+05	3.48E+05	4.50E+05	5.52E+05
Wear coefficient (k)(m^2/N)	7.61E-09	7.61E-09	7.61E-09	7.61E-09	7.61E-09
Wear depth (m)	1.10E-04	1.90E-04	2.69E-04	3.48E-04	4.27E-04

Specimen A

Specimen A (exp)					
Load (N)	3.4335	5.886	8.3385	10.791	13.2435
Wear coefficient (k)(m^2/N)	0	6.19E-10	1.75E-09	2.03E-09	1.93E-09
Wear depth (m)	0	1.96E-05	7.86E-05	0.000118	0.000138

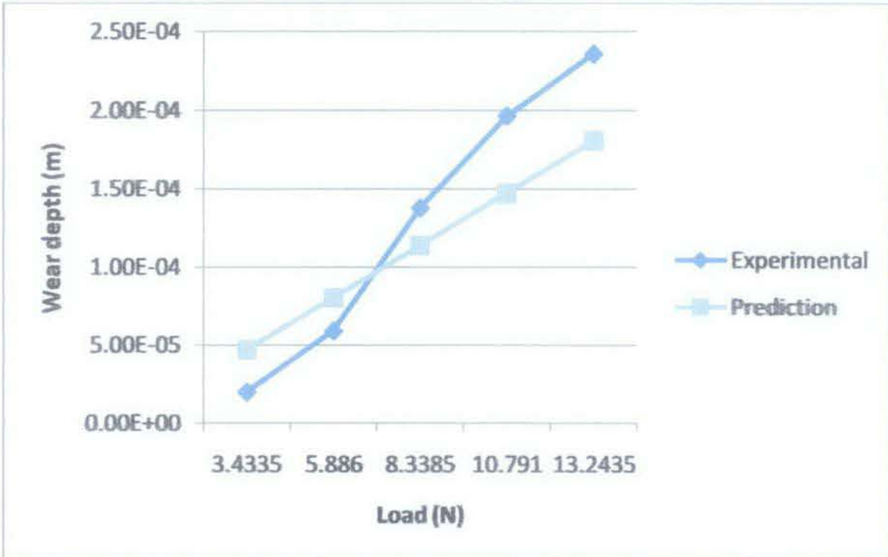
Prediction					
Contact Pressure (Pa)	1.82E+05	3.12E+05	4.42E+05	5.72E+05	7.03E+05
Wear coefficient (k)(m^2/N)	1.26E-09	1.26E-09	1.26E-09	1.26E-09	1.26E-09
Wear depth (m)	2.34E-05	4.01E-05	5.68E-05	7.35E-05	9.03E-05



Specimen B

Specimen B (exp)					
Load (N)	3.4335	5.886	8.3385	10.791	13.2435
Wear coefficient (k)(m^2/N)	1.06E-09	1.86E-09	3.06E-09	3.38E-09	3.3E-09
Wear depth (m)	1.96E-05	5.89E-05	0.000138	0.000196	0.000236

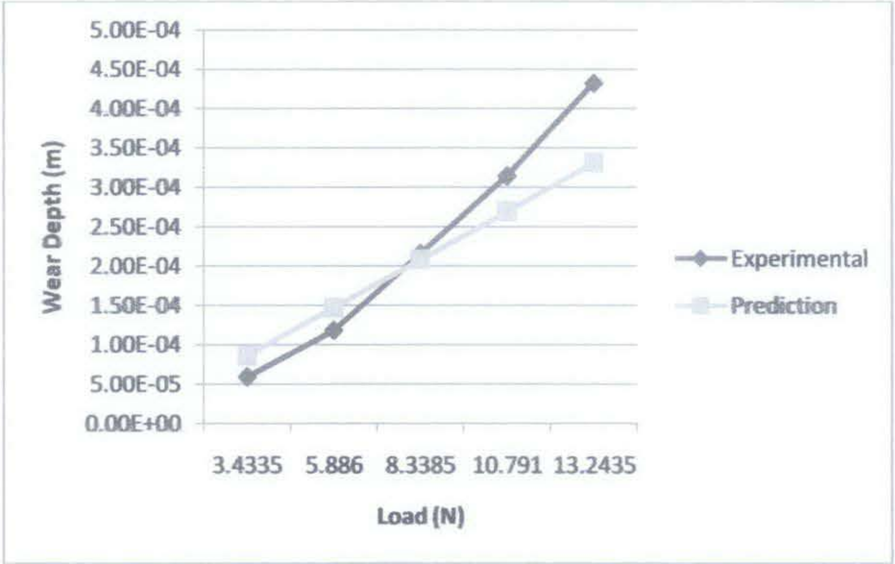
Prediction					
Contact Pressure (Pa)	1.82E+05	3.12E+05	4.42E+05	5.72E+05	7.03E+05
Wear coefficient (k)(m^2/N)	2.53E-09	2.53E-09	2.53E-09	2.53E-09	2.53E-09
Wear depth (m)	4.68E-05	8.03E-05	1.14E-04	1.47E-04	1.81E-04



Specimen C

Specimen C (exp)					
Load (N)	3.4335	5.886	8.3385	10.791	13.2435
Wear coefficient (k)(m^2/N)	3.19E-09	3.72E-09	4.81E-09	5.41E-09	6.06E-09
Wear depth (m)	5.89E-05	0.000118	0.000216	0.000314	0.000432

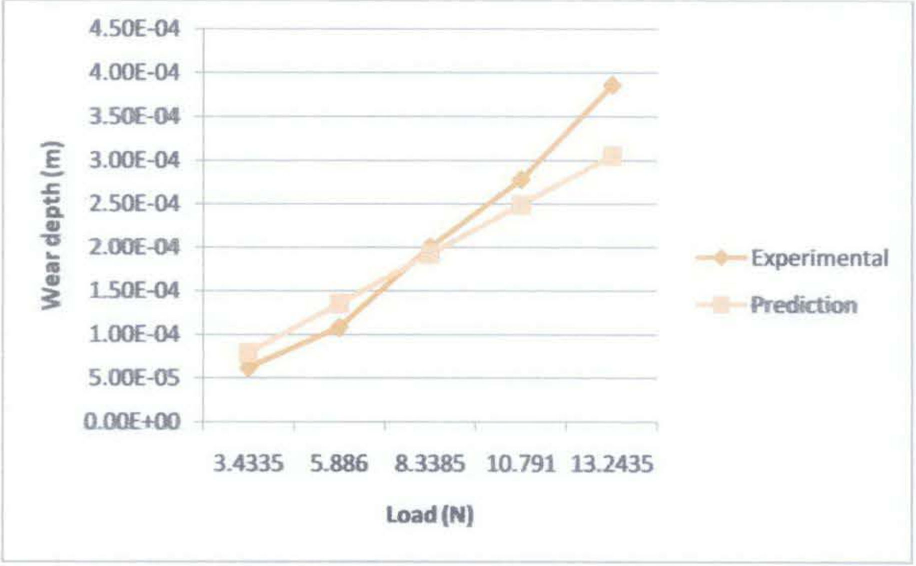
Prediction					
Contact Pressure (Pa)	1.82E+05	3.12E+05	4.42E+05	5.72E+05	7.03E+05
Wear coefficient (k)(m^2/N)	4.63E-09	4.63E-09	4.63E-09	4.63E-09	4.63E-09
Wear depth (m)	8.57E-05	1.47E-04	2.08E-04	2.69E-04	3.31E-04



Specimen E

Specimen E (exp)					
Load (N)	3.4335	5.886	8.3385	10.791	13.2435
Wear coefficient (k)(m^2/N)	4.25E-09	4.34E-09	5.68E-09	6.08E-09	6.88E-09
Wear depth (m)	6.17E-05	0.000108	0.000201	0.000278	0.000386

Prediction					
Contact Pressure (Pa)	143062.5	245250	347437.5	449625	551812.5
Wear coefficient (k)(m^2/N)	5.45E-09	5.45E-09	5.45E-09	5.45E-09	5.45E-09
Wear depth (m)	7.92E-05	1.36E-04	1.92E-04	2.49E-04	3.05E-04



APPENDIX XI

AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428
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Standard Test Method for Vickers Hardness of Metallic Materials[1]

This standard is issued under the fixed designation E 92; 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.

This standard has been approved for use by agencies of the Department of Defense. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

$^{\epsilon 1}$ NOTE—Section 27 was added editorially in October 1997.

1. Scope

1.1 This test method covers the determination of the Vickers hardness of metallic materials, using applied loads of 1 kgf to 120 kgf,[2] the verification of Vickers hardness testing machines (Part B), and the calibration of standardized hardness test blocks (Part C). Two general classes of standard tests are recognized:

1.1.1 *Verification, Laboratory, or Referee Tests*, where a high degree of accuracy is required.

1.1.2 *Routine Tests*, where a somewhat lower degree of accuracy is permissible.

1.2 *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:*

E 4 Practices for Force Verification of Testing Machines[3]

E 140 Hardness Conversion Tables for Metals (Relationship Between Brinell Hardness, Vickers Hardness, Rockwell Hardness, Rockwell Superficial Hardness, Knoop Hardness, and Scleroscope Hardness)[3]

E 384 Test Method for Microhardness of Materials[3]

3. Terminology

3.1 *Vickers hardness number, HV*—a number related to the applied load and the surface area of the permanent impression made by a square-based pyramidal diamond indenter having included face angles of 136° (see Fig. 1 and Table 1), computed from the equation:

$$HV = 2P \sin(\alpha/2)/d^2 = 1.8544P/d^2$$

where:

P = load, kgf,
d = mean diagonal of impression, mm, and
α = face angle of diamond = 136°.

3.2 *Vickers hardness test*—an indentation hardness test using calibrated machines to force a square-based pyramidal diamond indenter having specified face angles, under a predetermined load, into the surface of the material under test and to measure the diagonals of the resulting impression after removal of the load.

3.2.1 Vickers hardness tests are made at test loads of 1 kgf to 120 kgf.

3.2.2 For practical purposes the Vickers hardness number is constant when a square-based diamond pyramid with a face angle of 136° is used with applied loads of 5 kgf and higher. At lower test loads the Vickers hardness may be load-dependent. In Table 2 are given the Vickers hardness numbers for a test load of 1 kgf. For obtaining hardness numbers when other test loads are used, the Vickers hardness number obtained from Table 2 is multiplied by the test load in kilograms-force (Table 3).

NOTE 1—The Vickers hardness number is followed by the symbol HV with a suffix number denoting the load and second suffix number indicating the duration of loading when the latter differs from 10 to 15 s, which is the normal loading time.

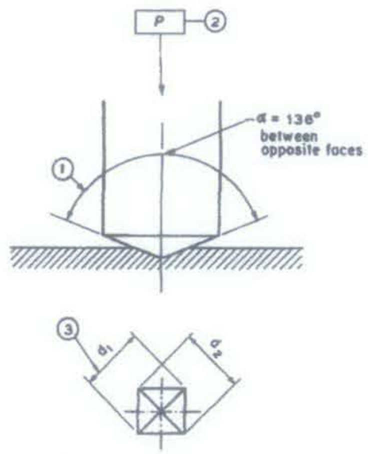

FIG. 1 Vickers Hardness Test (see Table 1)

TABLE 1 Symbols and Designations Associated with Fig. 1

Number	Symbol	Designation
1	. . .	Angle at the vertex of the pyramidal indenter (136°)
2	P	Test load in kilograms-force
3	d	Arithmetic mean of the two diagonals d^1 and d^2

[1] This test method is under the jurisdiction of ASTM Committee E-28 on Mechanical Testing and is the direct responsibility of Subcommittee E28.06 on Indentation Hardness Testing.

Current edition approved July 30, 1982. Published December 1982. Originally published as E 92 – 52 T. Last previous edition E 92 – 72 (1977).

[2] A procedure covering Vickers tests using applied loads of 1 gf to 1000 gf (1 kgf) may be found in Test Method E 384, Test Method for Microhardness of Materials, appearing in the *Annual Book of ASTM Standards*, Vol 03.01.

[3] *Annual Book of ASTM Standards*, Vol 03.01.

Example:

440 HV 30 = Vickers hardness of 440 measured under a load of 30 kgf applied for 10 to 15 s.
440 HV 30/20 = Vickers hardness of 440 measured under a load of 30 kgf applied for 20 s.

3.3 *verification*—checking or testing to assure conformance with the specification.

3.4 *calibration*—determination of the values of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

TABLE 2 Vickers Hardness Numbers
(Diamond, 136° Face Angle, Load of 1 kgf)

Diagonal of Impression, mm	Vickers Hardness Number for Diagonal Measured to 0.0001 mm									
	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009
0.005	74 170	71 290	68 580	66 020	63 590	61 300	59 130	57 080	55 120	53 270
0.006	51 510	49 840	48 240	46 720	45 270	43 890	42 570	41 310	40 100	38 950
0.007	37 840	36 790	35 770	34 800	33 860	32 970	32 100	31 280	30 480	29 710
0.008	28 970	28 260	27 580	26 920	26 280	25 670	25 070	24 500	23 950	23 410
0.009	22 890	22 390	21 910	21 440	20 990	20 550	20 120	19 710	19 310	18 920
0.010	18 540	18 180	17 820	17 480	17 140	16 820	16 500	16 200	15 900	15 610
0.011	15 330	15 050	14 780	14 520	14 270	14 020	13 780	13 550	13 320	13 090
0.012	12 880	12 670	12 460	12 260	12 060	11 870	11 680	11 500	11 320	11 140
0.013	10 970	10 810	10 640	10 480	10 330	10 170	10 030	9 880	9 737	9 598
0.014	9 461	9 327	9 196	9 068	8 943	8 820	8 699	8 581	8 466	8 353
0.015	8 242	8 133	8 026	7 922	7 819	7 718	7 620	7 523	7 428	7 335
0.016	7 244	7 154	7 066	6 979	6 895	6 811	6 729	6 649	6 570	6 493
0.017	6 416	6 342	6 268	6 196	6 125	6 055	5 986	5 919	5 853	5 787
0.018	5 723	5 660	5 598	5 537	5 477	5 418	5 360	5 303	5 247	5 191
0.019	5 137	5 083	5 030	4 978	4 927	4 877	4 827	4 778	4 730	4 683
0.020	4 636	4 590	4 545	4 500	4 456	4 413	4 370	4 328	4 286	4 245
0.021	4 205	4 165	4 126	4 087	4 049	4 012	3 975	3 938	3 902	3 866
0.022	3 831	3 797	3 763	3 729	3 696	3 663	3 631	3 599	3 567	3 536
0.023	3 505	3 475	3 445	3 416	3 387	3 358	3 329	3 301	3 274	3 246
0.024	3 219	3 193	3 166	3 140	3 115	3 089	3 064	3 039	3 015	2 991
0.025	2 967	2 943	2 920	2 897	2 874	2 852	2 830	2 808	2 786	2 764
0.026	2 743	2 722	2 701	2 681	2 661	2 641	2 621	2 601	2 582	2 563
0.027	2 544	2 525	2 506	2 488	2 470	2 452	2 434	2 417	2 399	2 382
0.028	2 365	2 348	2 332	2 315	2 299	2 283	2 267	2 251	2 236	2 220
0.029	2 205	2 190	2 175	2 160	2 145	2 131	2 116	2 102	2 088	2 074
0.030	2 060	2 047	2 033	2 020	2 007	1 993	1 980	1 968	1 955	1 942
0.031	1 930	1 917	1 905	1 893	1 881	1 869	1 857	1 845	1 834	1 822
0.032	1 811	1 800	1 788	1 777	1 766	1 756	1 745	1 734	1 724	1 713
0.033	1 703	1 693	1 682	1 672	1 662	1 652	1 643	1 633	1 623	1 614
0.034	1 604	1 595	1 586	1 576	1 567	1 558	1 549	1 540	1 531	1 522
0.035	1 514	1 505	1 497	1 488	1 480	1 471	1 463	1 455	1 447	1 439
0.036	1 431	1 423	1 415	1 407	1 400	1 392	1 384	1 377	1 369	1 362
0.037	1 355	1 347	1 340	1 333	1 326	1 319	1 312	1 305	1 298	1 291
0.038	1 284	1 277	1 271	1 264	1 258	1 251	1 245	1 238	1 232	1 225
0.039	1 219	1 213	1 207	1 201	1 195	1 189	1 183	1 177	1 171	1 165
0.040	1 159	1 153	1 147	1 142	1 136	1 131	1 125	1 119	1 114	1 109
0.041	1 103	1 098	1 092	1 087	1 082	1 077	1 072	1 066	1 061	1 056
0.042	1 051	1 046	1 041	1 036	1 031	1 027	1 022	1 017	1 012	1 008
0.043	1 003	998	994	989	985	980	975	971	967	962
0.044	958	953	949	945	941	936	932	928	924	920
0.045	916	912	908	904	900	896	892	888	884	880
0.046	876	873	869	865	861	858	854	850	847	843
0.047	839	836	832	829	825	822	818	815	812	808
0.048	805	802	798	795	792	788	785	782	779	775
0.049	772	769	766	763	760	757	754	751	748	745
0.050	742	739	736	733	730	727	724	721	719	716
0.051	713	710	707	705	702	699	696	694	691	688
0.052	686	683	681	678	675	673	670	668	665	663
0.053	660	658	655	653	650	648	645	643	641	638
0.054	636	634	631	629	627	624	622	620	617	615

TABLE 2 *Continued*

Diagonal of Impression, mm	Vickers Hardness Number for Diagonal Measured to 0.0001 mm									
	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009
0.055	613	611	609	606	604	602	600	598	596	593
0.056	591	589	587	585	583	581	579	577	575	573
0.057	571	569	567	565	563	561	559	557	555	553
0.058	551	549	547	546	544	542	540	538	536	535
0.059	533	531	529	527	526	524	522	520	519	516.8
0.060	515.1	513.4	511.7	510.0	508.3	506.6	505.0	503.3	501.6	500.0
0.061	498.4	496.7	495.1	493.5	491.9	490.3	488.7	487.1	485.5	484.0
0.062	482.4	480.9	479.3	477.8	476.2	474.7	473.2	471.7	470.2	468.7
0.063	467.2	465.7	464.3	462.8	461.3	459.9	458.4	457.0	455.6	454.1
0.064	452.7	451.3	449.9	448.5	447.1	445.7	444.4	443.0	441.6	440.3
0.065	438.9	437.6	436.2	434.9	433.6	432.2	430.9	429.6	428.3	427.0
0.066	425.7	424.4	423.1	421.9	420.6	419.3	418.1	416.8	415.6	414.3
0.067	413.1	411.9	410.6	409.4	408.2	407.0	405.8	404.6	403.4	402.2
0.068	401.0	399.9	398.7	397.5	396.6	395.2	394.0	392.9	391.8	390.6
0.069	389.5	388.4	387.2	386.1	385.0	383.9	382.8	381.7	380.6	379.5
0.070	378.4	377.4	376.3	375.2	374.2	373.1	372.0	371.0	369.9	368.9
0.071	367.9	366.8	365.8	364.8	363.7	362.7	361.7	360.7	359.7	358.7
0.072	357.7	356.7	355.7	354.7	353.8	352.8	351.8	350.9	349.9	348.9
0.073	348.0	347.0	346.1	345.1	344.2	343.3	342.3	341.4	340.5	339.6
0.074	338.6	337.7	336.8	335.9	335.0	334.1	333.2	332.3	331.4	330.5
0.075	329.7	328.8	327.9	327.0	326.2	325.3	324.5	323.6	322.7	321.9
0.076	321.0	320.2	319.4	318.5	317.7	316.9	316.0	315.2	314.4	313.6
0.077	312.8	312.0	311.1	310.3	309.5	308.7	307.9	307.2	306.4	305.6
0.078	304.8	304.0	303.2	302.5	301.7	300.9	300.2	299.4	298.6	297.9
0.079	297.1	296.4	295.6	294.9	294.1	293.4	292.7	291.9	291.2	290.5
0.080	289.7	289.0	288.3	287.6	286.9	286.2	285.4	284.7	284.0	283.3
0.081	282.6	281.9	281.2	280.6	279.9	279.2	278.5	277.8	277.1	276.5
0.082	275.8	275.1	274.4	273.8	273.1	272.4	271.8	271.1	270.5	269.8
0.083	269.2	268.5	267.9	267.2	266.6	266.0	265.3	264.7	264.1	263.4
0.084	262.8	262.2	261.6	260.9	260.3	259.7	259.1	258.5	257.9	257.3
0.085	256.7	256.1	255.5	254.9	254.3	253.7	253.1	252.5	251.9	251.3
0.086	250.7	250.1	249.6	249.0	248.4	247.8	247.3	246.7	246.1	245.6
0.087	245.0	244.4	243.9	243.3	242.8	242.2	241.6	241.1	240.6	240.0
0.088	239.5	238.9	238.4	237.8	237.3	236.8	236.2	235.7	235.2	234.6
0.089	234.1	233.6	233.1	232.5	232.0	231.5	231.0	230.5	230.0	229.4
0.090	228.9	228.4	227.9	227.4	226.9	226.4	225.9	225.4	224.9	224.4
0.091	223.9	223.4	222.9	222.5	222.0	221.5	221.0	220.5	220.0	219.6
0.092	219.1	218.6	218.1	217.7	217.1	216.7	216.3	215.8	215.3	214.9
0.093	214.4	213.9	213.5	213.0	212.6	212.1	211.7	211.2	210.8	210.3
0.094	209.9	209.4	209.0	208.5	208.1	207.6	207.2	206.8	206.3	205.9
0.095	205.5	205.0	204.6	204.2	203.8	203.3	202.9	202.5	202.1	201.6
0.096	201.2	200.8	200.4	200.0	199.5	199.1	198.7	198.3	197.9	197.5
0.097	197.1	196.7	196.3	195.9	195.5	195.1	194.7	194.3	193.9	193.5
0.098	193.1	192.7	192.3	191.9	191.5	191.1	190.7	190.4	190.0	189.6
0.099	189.2	188.8	188.4	188.1	187.7	187.3	186.9	186.6	186.2	185.5

TABLE 3 Decimal Point Finder for Use with Table 2

An example of determination of hardness numbers follows the table.

Diagonal Length, mm	Vickers Hardness (HV), 1-kgf Load
0.005	74 200
0.006	51 500
0.007	37 800
0.008	29 000
0.009	22 900
0.010	18 540
0.020	4 640
0.030	2 060
0.040	1 159
0.050	742
0.060	515
0.070	378
0.080	290
0.090	229
0.100	185.4
0.200	46.4
0.300	20.6
0.400	11.6
0.500	7.42
0.600	5.15
0.700	3.78
0.800	2.90
0.900	2.29
1.000	1.85
1.100	1.53
1.200	1.29
1.300	0.10
1.400	0.946
1.500	0.824
1.600	0.724
1.700	0.642
1.800	0.572
1.900	0.514
2.000	0.464

Example—Using a 50-kgf test load, the average measured diagonal length = 0.644 mm.

In Table 2 read:

HV = 447 at 0.0644-mm diagonal length at 1-kgf load.

Using Table 3 determine:

HV = 4.47 at 0.644-mm diagonal length at 1-kgf load.

50 × 4.47 = 224 HV for 50-kg test load.

A. GENERAL DESCRIPTION AND TEST PROCEDURE FOR VICKERS HARDNESS TESTS

4. Apparatus

4.1 *Testing Machine*—Equipment for Vickers hardness testing usually consists of a testing machine which supports the specimen and permits the indenter and the specimen to be brought into contact gradually and smoothly under a predetermined load, which is applied for a fixed period of time. The design of the machine should be such that no rocking or lateral movement of the indenter or specimen is permitted while the load is being applied or removed. A measuring microscope is usually mounted on the machine in such a manner that the impression in the specimen may be readily located in the optical field.

4.2 *Indenter:*

4.2.1 The indenter shall be a highly polished, pointed, square-based pyramidal diamond with face angles of 136° ± 30 min.

4.2.2 All four faces of the indenter shall be equally inclined to the axis of the indenter (within ±30 min) and meet at a sharp point, that is, the line of junction between opposite faces shall not be more than 0.001 mm in length as shown in Fig. 2.

4.2.3 The diamond should be examined periodically and if it is loose in the mounting material, chipped, or cracked, it should be discarded or reconditioned.

NOTE 2—The condition of the point of the indenter is of considerable importance where the test load is light and the impression is small. It is recommended that the point be periodically checked by examining an impression made in a polished steel block. Under a magnification of 600× or more, using a vertical illuminator, any chipping or rounding of the point can be detected and the extent of the defect measured with a filar micrometer. It is recommended that a diamond pyramid indenter should not be used for tests in which the maximum length of such a defect exceeds 5% of the length of the impression diagonal.

4.3 *Measuring Microscope*—The divisions of the micrometer scale of the measuring microscope or other measuring device shall be so constructed that the length of the diagonals of an impression in a properly surface-finished

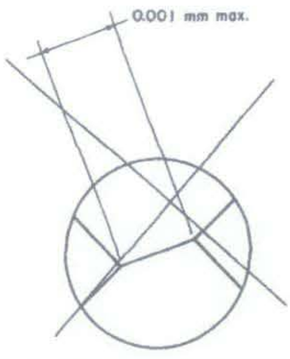

FIG. 2 Junction of Indenter Faces

specimen (see 5.1.2) can be measured to within ±0.0005 mm or ±0.5%, whichever is larger.

5. Test Specimens

5.1 The Vickers hardness test is adaptable to a wide variety of test specimens ranging from large bars and rolled sections to minute pieces in metallographic mounts. In general the backs of the specimens shall be so finished or the specimens shall be so clamped that there is no possibility of their rocking or shifting under the test load. The specimens shall also conform to the requirements given in the following 5.1.1, 5.1.2, and 5.1.3.

5.1.1 *Thickness*—The thickness of the test specimen shall be such that no bulge or marking showing the effect of the load appears on the side of the specimen opposite the impression. In any event the thickness of the specimen shall be at least one and one half times the length of the diagonal. When laminated material is tested, the thickness of the individual component being tested shall be used for the thickness-diagonal length relationship.

5.1.2 *Finish*—The surface of the specimen should be so prepared that the ends of the diagonals are clearly defined and can be read with precision of ±0.0005 mm or ±0.5% of the length of the diagonals, whichever is larger. Care should be taken in specimen preparation to avoid tempering during grinding, or work-hardening the surface during polishing.

5.1.3 *Alignment*—The specimen should be so prepared or mounted that the surface is normal to the axis of the indenter within ±1° of angle. This can readily be accomplished by surface grinding (or otherwise machining) the opposite side of the specimen to parallelism with the side to be tested.

5.1.4 *Radius of Curvature*—Until further investigative work is accomplished to determine the effect of the radius of curvature on readings, due caution should be used in interpreting or accepting the results of tests made on cylindrical surfaces.

NOTE 3—A method recommended by the International Organization for Standardization for correcting Vickers hardness readings taken on spherical or cylindrical surfaces is given in Tables 4, 5, and 6.

NOTE 4—These tables give correction factors to be applied to Vickers hardness values obtained when tests are made on spherical or cylindrical surfaces. The correction factors are tabulated in terms of the ratio of the mean diagonal *d* of the indentation to the diameter *D* of the sphere or cylinder. Examples of the use of these tables are:

TABLE 4 Correction Factors for Use in Vickers Hardness Tests Made on Spherical Surfaces

Convex Surface		Concave Surface	
d/D^A	Correction Factor	d/D^A	Correction Factor
0.004	0.995	0.004	1.005
0.009	0.990	0.008	1.010
0.013	0.985	0.012	1.015
0.018	0.980	0.016	1.020
0.023	0.975	0.020	1.025
0.028	0.970	0.024	1.030
0.033	0.965	0.028	1.035
0.038	0.960	0.031	1.040
0.043	0.955	0.035	1.045
0.049	0.950	0.038	1.050
0.055	0.945	0.041	1.055
0.061	0.940	0.045	1.060
0.067	0.935	0.048	1.065
0.073	0.930	0.051	1.070
0.079	0.925	0.054	1.075
0.086	0.920	0.057	1.080
0.093	0.915	0.060	1.085
0.100	0.910	0.063	1.090
0.107	0.905	0.066	1.095
0.114	0.900	0.069	1.100
0.122	0.895	0.071	1.105
0.130	0.890	0.074	1.110
0.139	0.885	0.077	1.115
0.147	0.880	0.079	1.200
0.156	0.875	0.082	1.125
0.165	0.870	0.084	1.130
0.175	0.865	0.087	1.135
0.185	0.860	0.089	1.140
0.195	0.855	0.091	1.145
0.206	0.850	0.094	1.150

^{A} *D* = diameter of cylinder.
d = mean diagonal of impression in millimeters.

Example 1. Convex Sphere:

Diameter of sphere, *D*	= 10 mm
Load	= 10 kgf
Mean diagonal of impression, *d*	= 0.150 mm
$d/D = 0.150/10 = 0.015$	
From Tables 2 and 3, HV	= 824
From Table 4, by interpolation, correction factor	= 0.983
Hardness of sphere = 824 × 0.983	= 810 HV 10

Example 2. Concave Cylinder, One Diagonal Parallel to Axis:

Diameter of cylinder, D	= 5 mm
Load	= 30 kgf
Mean diagonal of impression, *d*	= 0.415 mm
$d/D = 0.415/5 = 0.083$	
From Tables 2 and 3, HV	= 323
From Table 6, correction factor	= 1.075
Hardness of cylinder = 323 × 1.075	= 347 HV 30.

6. Verification of Apparatus

6.1 The hardness testing machine shall be verified as specified in Part B.

6.1.1 Two acceptable methods of verifying Vickers hardness testing machines are given in Part B.

7. Procedure

7.1 *Magnitude of Test Load*—Test loads of 1 kgf to 120

TABLE 5 Correction Factors for Use in Vickers Hardness Tests Made on Cylindrical Surfaces
(Diagonals at 45° to the axis)

Convex Surface		Concave Surface	
d/D^A	Correction Factor	d/D^A	Correction Factor
0.009	0.995	0.009	1.005
0.017	0.990	0.017	1.020
0.026	0.985	0.025	1.015
0.035	0.980	0.034	1.020
0.044	0.975	0.042	1.025
0.053	0.970	0.050	1.030
0.062	0.965	0.058	1.035
0.071	0.960	0.066	1.040
0.081	0.955	0.074	1.045
0.090	0.950	0.082	1.050
0.100	0.945	0.089	1.055
0.109	0.940	0.097	1.060
0.119	0.935	0.104	1.065
0.129	0.930	0.112	1.070
0.139	0.925	0.119	1.075
0.149	0.920	0.127	1.080
0.159	0.915	0.134	1.085
0.169	0.910	0.141	1.090
0.179	0.905	0.148	1.095
0.189	0.900	0.155	1.100
0.200	0.895	0.162	1.105
		0.169	1.110
		0.176	1.115
		0.183	1.120
		0.189	1.125
		0.196	1.130
		0.203	1.135
		0.209	1.140
		0.216	1.140
		0.222	1.150

^{A} D = diameter of sphere.
d = mean diagonal of impression in millimeters.

TABLE 6 Correction Factors for Use in Vickers Hardness Tests Made on Cylindrical Surfaces
(One diagonal parallel to axis)

Convex Surface		Concave Surface	
d/D^A	Correction Factor	d/D^A	Correction Factor
0.009	0.995	0.048	1.035
0.019	0.990	0.053	1.040
0.029	0.985	0.058	1.045
0.041	0.980	0.063	1.050
0.054	0.975	0.067	1.055
0.068	0.970	0.071	1.060
0.085	0.965	0.076	1.065
0.104	0.960	0.079	1.070
0.126	0.955	0.083	1.075
0.153	0.950	0.087	1.080
0.189	0.945	0.090	1.085
0.243	0.940	0.093	1.090
		0.097	1.095
Concave Surface		0.100	1.100
		0.103	1.105
d/D^A	Correction Factor	0.105	1.110
		0.108	1.115
		0.111	1.120
0.008	1.005	0.113	1.125
0.016	1.020	0.116	1.130
0.023	1.015	0.118	1.135
0.030	1.020	0.120	1.140
0.036	1.025	0.123	1.145
0.042	1.030	0.125	1.150

^{A} D = diameter of cylinder.
d = mean diagonal of impression in millimeters.

kgf may be used, depending on the requirements of the test. Although tests on homogeneous materials indicate that the Vickers hardness number is nearly independent of the test load, this condition will not be present in cases where there is a hardness gradient from the specimen surface to the interior of the specimen. The magnitude of the test load should therefore be stated in the test report (Section 11).

7.2 *Application of Test Load*—Apply the test load and release smoothly without shock or vibration. The time of application of the full test load shall be 10 to 15 s, unless otherwise specified.

7.3 *Spacing of Indentations*—The center of the impression shall not be closer to any edge of the test specimen or to another impression than a distance equal to two and one half times the length of diagonal of the impression. When laminated material is tested, a bond surface shall be considered as an edge for spacing of indentation calculations.

8. Measurement of Impression

8.1 Both diagonals of the impression shall be measured and their mean value used as a basis for calculation of the Vickers hardness number. It is recommended that the measurement be made with the impression centered as nearly as possible in the field of the microscope.

8.2 In the case of anisotropic materials, for example materials that have been heavily cold worked, there may be a difference between the lengths of the two diagonals of the impression. In such cases, the test specimen should be reoriented so that the diagonals of a new impression are approximately of equal length.

9. Accuracy

9.1 The accuracy of the Vickers hardness method is a function of the accuracies of the test force, indenter, and measuring device. The condition of the test and support surfaces and support of the test piece during application of the test force also affect accuracy. Under optimum conditions of these factors the accuracy that can be expected is the equivalent of 4 % of the Vickers hardness number of the standardized reference hardness test blocks (see 18.2). Under less than ideal conditions the reduction in accuracy, when required, can be established empirically by employing statistical methods.

10. Conversion to Other Hardness Scales or Tensile Strength Values

10.1 There is no general method for converting accurately Vickers hardness numbers to other hardness scales or tensile strength values. Such conversions are, at best, approximations and therefore should be avoided, except for special cases where a reliable basis for the approximate conversions has been obtained by comparison tests.

NOTE 5—Standard E 140 give approximate conversion values for specific materials such as steel, nickel and high-nickel alloys, and cartridge brass.

11. Report

11.1 The report shall include the following information:

11.1.1 The Vickers hardness number,

11.1.2 The test load used (see 3.2.2, Note 1), and

11.1.3 The loading time, if other than 10 to 15 s (see 3.2.2, Note 1).

12. Precision and Bias

12.1 Due to the wide variety of materials tested by this method and the possible variations in test specimens, the precision of this method has not been established. The accepted practice is to utilize the information in 9.1 when establishing hardness tolerances for specific applications. The precision of this method, whether involving a single operator, multiple operators, or multiple laboratories, can be established by employing statistical methods.

B. VERIFICATION OF VICKERS HARDNESS TESTING MACHINES

13. Scope

13.1 Part B covers two procedures for the verification of Vickers hardness testing machines and a procedure that is recommended for use to confirm that the machine has not become maladjusted in the intervals between the periodical routine checks. The two methods of verification are:

13.1.1 Separate verification of load application, indenter, and measuring microscope.

13.1.2 Verification by standardized test block method.

13.2 The first procedure (13.1.1) is mandatory for new and rebuilt machines.

13.3 The second procedure (13.1.2) shall be used for verifying machines in service.

14. General Requirements

14.1 Before a Vickers hardness testing machine is verified the machine shall be examined to ensure that:

14.1.1 The machine is properly set up.

14.1.2 The indenter holder is mounted normally in the plunger.

14.1.3 The load can be applied and removed without shock or vibration in such a manner that the readings are not influenced.

14.2 If the measuring device is integral with the machine, the machine shall be examined to ensure that:

14.2.1 The change from loading to measuring does not influence the readings.

14.2.2 The method of illumination does not affect the readings.

14.2.3 The center of the impression is in the center of the field of view.

15. Verification

15.1 *Separate Verification of Load Application, Indenter, and Measuring Microscope:*

15.1.1 *Load Application*—The applied load shall be checked by the use of dead weights and proving levers, or by an elastic calibration device or springs in the manner described in Practices E 4. Such dead weights or other loading devices shall be accurate to ±0.2 %. Vickers hardness testing machines shall be verified at a minimum of three applied loads including the test load specified. A minimum of three readings should be taken at each load. A Vickers hardness testing machine is acceptable for use over a loading range within which the machine error does not exceed ±1 %.

15.1.2 *Indenter*—The form of the diamond indenter shall be verified by direct measurement of its shape or by measurements of its projection on a screen. The angle between opposite faces of the pyramid shall be 136° ± 30 min. All four faces shall be equally inclined to the axis of the pyramid within ±30 min. The four faces of indenters used for laboratory, or routine tests, shall meet at a point no more than 0.001 mm in length (see Fig. 2). The four faces of indenters used in calibrating standardized hardness test blocks, shall meet at a point in which the line of junction between opposite faces is no more than 0.0005 mm in length (see Fig. 3). The quadrilateral that would be formed by the intersection of the four faces with a plane perpendicular to the axis of the indenter shall have angles of 90° ± 12 min.

15.1.3 *Measuring Microscope*—The measuring microscope or other device for measuring the diagonals of the impression shall be calibrated against an accurately ruled line scale (stage micrometer). The errors of the line scale shall not exceed 0.05 μm (0.00005 mm) or 0.05 % of any interval, whichever is greater. The measuring microscope shall be calibrated throughout its range of use and a calibration factor chosen such that the error shall not exceed ±0.5 %. It may be necessary to divide the complete range of the micrometer microscope into several subranges, each having its own factor.

15.2 *Verification by Standardized Test Block Method:*

15.2.1 A Vickers hardness testing machine used only for routine testing may be checked by making a series of impressions on standardized hardness test blocks (Part C).

15.2.2 A minimum of five Vickers hardness readings shall be taken on at least three blocks having different levels of hardness using a test load or loads as specified by the user with the test load applied for 12 s.

15.2.3 Vickers hardness testing machines shall be considered verified if the mean diagonal for five hardness impres-

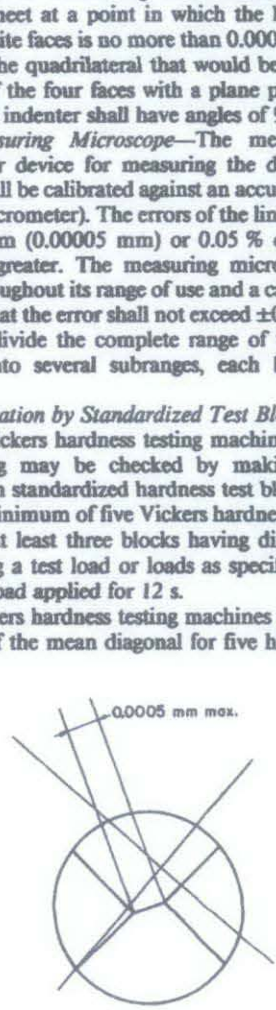

FIG. 3 Junction of Indenter Faces

sions meets the requirements of 17.2.

16. Procedure for Periodic Checks by the User

16.1 Verification by the standardized test block method (15.2.2) is too lengthy for daily use. Instead the following is recommended:

16.1.1 Make at least one routine check each day that the testing machine is used.

16.1.2 Before making the check, verify that the zero reading of the measuring apparatus is correctly adjusted.

16.1.3 Make at least five hardness readings on a standardized hardness test block on the scale and at the hardness level at which the machine is being used. If the values fall within the range of the standardized hardness test block the machine may be regarded as satisfactory; if not the machine should be verified as described in 15.2.2.

17. Repeatability and Error

17.1 *Repeatability:*

17.1.1 For each standardized block, let d_1, d_2, $\cdots$ d_5 be the arithmetic means of the two diagonals of the indentations, arranged in increasing order of magnitude.

17.1.2 The repeatability of the machine under the particular verification conditions is expressed by the quantity $d_5 - d_1$.

17.2 *Error:*

17.2.1 The error of the machine under the particular verification conditions is expressed by the quantity $\bar{d} - d$, where $\bar{d} = (d_1 + d_2 + \cdots d_5)/5$, and d is the reported mean diagonal of impressions on the standardized hardness test block.

18. Assessment of Verification

18.1 *Repeatability*—The repeatability of the machine verified is considered satisfactory if it satisfies the conditions given in Table 7.

18.2 *Error*—The mean diagonal for five impressions should not differ from the mean diagonal corresponding to the Vickers hardness of the standardized test block by more than 2 % or 0.5 µm (0.0005 mm), whichever is greater.

TABLE 7 Repeatability of Machines

Range of Standardized Hardness of Test Blocks	The Repeatability of the Machine Should be Less Than:	Examples of Equivalents in Hardness Units
100 to 240, incl	4 % of $d^{A,B}$	8 at 100 HV; 16 at 200 HV
Over 240 to 600, incl	3 % of $d^{A,B}$	18 at 300 HV; 36 at 600 HV
Over 600	2 % of $d^{A,B}$	28 at 700 HV

[A] $d = (d_1 + d_2 + \ldots + d_5)/5$.

[B] In all cases the repeatability is the percentage given or 1 µm (0.001 mm), whichever is the greater.

C. CALIBRATION OF STANDARD HARDNESS TEST BLOCKS FOR VICKERS HARDNESS MACHINES

19. Scope

19.1 Part C covers the calibration of standardized hardness test blocks for the verification of Vickers hardness testing machines as described in Part B.

20. Manufacture

20.1 Each metal block to be standardized shall be not less than ¼ in. (6 mm) in thickness.

20.2 Each block shall be specially prepared and heat treated to give the necessary homogeneity and stability of structure.

20.3 Each block, if of steel, shall be demagnetized by the manufacturer and maintained demagnetized by the user.

20.4 The lower surface of the test block shall have a fine ground finish.

20.5 The test (upper) surface shall be polished and free of scratches which would interfere with measurements of the diagonals of the impression.

20.5.1 The mean surface roughness height rating shall not exceed 4 µin. (0.0001 mm) center line average.

20.6 To ensure that no material is subsequently removed from the test surface of the standardized test block, an official mark or the thickness at the time of calibration shall be marked on the test surface to an accuracy of ±0.005 in.(±0.1 mm).

21. Standardizing Procedure

21.1 The standardized hardness test blocks shall be calibrated on a Vickers hardness testing machine verified in accordance with the requirements of 13.1.1.

21.2 The mechanism that controls the application of load should either:

21.2.1 Employ a device such as a spring to reduce the velocity of indentation of the indenter during the period of indentation, or

21.2.2 Employ a device to maintain a constant velocity of indentation of the indenter.

21.3 The full load shall be applied for 12 s.

22. Number of Indentations

22.1 At least five and preferably ten randomly distributed indentations shall be made on each test block.

23. Measurement of the Diagonals of the Indentation

23.1 The illuminating system of the measuring microscope shall be adjusted to give uniform intensity over the field of view and maximum contrast between the indentation and the undistributed surface of the block.

23.2 The measuring microscope shall be graduated to read 0.001 mm with estimates made to the nearest ±0.0002 mm.

23.3 The measuring microscope shall be checked by a stage micrometer, or by other suitable means, to ensure that the difference between readings corresponding to any two divisions of the instrument is correct within ±0.0005 mm.

23.4 It is recommended that each indentation be measured by two observers.

24. Repeatability

24.1 Let d_1, d_2, $\cdots$ d_n be the mean values of the measured diagonals as determined by one observer, arranged in increasing order of magnitude.

24.2 The repeatability of the hardness readings on the block is defined as $(d_{10} - d_1)$, when ten readings have been made or $1.32\ (d_5 - d_1)$ when five readings are taken on the block.

25. Uniformity of Hardness

25.1 Unless the repeatability of hardness readings as measured by the mean diagonals of five or ten impressions is within the limits given in Table 8, the block cannot be regarded as sufficiently uniform for standardization purposes.

26. Marking

26.1 Each block shall be marked with the following:

26.1.1 Arithmetic mean of the hardness values found in the standardization test (see also 3.2.2, Note 1).

26.1.2 The name or mark of the supplier,

TABLE 8 Repeatability of Hardness Readings

Range of Standardized Hardness of Test Block	The Repeatability of the Test Block Readings Shall be Less Than:
100 to 240, incl	3 % of d[A,B]
Over 240 to 600, incl	2 % of d[A,B]
Over 600	1.5 % of d[A,B]

[A] $d = (d_1 + d_2 + \ldots + d_n)/n$.

[B] In all cases the repeatability is the percentage given or 1 μm (0.001 mm), whichever is the greater.

26.1.3 The serial number of the block, and

26.1.4 The thickness of the test block or an official mark on the top surface (see 19.6).

NOTE 6—All of the markings except the official mark or thickness should be placed on the side of the block, the markings being upright when the test surface is the upper face.

27. Keywords

27.1 metallic; Vickers hardness

APPENDIX XII

Specimen A

Edge	Specimen A	d1	d2	Hv	
Trailing	x1	29.1	29.29	217.5	
	y1	30.31	29.04	210.5	Avg. Center (Hv)
Center	x2	31.2	30.52	194.7	203.6
	y2	30.2	29.87	205.5	
Leading	x3	33.23	29.98	185.6	
Average				202.2	

Specimen B

Edge	Specimen B	d1	d2	Hv	
Trailing	x1	29.67	29.02	215.3	
	y1	31.04	28.89	206.5	Avg. Center (Hv)
Center	x2	32.33	29.67	192.9	202.1
	y2	34.87	25.01	206.8	
Leading	x3	33.24	32.17	173.3	
Average				196.9	

Specimen C

Edge	Specimen C	d1	d2	Hv	
Trailing	x1	28.76	30.35	212.3	
	y1	31.22	28.42	208.5	Avg. Center (Hv)
Center	x2	31.55	30.33	193.7	198.5
	y2	27.34	34.6	193.3	
Leading	x3	32.65	33.32	170.4	
Average				193.7	

Specimen D

Edge	Specimen D	d1	d2	Hv	
Trailing	x1	27.56	31.99	209.1	
	y1	26.75	34.87	195.3	Avg. Center (Hv)
Center	x2	32.54	30.01	189.5	194.5
	y2	30.88	30.24	198.5	
Leading	x3	33.55	33.97	162.7	
Average				188.8	

Specimen E

Edge	Specimen E	d1	d2	Hv	
Trailing	x1	28.43	30.42	214.1	
	y1	32.35	27.65	206.0	Avg. Center (Hv)
Center	x2	33.21	28.04	197.7	193.9
	y2	35.08	29.44	178.1	
Leading	x3	31.75	34.65	168.2	
Average				192.1	

Specimen F

Edge	Specimen F	d1	d2	Hv	
Trailing	x1	30.13	32.45	189.4	
	y1	33.65	28.54	191.7	Avg. Center (Hv)
Center	x2	29.85	33.21	186.5	184.3
	y2	31.43	33.72	174.7	
Leading	x3	35.09	32.89	160.5	
Average				178.1	