DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615)576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

FINAL REPORT

for

**A STUDY OF COAL PARTICLE SHAPE
AND THREE-BODY WEAR**

**Part I: Design and Development of a
New Three-Body Wear Testing Machine**

**Part II: Particle Shape and
Three-Body Wear**

**DOE/PETC GRANT NO.
DE-FG22-88PC88941**

**N. N. Clark and K. H. Means
Principal Investigators**

**R. James and T. Thompson
Graduate Research Assistants**

Table of Contents

Page

Title Page	i
Table of Contents	ii
List of Appendices	iii
List of Figures	iv
List of Tables	xi
List of Nomenclature	xii
 PART I: DESIGN & DEVELOPMENT OF A NEW THREE-BODY WEAR TESTING MACHINE	
Chapter I-1. Introduction	1
Chapter I-2. Three-body Wear (Literature Review)	3
Chapter I-3. Three-body Wear Machine	14
I-3.1 Three-body Wear Stand	14
3.1.1 Stand	14
3.1.2 Spindle and Housing	16
3.1.3 Motor	19
3.1.4 A/D Converter	20
3.1.5 Positioning System	21
3.1.6 Load Cell	23
3.1.7 Light Chopper Disk	24
3.1.8 Upper Tower	26
I-3.2 Calibration	27
3.2.1 Force Calibration	27
3.2.2 Speed Calibration	29
I-3.3 Control	30
3.3.1 Force Algorithm	30
3.3.2 Speed Algorithm	34
3.3.3 Positioning Control	36
Chapter I-4. Experimental Three-body Wear	70
I-4.1 Experimental Setup and Procedure	70
I-4.2 Wear Test Analysis	74
I-4.2.1 Smooth Glass Spheres	75
I-4.2.2 Aluminum Oxide Particles	77

I-4.2.3 Coal Ash	79
Chapter I-5. Results	149
I-5.1 Comparisons of Results	149
5.1.1 Aluminum Oxide Particles	149
5.1.2 Smooth Glass Spheres	152
5.1.3 Coal Ash	153
5.1.4 Comparison of Results Between the Tests	153
5.1.5 Particle Shape Comparison	156
I-5.2 Uncertainty of Results	159
I-5.3 Wear Equation Development	168
Chapter I-6. Conclusions	177
Appendices	180
Insert "C"	
Appendix I-A: Wear Test Summary	
Appendix I-B: Listing of WEAR7 Program	
Appendix I-C: Listing of FORCE3 Program	
Appendix I-D: Listing of SLIDDIST Program	
Appendix I-E: Listing of LOADGET Program	
References	195
 PART II: PARTICLE SHAPE AND THREE-BODY WEAR	
II-1. Particle Shape Characterization	199
II-2. Particle Digitization	200
II-3. Shape Descriptor Algorithms	201
II-4. Data and Conclusions	222
II-5. Effect of Shape on Wear	222
II-6. Effect of Wear on Shape	225
Appendix II-A: Computer Code to Digitize Image	246
Appendix II-B: Polygonal Harmonic Algorithm	253
Appendix II-C: Fractal Dimension Algorithm	261
Appendix II-D: Two-Dimensional Aspect Ratio Algorithm	268
Appendix II-E: Fourier Analysis Algorithm	274
Appendix II-F: Fast Fourier Transform Algorithm	280
Appendix II-G: Not-Roundness Algorithm	283
Appendix II-H: Electron Microscope Photographs	285
Final Summary	289

List of Figures Part I

- Figure I-3.1 Side View Three-body Wear Stand**
- Figure I-3.2 Top View Three-body Wear Stand**
- Figure I-3.3 Spindle**
- Figure I-3.4 Elements, Constraints, and Forces for Steel Spindle**
- Figure I-3.5 Elements, Constraints, and Forces for Aluminum Spindle**
- Figure I-3.6 Von Mises Stress Plot for Steel Spindle**
- Figure I-3.7 Von Mises Stress Plot for Aluminum Spindle**
- Figure I-3.8 Deflection Plot for Steel Spindle**
- Figure I-3.9 Deflection Plot for Aluminum Spindle**
- Figure I-3.10 Bearing Housing**
- Figure I-3.11 Specimen Disk**
- Figure I-3.12 Specimen Disk Holding Tabs**
- Figure I-3.13 Front View of Load Cell**
- Figure I-3.14 Side and Top View of Load Cell**
- Figure I-3.15 Locations of Strain Gauges**
- Figure I-3.16 Light Chopper Disk**
- Figure I-3.17 Schematic of Light Sensing Circuit**
- Figure I-3.18 Sensor Holder**
- Figure I-3.19 Light Sensing Circuit**
- Figure I-3.20 Upper Tower Assembly**
- Figure I-3.21 Tower Aluminum Plate**

Figure I-3.22 Complete Assembly of Machine

Figure I-3.23 Control Schematic

Figure I-3.24 Bridge Voltage vs. Normal Force

Figure I-3.25 Bridge Voltage vs. Friction Force

Figure I-3.26 Bridge Voltage vs. Friction Force

Figure I-3.27 Bridge Voltage vs. Friction Force

Figure I-3.28 Bridge Voltage vs. Torque Load

Figure I-4.1 Weight Loss of Brass vs. Time, Aluminum Oxide Rough Particles

Figure I-4.2 Weight Loss of Brass vs. Time, Smooth Glass Spheres

Figure I-4.3 Weight Loss of Brass vs. Time, Coal Ash

Figure I-4.4 Weight Loss of Brass vs. Time, Smooth Glass Spheres with a Brass Disk

Figure I-4.5 Wear Coefficient K, Aluminum Oxide Rough Particles

Figure I-4.6 Wear Coefficient K, Smooth Glass Spheres

Figure I-4.7 Wear Coefficient K, Coal Ash

Figure I-4.8 Wear coefficient K, Smooth Glass Spheres with a Brass Disk

Figure I-4.9 Specific Wear Rate vs. Time, Aluminum Oxide Rough Particles

Figure I-4.10 Specific Wear Rate vs. Time, Smooth Glass Spheres

Figure I-4.11 Specific Wear Rate vs. Time, Coal Ash

Figure I-4.12 Specific Wear Rate vs. Time, Smooth Glass Spheres with a Brass Disk

Figure I-4.13 Wear Loads, Specimen #22, Aluminum Oxide Rough Particles

Figure I-4.14 Wear Loads, Specimen #23, Aluminum Oxide Rough Particles

Figure I-4.15 Wear Loads, Specimen #24, Aluminum Oxide Rough Particles

Figure I-4.16 Wear Loads, Specimen #25, Aluminum Oxide Rough Particles

Figure I-4.17 Wear Loads, Specimen #38, Smooth Glass Spheres

Figure I-4.18 Wear Loads, Specimen #39, Smooth Glass Spheres

Figure I-4.19 Wear Loads, Specimen #40, Smooth Glass Spheres

Figure I-4.20 Wear Loads, Specimen #41, Smooth Glass Spheres

Figure I-4.21 Wear Loads, Specimen #54, Aluminum Oxide Rough Particles

Figure I-4.22 Wear Loads, Specimen #55, Aluminum Oxide Rough Particles

Figure I-4.23 Wear Loads, Specimen #56, Aluminum Oxide Rough Particles

Figure I-4.24 Wear Loads, Specimen #57, Aluminum Oxide Rough Particles

Figure I-4.25 Wear Loads, Specimen #70, Smooth Glass Spheres

Figure I-4.26 Wear Loads, Specimen #71, Smooth Glass Spheres

Figure I-4.27 Wear Loads, Specimen #72, Smooth Glass Spheres

Figure I-4.28 Wear Loads, Specimen #73, Smooth Glass Spheres

Figure I-4.29 Wear Loads, Specimen #86, Coal Ash

Figure I-4.30 Wear Loads, Specimen #87, Coal Ash

Figure I-4.31 Wear Loads, Specimen #88, Coal Ash

Figure I-4.32 Wear Loads, Specimen #89, Coal Ash

Figure I-4.33 Wear Loads, Specimen #102, Coal Ash

Figure I-4.34 Wear Loads, Specimen #103, Coal Ash

Figure I-4.35 Wear Loads, Specimen #104, Coal Ash

Figure I-4.36 Wear Loads, Specimen #105, Coal Ash

Figure I-4.37 Wear Loads, Specimen #118, Smooth Glass Spheres with a Brass Disk

Figure I-4.38 Wear Loads, Specimen #119, Smooth Glass Spheres with a Brass Disk

Figure I-4.39 Wear Loads, Specimen #120, Smooth Glass Spheres with a Brass Disk

Figure I-4.40 Wear Loads, Specimen #121, Smooth Glass Spheres with a Brass Disk

Figure I-4.41 Weight Loss of Brass vs. Time for Coal Ash at 100 micron gap

Figure I-4.42 Weight Loss of Brass vs. Time for Blasting Sand

Figure I-4.43 Weight Loss of Brass vs. Time for Coal Ash at 200 micron gap

Figure I-4.44 Weight Loss of Brass vs. Time for Aluminum Oxide with a Brass Disk

Figure I-4.45 Wear Coefficient for Coal Ash on Brass at 100 micron gap

Figure I-4.46 Wear Coefficient for Blasting Sand

Figure I-4.47 Wear Coefficient for Coal Ash at a 200 micron gap

Figure I-4.48 Wear Coefficient for Aluminum Oxide on a Brass Disk

Figure I-4.49 Specific Wear Rate for coal Ash at a 100 micron gap

Figure I-4.50 Specific Wear Rate for Blasting Sand

Figure I-4.51 Specific Wear Rate for Coal Ash at a 200 micron gap

Figure I-4.52 Specific Wear Rate for Aluminum Oxide on a Brass Disk

Figure I-4.53 Wear Loads for Test No. 134

Figure I-4.54 Wear Loads for Test No. 135

Figure I-4.55 Wear Loads for Test No. 136

Figure I-4.56 Wear Loads for Test No. 137

Figure I-4.57 Wear Loads for Test No. 150

Figure I-4.58 Wear Loads for Test No. 151

Figure I-4.59 Wear Loads for Test No. 152

Figure I-4.60 Wear Loads for Test No. 153

Figure I-4.61 Wear Loads for Test No. 166

Figure I-4.62 Wear Loads for Test No. 167

Figure I-4.63 Wear Loads for Test No. 168

Figure I-4.64 Wear Loads for Test No. 169

Figure I-4.65 Wear Loads for Test No. 182

Figure I-4.66 Wear Loads for Test No. 183

Figure I-4.67 Wear Loads for Test No. 184

Figure I-4.68 Wear Loads for Test No. 185

Part II

Figure II-1 Experimental set up for particle digitization

Figure II-2 Graduate directions for edge follower routine

Figure II-3 Illustration of the Polygonal Harmonics of different images

Figure II-4 Hybrid structured walk used by algorithms

Figure II-5 Diameters used to calculate two-dimensional aspect ratio

Figure II-6 The 64 radii of a particle found using Fourier Analysis

Figure II-7 Illustration of the selection of radii for Fourier analysis algorithm

Figure II-8 Illustration of the 64 longest and shortest radii of a re-entrant coal ash particle

Figure II-9 Ten different views of the same side of a rock used to test reliability of shape description algorithms

Figure II-10 Distribution of the second harmonic persistence for ten views of the same side of a rock

Figure II-11 Distribution of the third harmonic persistence for ten views of the same side of a rock

Figure II-12 Distribution of the fourth harmonic persistence for ten views of the same side of a rock

Figure II-13 Distribution of aspect ratio for ten views of the same side of a rock

Figure II-14 Distribution of not-roundness for ten views of the same side of a rock

Figure II-15 Distribution of fractal dimension for ten views of the same side of a rock

Figure II-16 Distribution of the second Fourier coefficient for ten views of the same side of a rock

Figure II-17 Distribution of the third Fourier coefficient for ten views of the same side of a rock

Figure II-18 Distribution of the fourth Fourier coefficient for ten views of the same side of a rock

Figure II-19 Distribution of the fifth Fourier coefficient for ten views of the same side of a rock

Figure II-20 Distribution of the sixth Fourier coefficient for ten views of the same side of a rock

Figure II-21 Distribution plots of aspect ratio for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-22 Distribution plots of second harmonic persistence for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-23 Distribution plots of third harmonic persistence for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-24 Distribution plots of fourth harmonic persistence for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-25 Distribution plots of not-roundness for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-26 Distribution plots of fractal dimension for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-27 Distribution plots of the second Fourier coefficient for aluminum oxide after 0, 10, 20 and 30 minutes of wear testing

Figure II-28 Distribution plots of the third Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

Figure II-29 Distribution plots of the fourth Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

- Figure II-30** Distribution plots of the fifth Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-31** Distribution plots of the sixth Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-32** Mean value within one standard deviation of the second harmonic persistence for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-33** Mean value within one standard deviation of the third harmonic persistence for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-34** Mean value within one standard deviation of the fourth harmonic persistence for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-35** Mean value within one standard deviation of aspect ratio for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-36** Mean value within one standard deviation of not-roundness for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-37** Mean value within one standard deviation of fractal dimension for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-38** Mean value within one standard deviation of the second Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-39** Mean value within one standard deviation of the third Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-40** Mean value with one standard deviation of the fourth Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-41** Mean value within one standard deviation of the fifth Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing
- Figure II-42** Mean value within one standard deviation of the sixth Fourier coefficient for aluminum oxide particles after 0, 10, 20 and 30 minutes of wear testing

List of Tables
Part I

Table I-3.1	Calibration Table for Relationship of Voltage versus Force for the Loadcell Setup
Table I-3.2	Deflection of Test Apparatus versus Load Applied
Table I-3.3	Calculation of Calibration Forces Using Calibration Constants
Table I-5.1	Results from the Wear Tests
Table I-5.2	Shape factors of test particles
Table I-5.3	Values used in the Error Analysis
Table I-5.4	Error Analysis Results

Part II

Table II-1	Three-body wear data for aluminum oxide particles, glass spheres, and coal ash
Table II-2	Various shape descriptors for aluminum oxide particles, glass spheres, and coal ash along with average wear test results
Table II-3	Average values of shape descriptors from sample groups of 40 aluminum oxide particles

List of Nomenclature

Upper Case English

- A_i - ADC code for V_{fi} , counts
- AVG1 - Constant, volts / unit lbf
- A1DAT - ADC code for V1DAT, counts
- D - Diameter of the particle, microns
- D_{eff} - Effective size of the wear particles, microns
- D_v - Difference between bridge amp signals, volts
- E_i - Modulus of Elasticity for surface i, psi
- F_v - Frictional force voltage component, volts
- Fy - Normal load, lbf
- H - Hardness of test specimen, psi
- H_a - Hardness, abrasive, psi
- H_{wd} - Hardness, wear disk, psi
- H_{ws} - Hardness, wear specimen, psi
- K_2 - Wear coefficient, two-body wear, in./in.
- K_3 - Wear coefficient, three-body wear, in./in.
- L - Sliding distance, in.
- N_v - Normal force voltage component, volts
- P - Load, lbf
- PERIOD - Time between pulses of the light chopper circuit,
sec.
- PULWID - Pulsewidth of the pulses from the light
chopper circuit, count

SD -Sliding distance, in.

V - Volume of material lost, in³

V_a - Volume loss, abrasive, in³

V_{wd} - Volume loss, wear disk, in³

V_{ws} - Volume loss, wear specimen, in³

V_{#i} - Voltage from the i-th bridge amp circuit, volts

V1DAT - Calibration voltage, volts

V1P - Average difference between V_{#1} and V_{#2}, volts

W - Normal load, lbf

W_a - Uncertainty of variable a

WR - Wear rate, three-body wear, in³ / (lbf x in.)

W₂ - Wear rate, two-body wear, in³

Lower_Case_English

a_i - Radius of the spherical contact for contact #1,
microns

d_i - Depth of penetration due to contact # i, microns

h_{gap} - Gap between the wear specimen and wear disk,
microns

rpm - Velocity of the spindle, rev. / min.

sc_i - Unit compressive stress due to contact # i, psi

time - Total time of test, sec.

w - Calibration weight, lbf

Greek Symbols

γ_i - Relationship for surface interaction # i

ν_i - Poisson's ratio for surface i

Chapter I-1 Introduction

Three-body wear is an important process that affects the life of components of internal combustion engines, machine tools, valves, coal handling equipment, tracked vehicles, etc. Piston and ring wear is a direct three-body wear process. With today's exotic and expensive materials for engine components it is very important to understand how a component is worn, what process causes the surface to be worn, and how long it takes to wear a part out.

Wear, in general, is the loss of material from a surface. Two of the more prominent types of wear are two-body wear and three-body wear. In two-body wear, a surface is worn by a fixed moving particle which gouges and scratches a surface. An example of this type of wear would be sandpaper abrading a surface. The three-body case involves two surfaces and an intermediate particle. The particle is trapped between the surfaces and wear occurs at the interfaces of the particle and the surfaces.

With re-emphasis of the coal-fired diesel engine the analysis of this type of wear has sparked new research. Ash is a main product of the combustion process and has been traced to wear of all parts of the engine. With the potential to cause so much damage it is very important to

understand the wear process. This thesis deals with the three-body wear process, and investigates the effect of particle shape on the process.

A machine has been constructed to measure normal and frictional forces due to three-body wear. This machine accurately positions specimens a predetermined distance apart from each other and introduces particles to the interface between wear the specimens. Different types of specimen combinations have been tested to give a variety of data. Loads that result from the wear test are sampled and stored. Wear coefficients and rates of wear have been calculated for all the specimens.

Three distinctly different particle types have been used in the tests. Aluminum oxide, smooth glass spheres, and coal ash have all been run through a series of wear tests. In related research, particle shape descriptors are found for all three sets of particles. A set of equations is then formulated, based upon the modified Archard equation (1), to account for volume wear loss as it depends upon load, sliding distance, hardness, and particle shape.

Chapter 1-2 Three-body Wear (Literature Review)

The study of three-body wear effects due to particle shape requires a thorough understanding of the principles of three-body wear. In order to convey the basic aspects of the three-body wear process it is necessary to review a few definitions of wear in general.

The term wear has been used for many years and has picked up many definitions. Wear has traditionally been defined as an unwanted waste of matter brought about by a mechanical process (2). A committee of the Institute of Mechanical Engineers decided on the following definition: 'The progressive loss of substance from the surface of a body brought about by mechanical action' (3). Kragelskii defines wear as: 'The destruction of material produced as a result of repeated disturbances of the frictional bonds' (4). Rebinder and his colleagues hold that the wear process results from surface disintegration caused by repeated plastic deformation leading to hardening and fatigue failure (5). One can easily see that all four definitions are similar with the only difference being semantic. This author will give this definition: Wear is the loss/gain of material of (a) surface(s) due to a frictional pair contact. A frictional pair contact is one that produces friction between the surfaces of either a

two-body or a three-body contact. The base concept is that friction is the overriding mechanism in wear. Being that the definition covers only the mechanical aspect in wear, the possible chemical and electrical wear mechanisms are not covered. Wear can also be broken down into different mechanisms or processes by which to operate.

Wear occurs as a natural consequence when two surfaces with a relative motion interact with each other (6). This is the overall view of the wear process but it can be subdivided into several different mechanisms of wear. Many researchers have listed different mechanisms of wear and here are a few of their observations. Burwell (7) lists four mechanisms of wear:

1. Adhesive wear
2. Abrasive wear
3. Corrosive wear
4. Surface fatigue

Burwell and Strang (8) suggest the following wear mechanisms:

1. Adhesion or Galling
2. Corrosion
3. The presence of loose abrasive particles

4. Cutting or ploughing of a soft material by a harder rough surface
5. Less common factors such as erosion, surface fatigue, etc.

Kislik (9) suggested the following wear mechanisms:

1. Mechanical destruction of interlocking asperities
2. A form of fatigue failure due to repeated mechanical interaction between asperities or to the variations in the pressure developed in the lubricant
3. Failure due to work-hardening and increasing brittleness caused by deformation
4. Flaking away of oxide films
5. Mechanical damage due to atomic or molecular interactions
6. Mechanical destruction of the asperities due to high temperature produced by frictional heating

Kostetski (10) suggests the following four processes occurring in the surface layers of metals under the action of frictional forces:

1. Oxidation wear, associated with the interaction between atmospheric oxygen and the surface layers

of the metal

2. Thermal wear
3. Abrasive wear
4. Wear by pitting

Of all the mechanisms listed above, abrasive wear is the most covered in research. This research makes use of the abrasive wear mechanism to relate the wear rate and wear coefficient of a test to a particle shape characterization factor.

Abrasive wear has many definitions. One is that abrasion is wear by displacement of material from surfaces in relative motion, caused by the presence of hard particles, either between the surfaces or embedded in one of them (11). Another is that abrasive wear of a surface is defined as material removal owing to sliding contact with abrasive particles or a rough surface (12). Still another is that abrasive wear occurs when there is friction between a metal or other material under stress and a harder body or grain (13). It is clear that abrasive wear is the process of material removal/dislocation due to some form of sliding contact under pressure.

Abrasive wear itself can be divided into a few separate types. Traditionally the abrasive wear process is

divided into two categories: two-body and three-body abrasive wear (14). Two body abrasive wear occurs when a rough surface or fixed abrasive particles slide across a surface to remove material and in three-body abrasive wear the particles are loose and may move relative one another and possibly rotate while sliding across the wearing surface (15). Misra and Finnie (16) also subdivide the three-body wear case in the following manner:

They offered the following definitions for the subdivisions. Open three-body abrasive wear occurs when the particle size is several times smaller than the distance between the surfaces. The gouging case of open three-body wear occurs when rocks or other coarse abrasive particles cut into a surface to remove relatively large amounts of material. High stress abrasion occurs where the abrasive is crushed in the wear process, while the low stress abrasion occurs when abrasive particles do not fracture during the wear process. Closed three-body abrasive wear occurs when loose abrasive particles are trapped between two sliding or rolling surfaces which are

separated by a gap which is the same size or smaller than the abrasive particles. The closed three-body abrasive wear case is the type of wear mechanism that is studied in this research.

Now that the concept of wear and its different mechanisms have been mentioned, it is time to discuss what happens at the surface level during wear. Most of the statements pertain to two-body abrasive wear but they can easily include the three-body case as well.

When real surfaces are pressed together they touch at a large number of high spots which deform elastically or plastically to form micro contact areas (17). Holm (18), in 1946, reached the following conclusions:

1. The real area of contact is formed by plastic deformation of contacting asperities.
2. Wear is caused by atomic interaction between the two surfaces.

Burwell and Strang (19) translated Holm's theory into macroscopic terms, assuming that wear occurs by the removal of particles rather than of individual atoms, and that interaction occurs between surface roughnesses rather than between atoms. In the three-body case the two surfaces do

not contact each other but rather contact an intermediate abrasive particle. The statement by Burwell and Strang holds true for the current research because particle sizes are much larger than the atomic scale of interaction that Holm referred to.

During the wear process, when the three bodies come into contact (without sliding) the abrasive particle pushes into at least one of the surfaces. The role of an abrasive is to concentrate stress on a wearing face and when such stress exceeds the strength of the surface the deterioration that is known as wear is engendered (20). The hardness of a material is clearly an important property in determining abrasive wear because it controls the depth of penetration of the abrading surfaces (21). Wear resistance is approximately proportional to the hardness of the metal (22). It is well known that wear resistance increases with hardness (23). In most experiments on two- or three-body abrasive wear the rough surface or particles are harder than the surface whose wear is being studied (24). This is to make sure that the surface being studied receives the most wear. However, abrasion wear occurs, although at a greatly reduced rate, even when the wearing surface is harder than the abrading material (24). It should be mentioned that the relative wear resistance of a material depends both on its hardness and on the nature of

interatomic bonds (25). That and other factors, such as surface profile, allow a softer body to wear a harder body.

The wear process tends to work-harden the surfaces involved as they interact. The wearing surface may, in fact, reach a limiting hardness for the material (26). It is at this point that any further action against the surface will no longer affect the hardness. However, the deduction that the surface hardens fully during wear is seen to be invalid when it is realized that a degree of alternating strain, applied by the abrading particles, could cause softening in a fully worked surface (26).

The fact that the hardness is involved in the wear process is a testament that plastic deformation is a major contributor to wear. Though abrasive wear occurs largely through plastic deformation, elastic properties must usually be involved in groove and chip formation, in a functionally different way from that already accounted for in the hardness (25). The material around the groove or chip area that was at first pushed to the sides will rebound elastically back into its original position. Another fact is that surface scratching itself does not cause wear (26). The material displaced from the scratch is not removed as chips but is mounded up, the scratches being produced in a manner similar to ploughing (26).

It has been stated that the main types of material displacement are groove and chip formation. The general consensus of researchers is that the type of displacement that occurs is dependent upon the orientation of the abrasive particle. Generally, material is removed from a surface by particles of abrasive that are suitably oriented to cut a chip, whilst other particles merely displace the material to form a groove (27). In fact it is a small minority of favorable oriented particles that cut a chip and the remainder rub a groove without displacing much material (28). One author writes that it seems that indentations into a surface occur when an abrasive is rolling on its sharp edge (29). This is an interesting concept, especially when spherical particles are used and they do not fracture.

Researchers have for many years tried to quantify abrasive wear data in the form of an equation. More than thirty years ago, Holm and then Archard derived an important wear model in a very simple form as

$$W_2 = \frac{K_2 \times W}{H} \quad (2.1)$$

where the wear rate W_2 (in^3/in or m^3/m) is proportional to

the normal load W (lbf or N), and inversely proportional to the material hardness H (psi or Pa) (30). The dimensionless proportional constant K_2 , known as the wear coefficient probability, can vary from $10E^{-1}$ to $10E^{-10}$ (in/in or m/m) (30). Although the idealized classical model of abrasive wear provides a qualitative basis it deviates from experimental results in two significant aspects: First, the predicted wear coefficient is at least an order of magnitude larger than experimentally observed values and it cannot predict the effect of grit size on wear and friction coefficients (31). Secondly, the problem with the equation is that it does not take into account factors such as particle shape and particle size. The equation assumes that the wear that occurs will be the worst case possible during the test. If the particles are less efficient at removing material then the wear coefficient will decrease. If the particles tend to break up during a test the severity of the wear will decrease and eventually so will the wear coefficient.

The three-body case of wear has an equation of its own to quantify wear data. The modified Archard equation, as it is known, for three-body wear is of the form

$$V = \frac{K_3 \times W \times L}{3 \times H} \quad (2.2)$$

where V is the volume of material lost from the surface, W is the normal load, L is the sliding distance, and H is the material hardness (1). K_3 is the dimensionless wear coefficient and the factor of 3 is added to the equation to account for the lower volume loss due to three-body wear. The K_3 in the modified Archard equation (2.1) and the K_2 in the Archard equation (2.2) are different. The Archard equation K_2 is more of a probability function and the K_3 in the modified Archard equation is a true constant for the wear process.

In research to date, no analysis has been done on how particle shape affects the results of wear tests. It is quite possible to have a constant number for a wear coefficient for three-body wear, and the particle shape factors and test conditions cause this number to vary. There has been research covering the hardness aspect of the particle and how it affects the test results, but no other parameters have been included in the analysis. The research being presented here tries to include the particle shape parameters in the wear analysis and see how they affect the results.

Chapter I-3 Three-body Wear Machine

The primary goal of this research was to develop a three-body wear test machine. This machine must have a sophisticated control system to allow precise speed sensing, force sensing, and very accurate control of spacing between a wear sample and moving surface. Other types of three-body wear machines used more of a forced two-body wear process and were not true three-body wear machines. This new machine has three distinct bodies: a wear specimen (first body), a rotating disk (second body), and abrasive particles (third body).

Development of the machine is divided into three distinct tasks. The first task is the manufacture of the three-body wear machine. The second task is the calibration of the machine. The last task concerns control of the machine during wear tests.

I-3.1 Three-body Wear Machine Development

I-3.1.1 Stand

The stand for the wear machine was designed to be very rigid and provide a mounting platform for various instruments used in the analysis. It must be mobile for

purposes of relocation of the machine but in the same sense it could not lose any of its rigidity. It also had to allow anchoring to any surface.

The design is a box style construction (see Fig. 3.1 and Fig. 3.2). It is constructed of 1 1/2" X 1 1/2" mild steel angle cut to length and welded together. The long legs have adjusters attached to their bottoms which allow leveling of the stand and the capability for the stand to be bolted to the floor.

The stand houses the main components of the machine. The small square box at one end is for the bearing housing of the spindle assembly. Eight set screws hold the housing in place and allow leveling of the spindle assembly separate from the stand leveling mechanism. The large open bay opposite the housing box is for the motor and upper tower. The motor sits near the bottom of the stand and is mounted rigidly to the lower two frame rails. The upper tower, which holds the positioning and force sensing systems, is mounted on the top of the stand, straddling the open space and positioned over the motor. It spans the width of the stand and provides extra strength and rigidity across the open bay. The light sensor circuit for the light chopper disk is mounted to the stand on the bottom rail to allow alignment of the disk and the circuit.

I- 3.1.2 Spindle and Bearing Housing

The spindle of the three-body wear machine supplies the relative motion needed between the three bodies involved. It must provide an accurate turning surface and give minimum deflection of the surface. For this reason the spindle was made stiff and massive. This also provides inertia to overcome any momentary loads on the surface that the motor could not match in torque.

The spindle is made of 1020 mild steel (see Fig. 3.3). It is a 10" long drive shaft with a 6" wide by 1 1/2" thick disk attached to it. The long shaft has two raised platforms for bearings. The bearings are Fafnir counterbore bearings, numbers 7306WN-DU and 7307WN-DU, with angular contact seats mounted in a dual opposing configuration. The top set takes the thrust load and the bottom set keeps alignment straight.

A finite element analysis was performed on the spindle using the SDRC I-DEAS package at West Virginia University. The analysis determined how far the disk would deform using a maximum normal test load (in this case 22 lb., limited because of the maximum load of the positioning system). The model was made of quadrilateral elements (see Fig. 3.4

and Fig. 3.5). Constraints were placed at the contact points of the bearings. A force of 22 lbs. was placed downward on the top surface of the disk over a 1" wide region at the outer edge of the disk. Results showed minimal stresses, and deflections approximately 100 times less than the 1-2 micron resolution that was desired (see Figs. 3.6, 3.7, 3.8, 3.9).

The bearing housing of the three-body wear machine keeps the spindle in position. It must match the stiffness of the spindle to hold it straight all throughout the test. It must also stay securely attached to the stand.

The housing is made of 1020 mild steel (see Fig. 3.10). The design complements the spindle so that the bearing races all line up. It has pilot holes drilled on its outside surface which mate with the set screws on the stand for secure mounting and leveling of the housing.

In order to provide a variety of tests between different metals, it was necessary to be able to change the disk surface metal and change the specimen metal. The change of specimen metals entailed the manufacture of new specimens of the different metal type. The disk surface, though, was more involved. The original surface was mild steel and the only way to change the surface metal was to

attach a different specimen plate or disk to the surface. A separate specimen disk was designed that would accomplish this task (see Fig. 3.11). The disk was made of the metal chosen for a test. The disk was actually larger in diameter than the spindle to allow the machining of four flat mounting points on the disk. Four rectangular tabs (see Fig. 3.12) were then bolted to these mounting points and the entire assembly was placed on the spindle. The disk was held in place on the spindle by set screws on the tabs that applied pressure to the side of the spindle. This works very well and does not turn on the spindle during high loads. The leveling method used for the disk is given in section 4.1.

A separate ring has been attached to the specimen disk that keeps particles on the disk during wear testing. Earlier tests showed the futility of trying to keep the particles on a flat surface that was turning. A deflector on the positioning system keeps the particles from conglomerating on the edge of this ring and pushes them back to the center. This deflection system allows crushed particles to roll past the deflector to the outer edge to keep them from stacking up under the specimens. There is at this time, however, no method to control the number of particles under the specimen.

I- 3.1.3 Motor

The motor for the three-body wear machine was chosen to meet three criteria. First, it must fit in the stand with no major modifications. Secondly, it had to have a variable speed range, attain the required speed quickly and maintain that speed. This meant a D.C. motor was preferred. Lastly, it had to provide enough drive power for the system.

The motor selected is the model 2Z846B adjustable speed permanent magnet D.C. motor from Dayton Electric Manufacturing Co. The motor runs on 120 volts A.C. which is rectified to a D.C. voltage. It supplies a constant torque up to 3/4 hp and has a speed range of 0 - 2500 rpm. With a 4:1 drive ratio this gives the spindle a range of 0 - 625 rpm.

The control system for the motor has several features. The power switch has forward, off, and reverse settings with a lockout to guard against instant direction reversal. The control panel also features a power on indicator light and an adjustable speed control knob. The controller has fused protection for the motor and controller, line voltage compensation, and transient surge protection. Another useful item is a soft start acceleration. This speeds the

motor up slowly to minimize jerk in the system. This is a very useful feature if the spindle surface is loaded with particles.

Power is transferred from the motor to the spindle via a pulley system. A 3" pitch diameter pulley is fastened to the motor with a tapered hub. A similar pulley, but with a 12" pitch diameter, is mounted with a similar hub to the spindle. A type-A drive belt is used to transfer power between the two. Tension in the belt is controlled by tightening or loosening of the motor mount bolts. The tension in the belt does not noticeably deform the stand. As long as the tension stays constant during a test run, the deformation will play no part in adding error to the analysis.

I-3.1.4 A/D Converter

The A/D converter chosen for the machine was selected to meet four criteria. First, the converter had to have at least 8 bit resolution. Second, it had to accept a signal that varied between ± 5 volts. Third, it had to have the ability to sample signals at up to 2000 conversions per sec. Lastly it had to provide input/output signals and voltages to run the light chopper assembly and signal conditioner.

The A/D converter system chosen for the wear machine was the DAS-8 Converter and Timer board assembly from Metrabyte, Inc. It is an 8-channel input A/D converter with 12 bit resolution. It allows ± 5 volt inputs on all channels and has a separate programmable timer circuit. It can be driven through GWBASIC to give up to 4000 conversions per second.

Also used to communicate with the A/D board is the STA-08 Screw Terminal Board. It is a separate box connected via a bus line to the main board. It has screw terminals for all input and output lines and houses a bread board which can be used to fabricate signal conditioning circuits.

I-3.1.5 Positioning System

The positioning system for the three-body wear machine had to meet very stringent requirements. It had to be accurate to ± 1 micron and be able to withstand forces that would be encountered during the wear test run. The system chosen was manufactured by Melles Griot. It is the Nanomover Advanced System package. This system is commonly used for positioning of optical instruments but it was modified for use on the wear machine.

The system employs a stepper motor which is controlled by a power chassis and computer input/output. The motor is capable of microsteps, very small and precise rotations of a 400-steps-per-revolution stepper motor operating at 10,000 microsteps per revolution (from the Melles Griot catalog). When attached to a precision micrometer screw, machined at 2 threads per mm, these microsteps give very accurate positioning control. The Nanomover motor, which is the assembly which houses the stepper motor and micrometer screw, is capable of 50 nanometer unidirectional resolution with ± 100 nanometer bidirectional repeatability. It has a travel range of 25 mm and 1 micron absolute accuracy. The motor can handle a 22 lb. load (any higher would damage the micrometer screw) which was used as the limiting factor for the entire machine. The motor is controlled by either the main menu driven control routine for the Nanomover or in GWBASIC via a user written basic program.

On the stand the Nanomover is attached to a translation stage. This stage is available from Melles Griot specifically made to mate with the motor. Normally this setup would be used to position pieces horizontally but for this use it is rotated up to give positioning accuracy vertically. A special z-motion adapter plate and

a right angle bracket was also purchased to allow this rotation. The adapter plate lends easy mounting of the stage in a vertical orientation. The bracket gives a horizontal surface to allow for mounting of specimens.

The rotation of the translation stage to a vertical orientation does pose one problem. The translation stage has internal springs that apply a force to preload the system and keep the stage in contact with the Nanomover motor at all times. The rotation lets the stage move down via its own weight and then it loses contact with the Nanomover and positioning accuracy is lost. A separate spring has been added to the end of the stage to allow preloading of the system and keep the stage and Nanomover in contact.

I- 3.1.6 Load Cell

The load cell setup for the three-body wear machine is such that it can measure both normal and frictional forces encountered in a wear test. Conventional load cells can measure only one force in one direction per cell. For this application, that would mean stacking two load cells on top of one another requiring too much space.

A custom designed load cell arrangement is used (see

Fig. 3.13 and Fig. 3.14). The base of the cell is made of billet aluminum. It is made with two thin arms to either side connecting the top and bottom halves. Due to the small cross section of the arms, small loads will be sensed in the load cell. The top and bottom edges of the load cell have extra material allow mounting of components. Four strain gauges are placed on the two strain arms of the cell (see Fig. 3.15). The placement of the gauges is very important for the ability to sense both force components. Each gauge on the cell has a set of three dummy gauges to complete the bridge for each of the four strain gauges. This gives four separate signals from the one load cell. By using two of the signals (gauges #1 and #2) it is possible to determine the force components because each responds differently to an applied load.

I-3.1.7 Light Chopper Disk

The light chopper disk of the three-body wear machine is used to read rotational velocity of the spindle. It needs to provide a steady signal to a circuit which calculates the velocity. The disk must be light, be easily mounted to the spindle assembly, and not impart an imbalance to the system.

The disk is made of aluminum plate which is 6" round

and 1/16" thick (see Fig. 3.16). It has 36 - 1/8" wide by 1/2" long slots cut radially inward from the edge of the disk. One slot has a length of 1" to mark an absolute zero position. The slots occur at every 10 deg. around the disk.

Straddling the disk is the light sensing circuit (see Figs.. 3.17, 3.18, 3.19). The circuit is composed of two infrared LED's (Light Emitting Diode) and two infrared light sensors. One set of the LED and light sensor pair is used for sensing of the short slots and the other pair is used for sensing of the one long slot. All the sensors and circuitry are fastened to a piece of aluminum which gives a steady mount that straddles the disk and helps to align and protect the sensors.

The circuit utilizes +5 volts and ground from the computer. The circuit delivers two signals which vary from +5 volts for an open slot and 0 volts elsewhere. The signal of the short slot is inverted and fed to the timer circuits of the A/D board where the velocity is calculated. The signal of the long slot is used to trigger the A/D conversion to read data from the load cell. The long slot signal also controls how fast the conversion of input data takes place.

I-3.1.8 Upper Tower

The upper tower of the three-body wear machine holds the load cell and positioning system (see Fig. 3.20). The tower itself must be very rigid and undergo small deflections during a test run. It is mounted to the stand in a way that allows alignment of all parts.

The backbone of the tower assembly is made up of 1 1/2" X 1 1/2" angle iron. It consists of a 20" long piece which straddles the open area of the stand and two uprights which angle up and inward from the back edge of the stand. A 3/8" aluminum plate is also used on the tower (see fig. 3.22). This plate is bolted to the long angle iron piece that straddles the stand on its lower end. Its upper edge is bolted to the uprights and positioned to make sure the plate is in a vertical position compared to the stand. Two more pieces of angle are bolted to the back of the plate to insure extra rigidity of the plate.

This now concludes the discussion of the components of the three-body wear machine. A view of the complete assembly is given in Figure 3.22.

I-3.2 Calibration

I-3.2.1 Force Calibration

The force sensing circuit uses two of the four strain gauges on the load cell, both on the same arm of the load cell. The A/D system has to read both gauges simultaneously at any time to get the unbalanced voltage in each bridge circuit. These voltages are then used in the force algorithm to resolve the normal and friction force components which are orthogonal to each other. In order to derive the force algorithm it is necessary to establish the strain gauge bridge amp response to a given force condition. This section deals with initial calibration of the force sensing circuit to associate the voltages from the gauges to a force.

The calibration of the force sensing circuit involved placing weights on the system to simulate loads. The loads must be oriented correctly to simulate the same type of loads that would act on the system as if a test was running. The loads were applied to the specimen mount to simulate a normal and frictional force. The loads that were placed directly above the mount simulated the normal force. A cable attached to the specimen mount pulled tangentially to the specimen face to simulate the friction

force.

Table 3.1 was produced to establish the relationship between forces and voltages. This table lists the type of load was present, normal and frictional, and the voltage resulting from each load combination. The load ranged from 0 to 25 pounds in 5 pound increments for both normal and frictional loads. 22 pounds is the limit for the normal load as that was the maximum that the Nanomover motor could experience, but 25 pounds was used and no problems developed with the motor.

Analysis was done to determine how much deflection would occur due to the loading of the load cell. The only load that caused concern was the normal load as it would affect the gap between the specimens. Table 3.2 shows the load and the deflection that was experienced. The analysis shows that the deflection of the setup is approximately 75 μm / lb. This number produces a dilemma. In order to sense small loads an extremely sensitive load cell is needed. An extremely sensitive load cell will give a good deal of deflection. The ultimate setup would be a totally rigid specimen but this will give no load sensitivity. On the other hand, too much sensitivity gives too much deflection. The deflection of the load cell, however, allows the wear to take place with less damage to the

particle which helps in determining the effect of particle shape on wear. Also, this is similar to the situation found in journal bearings.

1- 3.2.2 Speed Calibration

It is necessary during the wear tests to record the speed at which a test is occurring. This speed, when coupled with the time of the test, gives an accurate account of the sliding distance of the test. To record the speed of the spindle on the three-body wear machine it is necessary to get a signal from it that represents the speed at which it (the spindle) is turning. This signal comes from the light sensor circuit.

The signal from the light sensor circuit is a pulse of +5 volts for every time an open slot on the disk passes the sensors, which are above and below the disk. This signal is then run through an inverter which makes the signal a constant +5 volts with pulses down to 0 volts for each slot. This signal is run to the internal timer circuit of the A/D converter. It gives a timer count for the time the signal is high (+5 volts). This count corresponds to the time for one slot to pass the sensor and the next slot to enter.

The speed algorithm, which will be discussed later, was checked for different speeds. The spindle was cycled through different rpm ranges and the speed was calculated using the algorithm. Also the speed that was calculated was compared to that found using a stroboscope. Results agreed to within $\pm 5\%$, and at the actual test speed the error between the stroboscope and the algorithm was below $\pm 5\%$ error.

I-3.3 Control

Figure 3.23 shows a schematic of the systems controlled during a wear test run. Algorithms for the force and speed sensing are listed as well as the plan to control the positioning system. Each item is discussed in detail below.

I-3.3.1 Force Algorithm

As was mentioned previously, a table was constructed that showed how the simulation of normal and frictional loads upon the specimen mount affected the strain gauges. The unbalanced bridge voltages of gauges #1 and #2 are recorded in this table (table 3.1) due to the loads that are present.

In this table, there were two configurations that resulted which gave either a pure normal force or a pure friction force. The voltage versus force curves for the pure normal force load and the pure friction force load are presented in figures 3.24 and 3.25, respectively. The graphs show linear voltage response for a normal load but the voltage for the friction load has a great deal of error.

At this point a calibration again run in the friction force direction using from 0 to approximately 5 pounds. The results, seen in figure 3.26, show that the curves are linear but tend to separate as the load increases. At this point it was determined that the torque load that the friction force applies due to a moment arm was the factor that caused the separation. Another calibration was performed after moving the specimen mount to the center of the positioning system, the centerline of the load cell, and reapplying the load. The results, seen in figure 3.27, show that the curves are again linear and are on top of one another. The torque experienced in the first recalibration can be seen in figure 3.28. The torque and friction components can be added to give the curves shown in figure 3.26.

It is desirable to develop two equations to resolve

the normal and friction components from the voltages of the bridge amp circuits. Equations of the form

$$V_1 = a_{11} \times F_1 + a_{12} \times F_2 + a_{13} \times F_2 \quad (3.1)$$

$$V_2 = a_{21} \times F_1 + a_{22} \times F_2 + a_{23} \times F_2 \quad (3.2)$$

where

V_1, V_2 = Voltage from unbalanced bridge circuits
#1 and #2

F_1 = Normal force

F_2 = Friction force

$a_{11}, a_{21}, a_{12}, a_{22}$ = Constants

a_{13}, a_{23}

will be used for this analysis. The constants a_{ij} can be found by finding the slope of the line of the curve of voltage e_i versus force F_j . These constants are then of the form

$$a_{11} = \left(\frac{\partial V_1}{\partial F_1} \right)_{F_2 = \text{constant}} \quad (3.3a)$$

$$a_{21} = \left(\frac{\partial V_2}{\partial F_1} \right)_{F_2 = \text{constant}} \quad (3.3b)$$

$$a_{12} = \left(\frac{\partial V_1}{\partial F_2} \right)_{F_1 = \text{constant}} \quad (3.3c)$$

$$a_{22} = \left(\frac{\partial V_2}{\partial F_2} \right)_{F_1 = \text{constant}} \quad (3.3d)$$

$$a_{13} = \left(\frac{\partial V_1}{\partial F_2} \right)_{F_1 = \text{constant}} \quad (3.3e)$$

$$a_{23} = \left(\frac{\partial V_2}{\partial F_2} \right)_{F_1 = \text{constant}} \quad (3.3f)$$

Note that even though equations 3.3c,e and 3.3d,f are the same, the c and d equations are for give the constants for friction force and e and f are for the torque.

The slopes are found analytically using a least squares fit of the data. The values for these constants and their standard deviations are

$a_{11} = 0.066813$	$\sigma = 0.00013528$
$a_{21} = -0.065458$	$\sigma = 0.00005154$
$a_{12} = -0.020768$	$\sigma = 0.00018526$
$a_{22} = -0.021431$	$\sigma = 0.00020456$

$$a_{13} = -0.001598$$

$$\sigma = 0.00008524$$

$$a_{23} = 0.001598$$

$$\sigma = 0.00008524$$

Now that the constants are known, the forces can be found by manipulating the original equations to get

$$F_1 = \begin{pmatrix} \frac{v_1}{a_{12} + a_{13}} - \frac{v_2}{a_{22} + a_{23}} \\ \frac{a_{11}}{a_{12} + a_{13}} - \frac{a_{12}}{a_{22} + a_{23}} \end{pmatrix} \quad (3.4)$$

$$F_2 = \begin{pmatrix} \frac{v_1}{a_{11}} - \frac{v_2}{a_{21}} \\ \frac{a_{12} + a_{13}}{a_{11}} - \frac{a_{22} + a_{23}}{a_{21}} \end{pmatrix} \quad (3.5)$$

Table 3.3 shows the calculation of the forces from the voltage data of table 3.1 with comparisons to the original forces.

I-3.3.2 Speed Algorithm

The light chopper circuit gives one signal which goes through an inverter then into the internal timer circuit of the A/D system. The timer circuit yields a number that represents the counts reported to take the signal to go

from low to high to low again. This count is changed to a real time using the equation

$$\text{Period} = \text{Pulwid} * 0.41905 / 1000000! \quad (3.6)$$

where Pulwid is the count from the timer circuit between 0 and 65536. Period is in seconds and it is the time between slots on the disk.

It is now possible to find the velocity of the disk using the equation

$$\text{rpm} = ((0.5 / \text{Period}) * 60) / (3 * 2 * \pi) \quad (3.7)$$

The number 0.5 represents the space between the slots in inches. $(0.5 / \text{Period})$ gives the velocity of the disk in in./sec. The multiplication by 60 gives in./min. The division by $(3 * 2 * \pi)$ gives the final relation of rpm for the speed of the disk. This is now coupled with the time of the test and the radius of the testing surface in the equation

$$\text{SD} = \text{rpm} * (1 \text{ min} / 60 \text{ sec}) * 2 * \pi * (1.5 \text{ in}) * \text{time} \quad (3.8)$$

to give a sliding distance for the test.

I- 3.3.3 Positioning Control

This section deals with control of the positioning system. The Nanomover software allows control via GWBASIC for test runs and a separate menu driven program to aid in the positioning of the specimens. Positioning of the specimens entails moving the specimen down to the wear disk then retreating until the proper gap is achieved. Contact with the surface is confirmed by the A/D system; when the specimen touches the disk the force of the interaction shows up on the system.

After the specimen has been positioned the GWBASIC program WEAR7.BAS, written by the author and found in appendix B, is started. A subroutine in the program allows for repositioning of the specimen during a wear test. When the subroutine is started the latest file name is stored to the hard drive. The memory of the computer is then reset and addressed to run the positioning system. At this time the positioning system is ready to be moved.

The subroutine has two options at this point. It can be set up to ask for a distance to move and then move the motor or it can have a preset value for the motor to move. The first option is for the case when a particular setup is

in error and the specimen has to be repositioned. The second case is used for a long term test. After a few minutes in the test rig the surfaces actually have a larger gap between them than when they started due to the wearing of the specimens. For a long term test the gap could eventually open up enough to where there was no wear process occurring. So, in this case, the surfaces are brought nearer as the test progresses. The number used here is not arbitrary. Data was collected during the shorter length tests as to how much the height of the specimens changed between test runs. Now knowing an average change per unit time it was possible to move the specimen closer to the disk as a wear test was running with no user intervention.

After the system has finished moving, the program returns to the beginning. It is here that the A/D Converter is reinitialized. Also the last file name that was stored is read from the hard drive and the wear test is restarted where it left off.

The program which allows repositioning of the specimen during the test is called WEAR8.BAS. Because the test lengths were short for this research (20 and 30 minute runs) the program was not utilized. A few of the load plots showed that the load dropped off as time progressed

in the test. This showed that the squeeze effect of the particles wedging between the surfaces decreased as the surfaces became farther apart. This observation indicates that the WEAR8.BAS program could have been utilized for the tests but at the time that the first tests were being conducted it was not written. In order to keep the testing conditions similar the WEAR7.BAS program was kept in use.

FIG. I-3.1 SIDE VIEW THREE-BODY WEAR STAND

FIG. 1-3.2 TOP VIEW THREE-BODY WEAR STAND

FIG I-3.3 SPINDLE

FIG I-3.4 ELEMENTS, CONSTRAINTS, AND FORCES
FOR A STEEL SPINDLE

FIG I-3.5 ELEMENTS, CONSTRAINTS, AND FORCES
FOR AN ALUMINUM SPINDLE

FIG I-3.6 VON MISES STRESS PLOT FOR STEEL SPINDLE

FIG I-3.7 VON MISES STRESS PLOT FOR ALUMINUM SPINDLE

FIG I-3.8. DEFLECTION PLOT FOR STEEL SPINDLE

FIG I-3.9 DEFLECTION PLOT FOR ALUMINUM SPINDLE

FIG 1-3-10, BEARING HOUSING

FIG I-3.12 SPECIMEN DISK HOLDING TABS

[illegible]

FIG I-3.14 SIDE AND TOP VIEW OF LOAD CELL

FIG I-3.15 LOCATIONS OF STRAIN GAUGES

FIG I-3.16 LIGHT CHOPPER DISK

FIG I-3.18 SCHEMATIC OF LIGHT SENSING CIRCUIT

FIG I-3.18 SENSOR HOLDER

FIG I-3.19 LIGHT SENSING CIRCUIT

FIG I-3.20 . UPPER TOWER ASSEMBLY

FIG I-3.21 TOWER ALUMINUM PLATE

FIG 1-3.22 COMPLETE ASSEMBLY OF MACHINE

FIG I-3.23 CONTROL SYSTEM DIAGRAM

Fig. 1-3.24
Bridge Volt. vs. Normal Force

Fig. I-3.25
Bridge Volt. vs. Friction Force

Fig. 3.26
Bridge Volt. vs. Friction Load

Fig. I- 3.27
Bridge Volt. vs. Friction Load

Fig. 3.28
Bridge Volt. vs. Torq. Load

Table I-3.1 Calibration Table for Relationship of
Voltage versus Force for the Loadcell

Normal Force lbs	Friction Force lbs	Voltage #1 volts	Voltage #2 volts
0	0	-0.05072998	0.0446655
0	4.94	-0.1808066	-0.1668091
0	9.92	-0.2660279	-0.3065698
0	14.93	-0.2665821	-0.3115357
0	19.915	-0.3819775	-0.5076929
0	24.925	-0.3609741	-0.4786817
4.99	0	0.2760815	-0.2815112
4.99	4.94	0.1393677	-0.4999585
4.99	9.92	0.08936279	-0.5849195
4.99	14.93	0.03508057	-0.7005884
4.99	19.915	0.0265918	-0.7140283
4.99	24.925	-0.01875244	-0.7869556
9.95	0	0.6145947	-0.6059985
9.95	4.94	0.4784327	-0.8268823
9.95	9.92	0.3929883	-0.9741456
9.95	14.93	0.3815137	-0.9954908
9.95	19.915	0.264021	-1.203215
9.95	24.925	0.2689624	-1.197227
14.945	0	0.9490015	-0.9319751
14.945	4.94	0.8243164	-1.132778
14.945	9.92	0.7717432	-1.220125
14.945	14.93	0.7607398	-1.238489
14.945	19.915	0.6943653	-1.354993
14.945	24.925	0.6004712	-1.525635
19.94	0	1.281428	-1.258462
19.94	4.94	1.15406	-1.463557
19.94	9.92	1.075169	-1.597849
19.94	14.93	1.075129	-1.601802
19.94	19.915	0.9821045	-1.761494
19.94	24.925	0.9845581	-1.75958
24.94	0	1.611594	-1.589055
24.94	4.94	1.546028	-1.692988
24.94	9.92	1.488648	-1.794019
24.94	14.93	1.362744	-2.003596
24.94	19.915	1.3601	-2.007317
24.94	24.925	1.310767	-2.097615

Table I-3.2 Deflection of Test Apparatus versus Load Applied

Load lbs.	Deflection μm
0.0	0
0.22	15
0.44	15
0.66	16
0.88	17
1.10	17
1.32	15
1.54	17
1.76	17
1.98	15
2.20	17
2.42	16
2.64	17
2.86	18
3.08	17
3.30	16
3.52	15
3.74	17
3.96	17
4.18	17
4.40	18

Table I-3.3 Calculation of Calibration Forces
using Calibration Constants

Normal Force	Calc. Normal Force	Friction Force	Calc. Friction Force
0	0.0	0	0.0
0	-0.1146	4.94	10.49
0	-0.08865	9.92	17.11
0	-0.06624	14.93	17.28
0	-0.06971	19.915	26.69
0	-0.03178	24.925	25.18
4.99	4.924	0	0.1824
4.99	4.842	4.94	10.90
4.99	4.841	9.92	14.98
4.99	4.969	14.93	20.12
4.99	4.964	19.915	20.78
4.99	4.939	24.925	24.36
9.95	9.951	0	-0.03544
9.95	9.888	4.94	10.74
9.95	9.897	9.92	17.78
9.95	9.906	14.93	18.77
9.95	9.948	19.915	28.60
9.95	9.961	24.925	28.27
14.945	14.94	0	-0.08557
14.945	14.88	4.94	9.745
14.945	14.86	9.92	13.97
14.945	14.86	14.93	14.85
14.945	14.88	19.915	20.38
14.945	14.94	24.925	28.38
19.94	19.92	0	-0.06111
19.94	19.85	4.94	9.980
19.94	19.85	9.92	16.42
19.94	19.88	14.93	16.54
19.94	19.88	19.915	24.17
19.94	19.89	24.925	24.04
24.94	24.90	0	0.1557
24.94	24.86	4.94	5.275
24.94	24.88	9.92	10.06
24.94	24.85	14.93	20.19
24.94	24.84	19.915	20.38
24.94	24.88	24.925	24.60

Chapter I-4. Experimental Three-body Wear

The purpose of the experiments with the wear machine was to relate three-body wear data to shape characteristics of wear particles. This was done by running tests with various types of particles under controlled conditions. The particles were then analyzed using shape algorithms from Shuker (1989) to give shape characteristics. Details of all the tests and procedures are discussed below.

I-4.1 Experimental Setup and Procedure

The experimental method used for the three-body wear tests required careful preparations. First the specimens were prepared. They are made from 7/8" round stock brass. One end is turned down on a lathe and tapped with 1/4" - 20 threads. The opposite end, which is the wearing surface, is prepared in a mill. Using a fly-cutter tool the sample is passed under the tool with a low table feed rate. The surface that results is very smooth (29 μ in roughness) with any noticeable roughness visible only by microscope. The sample is now ready to be mounted to the positioning system.

The second step is the preparation of the specimen disk. The disk is usually new, but if it has been

previously used, the face will first be turned on a lathe to give a smooth surface (250 μ in roughness). The deflector and mounting tabs are now secured to the disk and the whole assembly is lowered onto the spindle. The disk is fastened to the spindle via the set screws in the mounting tabs. It is also shimmed up above the surface of the spindle to give room for leveling of the disk. The leveling of the disk refers to making the disk surface parallel to the wear specimen surface. Leveling of the disk is a tedious process. A pointer is attached to the positioning system. This pointer is brought down to near the disk surface and the disk is rough leveled by hand until little variation is seen in the gap between the pointer and the disk as the spindle is rotated. The actual variation in the surface is checked using the positioning system. It is nearly impossible to get the disk totally level. There is no ripple in the disk itself, but because there are four tabs to move the process results in a waviness of the wear surface of 30 microns. This is at least one order of magnitude less than the size of the particles. There is concern as to whether the waviness of the surface has affected the tests in any way but there is no way at the present time to address the problem as it was the best possible test conditions that could be produced.

The procedure for the testing was followed rigidly at

all times. All samples were prepared with a milled smooth surface unless they were in the second or later stages of testing. All particles entered onto the surface were fresh and unworn. All specimens were mounted on the rig and marked so they could be remounted in the same orientation to keep conditions the same for all the tests.

Test procedure:

1. The specimens are weighed in.
2. The specimens were mounted to the positioning bracket and marked so that the mounting position could be used again.
3. The specimens were then lowered to give a gap between the specimen and wear plate
4. The specimens were then worn for 20 minutes, or 30 minutes.
5. The specimens were weighed again to record a change in weight.
6. The test rig was cleaned and samples of particles and wear debris were collected and examined.
7. The specimen is now remounted in the stand and the process is repeated.

This procedure accounts for either an 80 or a 120 minute total time run for each separate specimen with 4 readings of its change of weight occurring at either 20 or 30 minute intervals. The only time the brass specimen has a smooth surface is the first time it enters the rig. After that test the specimen is remounted on the machine in

the same orientation, the gap between the surfaces is reset, and the wear test is restarted. This is to allow the wear process to continue where it left off. It is possible to do this because the particles that enter the gap are always fresh. The glass spheres, however, were used over because they encountered little or no damage.

The tests were run using three different types of particles. Particle types used were aluminum oxide, smooth glass spheres, and coal ash from Pittsburgh Seam coal burned in a hand fired furnace. All the particles were screened to be under 850 microns and over 300 microns in size. However, the effective particle sizes were much different. The effective size of the particle is the size that the particle acts as in a wear test, i.e. the particle may "stand up" during a wear test and act as a larger particle. Some of the particles that made their way through the sieves were long and thin, but when they reached the testing surface they acted as a much larger set of particles. That was the case with the aluminum oxide and coal ash particles. The smooth glass spheres all fit through the sieve but their effective size is smaller than the sieve. Also of importance is to note that, especially with the spheres, if the gap was placed to 850 microns no wear occurred. This is because the gap was too large to allow the three-body wear process to occur. This effect

was not noticed with the aluminum oxide particles, as their effective size was greater than 850 microns, but the coal ash acted much smaller despite their larger appearance. The aluminum oxide had an effective size of 1000 microns, the glass spheres were 800 microns and the coal ash particles were 300 microns.

Each particle type was run for four test sessions of 20 minutes each (80 minute total test) and also four test sessions of 30 minutes each (120 minute total test). At the end of each test the wear specimen was weighed and the stand cleaned off so as to introduce new particles instead of allowing old particles to contaminate the data. A Mettler H-80 balance was used for weighing of the samples. The balance gives weights to 0.1 mg accuracy, but, because the specimens were not degreased or ultrasonic cleaned the best accuracy that can be stated is 1 mg. The same balance was used for all the specimens.

I- 4.2 Wear Test Analysis

This section goes into detail concerning data obtained from each of the wear tests. Each particle type has a section devoted to it to describe the results that have been observed. Figures 4.1 to 4.4 show weight loss versus time, Figures 4.5 to 4.8 show wear coefficient versus time,

and Figures 4.9 to 4.12 show specific wear rates versus. time for each of the separate tests. Figures 4.13 to 4.40 show wear loads for all the specimens that were tested.

I-4.2.1 Smooth Glass Spheres

The smooth glass spheres used in testing were No. 8 calibration beads, nominal diameter of 841 to 210 microns. The particles were sieved to ensure that sizes between 850 to 300 microns were in each batch.

Observation of the disk and specimen after each test show a rolling type of motion. There were many indentations and gouges in the specimen but all of these had rolling marks leading up to their areas and their sides rounded off with no sharp protruding edges. Many areas could be observed where foil-like wear particles were ready to detach themselves from the specimen surface. Debris analysis showed the same style of particles. This type of wear has come to be known as delamination wear as described by Suh (33). In this type of wear the particles (either in a two- or three-body situation) will gouge the surface and produce a trough, with ridges to either side of the trough. As subsequent gouges occur along the length of the trough, the bulge of metal that was the ridge is slowly pushed and flattened out to the side. The result is a foil-like particle which eventually thins out along an edge and

breaks away as a wear particle to either leave the system or do damage elsewhere. Examination of the wear debris from the tests confirmed this type of wear with the presence of foil-like particles of brass. This process has been observed for all the brass specimens using the smooth glass spherical particles.

There were times when the entire surface of the specimen was not worn. The explanation for this is that the wear specimen and wear disk were not perfectly parallel. When this occurred a small crescent of little to no wear was observed. Most of the surfaces like this have three distinct regions. This first is where there seems to be little or no damage at all. The surface appears fresh with a few indentations and rolling marks scattered across this region. The second region has the entire area covered with rolling marks and indentations. The third region is the same as the second, but it has visible foil-like particles ready to become detached. Also visible in this region are areas where the debris has lifted off and the underlying surfaces have not been covered up again. The surface underneath appears very rough, even when compared to the worked upper surface. One possible explanation is that the particles smooth the upper surface while the debris scars the underlying material as it is stretched and flattened.

There is a question as to whether it is valid or not to use this data when a surface does not completely wear. Because this research is supposed to simulate actual conditions, it is hard to actually pinpoint whether this condition is valid. It is possible that in an actual wear condition this behavior will happen.

1-4.2.2 Aluminum Oxide Particles

The aluminum oxide particles were very coarse and hard. They were sieved between 850 and 300 microns. Observation of the particles under a microscope showed that the majority of the particles were polygonal in shape, with sharp, triangular asperities along the particles edges.

The particles severely wore the specimen surfaces that were tested. All of the specimens acquired a completely worn surface during the testing because of the severe wear. Gouges and scratches could be seen scattered across the surface. There is a lack of long wear tracks on the surface of the specimen which indicates that the particles tended to roll in the gap between the surfaces. Indentations into the surface were present over the entire surface. In these indentations were broken aluminum oxide particles. It appears that as the particles cut into the

surface the yield stress of the contacting asperities was exceeded and failure occurred. Some of these pieces of wear debris remained attached to the surface but the majority exited the wear system and rested on the outer edge of the wear disk. Fresh particles were always used for the tests so none of the wear debris that was collected could have come from the pre-test particles; all of the wear debris was a product of the tests and was not put into the system as dust on the particles.

Wear debris that came from the wear specimen was hard to find in the samples. Unlike the delamination wear, the aluminum oxide particles either gouged the surface or produced chips of brass. Most of the brass wear debris was very small. This is due to the size of the contacts that produced the debris. When a chip was formed, only the asperities of the particles would make contact with the surface. Therefore the cross-sectional area of contact was small. This, coupled with the fact that the gouges were short in length resulted in very small chips being produced. Wear debris also resulted from the indentations. This debris was the result of repeated plastic deformation of the surface; that is a fatigue failure. This debris was small and had the same shape of the aluminum oxide particles (there is no correlation here, just a description of the shape). This process resembles the delamination

wear process but is much different. Instead of the particles flattening the edges of the gouges the particles take the material and push it around into mounds. These are continuously worked until debris breaks off. This type of process was observed for all the specimens. At this point it is hard to establish which mechanism, the chip formation or the fatigue of the surface, contributed more to the metal removal process.

I-4.2.3 Coal Ash

The coal ash particles were flat in appearance. Like the other two particle types, these were sieved to be between 850 and 300 microns. A closer look at the particles showed them to be primarily porous in nature with interspersed particles of coke, flakes of limestone, and unburnt coal. The particles seemed large enough to use a larger gap between the specimen and disk but they were so soft and flat that they either broke up or slid through the test area. A 300 micron gap was finally chosen because the wear at this level resembled that of the other types of particles.

The specimen surface resembled that of the aluminum oxide wear specimens but at a much smaller scale. The surface appeared as though it merely had a film on it but a

microscopic examination revealed that the surface had indeed been worn. The severity was much less than both the aluminum oxide and quartz spheres. The mechanism of wear for the coal ash appears to be the same as was seen for the aluminum oxide. The surface shows many small indentations and scattered scratches across the specimen.

Fig. I-4.1

Weight Loss of Brass vs. Time

Aluminum Oxide Rough Particles

Fig. I-4.2

Weight Loss of Brass vs. Time

Smooth Glass Spheres

Fig. I-4.3

Weight Loss of Brass vs. Time

Coal Ash

Fig. I-4.4

Weight Loss of Brass vs. Time

Smooth Glass Spheres with a Brass Disk

Fig. I-4.5

Wear Coeff. of Brass vs. Time

Aluminum Oxide Rough Particles

Fig. 4.6

Wear Coeff. of Brass vs. Time

Smooth Glass Spheres

Fig. I-4.7
Wear Coeff. of Brass vs. Time

Coal Ash

Fig. I-4.8
Wear Coeff. of Brass vs. Time

Smooth Glass Spheres with a Brass Disk

Fig.I-4.9

Specific Wear Rate vs. Time

Aluminum Oxide Rough Particles

Fig. 4.10

Specific Wear Rate vs. Time

Smooth Glass Spheres

Fig. I-4.11

Specific Wear Rate vs. Time

Coal Ash

Fig. I-4.12

Specific Wear Rate vs. Time

Smooth Glass Spheres with a Brass Disk

Fig.I-4.13 Wear Loads, Specimen No. 22

Fig.14.14 Wear Loads, Specimen No. 23

Fig.1-4.15 Wear Loads, Specimen No. 24
Aluminum Oxide Rough Particles

Fig. 14.16 Wear Loads, Specimen No. 25

Fig.14.17 Wear Loads, Specimen No. 38

Fig. 14.18 Wear Loads, Specimen No. 39

Fig.I-4.19 Wear Loads, Specimen No. 40

Fig.14.20 Wear Loads, Specimen No. 41
Smooth Glass Spheres

Fig. I-4.21 Wear Loads, Specimen No. 54

Fig.1-4.22 Wear Loads, Specimen No. 55

Fig.14.23 Wear Loads, Specimen No. 56

Fig. 14.24 Wear Loads, Specimen No. 57

Fig. 14.25 Wear Loads, Specimen No. 70

Fig.14.26 Wear Loads, Specimen No. 71

Fig. 14.27 Wear Loads, Specimen No. 72

Fig.14.28 Wear Loads, Specimen No. 73

Fig. 14.29 Wear Loads, Specimen No. 86

Fig.1-4.30 Wear Loads, Specimen No. 87

Fig.14.31 Wear Loads, Specimen No. 88

Fig. 14.32 Wear Loads, Specimen No. 89

Fig.14.33 Wear Loads, Specimen No. 102

Fig. 14.34 Wear Loads, Specimen No. 103

Fig.1-4.35 Wear Loads, Specimen No. 104

Fig. 14.36 Wear Loads, Specimen No. 105

Fig.14.37 Wear Loads, Specimen No. 118

Quartz Spheres, Brass Disk

Fig.1-4.38 Wear Loads, Specimen No. 119

Fig. 14.39 Wear Loads, Specimen No. 120

Fig. 14.40 Wear Loads, Specimen No. 121

Weight Loss of Brass vs. Time

Coal Ash, 100 Micron Smaller Gap

FIG I-4.42

Weight Loss of Brass vs. Time

Blasting Sand

FIG I-4.43

Weight Loss of Brass vs. Time

Coal Ash, 200 Micron Smaller Gap

FIG I-4.44

Weight Loss of Brass vs. Time

—●— Sp. #1 —+— Sp. #2 —*— Sp. #3 —□— Sp. #4

Aluminum Oxide Particles with Brass Disk

FIG I-4.45

Wear Coefficient K Brass vs. Time

—•— Sp. #1 —+— Sp. #2 —*— Sp. #3 —□— Sp. #4

Coal Ash, 100 Micron Smaller Gap

FIG I-4.46

Wear Coefficient K Brass vs. Time

Blasting Sand

FIG I-4.47

Wear Coefficient K Brass vs. Time

Coal Ash, 200 Micron Smaller Gap

FIG I-4.48

Wear Coeff. of Brass vs. Time

Al. Ox. Rough Particles, Brass Disk

FIG I-4.49

Specific Wear Rate Brass vs. Time

Coal Ash, 100 Micron Smaller Gap

FIG I-4.50

Specific Wear Rate Brass vs. Time

Blasting Sand

FIG I-4.52

Specific Wear Rate Brass vs. Time

Coal Ash, 200 Micron Smaller Gap

FIG I-4.52

Specific Wear Rate vs. Time

Al. Ox. Rough Particles, Brass Disk

FIG I-4.53

Wear Loads for Test No. 134

Coal Ash, 100 Micron Smaller Gap

FIG I-4.54

Wear Loads for Test No. 135

Coal Ash, 100 Micron Smaller Gap

FIG I-4.55

Wear Loads for Test No. 136

Coal Ash, 100 Micron Smaller Gap

FIG I-4.56

Wear Loads for Test No. 137

Coal Ash, 100 Smaller Gap

FIG I-4.57

Wear Loads for Test No. 150

Blasting Sand, 20 Minute Test

FIG I-4.58

Wear Loads for Test No. 151

Blasting Sand, 20 Minute Test

FIG I-4.52

Wear Loads for Test No. 152

Blasting Sand, 20 Minute Test

FIG I-4.60

Wear Loads for Test No. 153

Blasting Sand, 20 Minute Test

FIG I-4.61

Wear Loads for Test No. 166

Coal Ash, 200 Micron Smaller Gap

FIG I-4.62

Wear Loads for Test No. 167

Coal Ash, 200 Micron Smaller Gap

FIG I-4.63

Wear Loads for Test No. 168

Coal Ash, 200 Micron Smaller Gap

FIG I-4.64

Wear Loads for Test No. 169

Coal Ash, 200 Micron Smaller Gap

FIG I-4.65

Wear Loads for Test No. 182

Aluminum Oxide, Brass Disk

FIG I-4.66

Wear Loads for Test No. 183

Aluminum Oxide, Braes Disk

FIG I-4.67

Wear Loads for Test No. 184

Aluminum Oxide, Brass Disk

FIG I-4.68

Wear Loads for Test No. 185

Aluminum Oxide, Brass Disk

Chapter I-5 Results

Comparisons are made here of the loads, change in volume, wear coefficients, specific wear rates, and particle shape factors. Analysis of the uncertainty of the results is presented for all the tests. Also included is a discussion of how the particle shape may be included in the wear equation.

I-5.1 Comparisons of Results

Tables 5.1 and 5.2 show average results from the series of tests. Each item is measured at the end of each time period. Because most of the tests used 20 and 30 minute time intervals a discussion will first be given about the comparison between the two test times for each particle type and then an overall comparison between all the runs will be given.

I-5.1.1 Aluminum Oxide Particles

Analysis of the tests run with aluminum oxide particles for the 20 and 30 minute tests showed that the loads for the tests were approximately the same. Sliding distances were different mainly because of the times involved in the tests. This was the same for all the tests

of all the particle types. In the aluminum oxide tests, the volume comparison showed that 20 and 30 minute tests both had approximately the same volume change. This manifested itself in the wear coefficients and rates. Consider the equations

$$K = \frac{3 \times V \times H}{W \times L} \quad (5.1) \quad \text{and} \quad WR = \frac{V}{W \times L} \quad (5.2)$$

where V is the volume, H is the hardness, resistance to penetration of an indenter into a surface, of the wear specimen, W is the load, L is the sliding distance, K is the wear coefficient and WR is the specific wear rate. It is seen that the V's and W's are nearly the same for all the tests with the only variable that changes being L, between the 20 and the 30 minute tests, K and WR are then smaller for the longer tests. Figures 4.23 and 4.24 show ramp patterns for the normal loads that show that the normal load decreased over time which explains why the normal load was lower than expected for the longer tests.

The cause for this appears to result from the wear-in process of the specimens. At the start of testing all the specimens were smooth. By the end of the second run all the specimens had their entire surface worn by the particles. It is the first two test sessions when the surfaces were being worn in that caused the difference. If

one set of specimens needed more material removed to get a worn surface than that would affect the cumulative volume loss. In these tests it appears that the specimens in the 20 minute tests needed more volume removed and in turn, at the end of the test series, showed the same volume loss as the 30 minute tests.

There is one way to account for this effect. Each specimen should be run on the machine until the entire surface is worn. It is at this point that testing should begin. This method would ensure that the wear-in procedure would not affect the results and that the surfaces are approximately parallel to each other.

One effect that may be a factor in the wear rates is the work-hardening of the materials. If the material becomes work-hardened, it will take more force to deform the surface and remove material. After the material reaches a certain hardness, it becomes brittle and takes less force to break away. This could be the case here in that the surface is being work-hardened and then does not suffer as much material loss. This effect must be studied by further research.

I-5.1.2 Smooth Glass Spheres

For these runs, the volume loss for the 30 minute tests was greater than the 20 minute tests. This was to be expected, as it was in the aluminum oxide tests but came to fruition in these tests. The loads of the two tests showed a great difference. The 20 minute test loads were 2 1/2 to 3 times less in magnitude than the 30 minute tests. This difference could be caused by several factors, two of which are the actual level of the wear disk and the misalignment of the disk and specimen. If the disk is out of level a high spot could cause a higher load to be induced to the surfaces because of the smaller gap. This load would occur each rotation of the disk. The impulse that this would create would affect the average load only slightly so this is dismissed as a major cause of the higher load. The misalignment would leave one edge of the specimen at a lower level than the gap that was set above the disk. The wedge effect of the surfaces could cause a higher load, especially if the specimens tended to be harder and not lose as much material during a test, or if as in the aluminum oxide tests the surfaces became work-hardened it would take much more load to cause wear to the surface.

Using the previous equations it can be seen that, because the load is so much greater, the wear coefficients

and wear rates will be much lower. This reinforces the statement that the specimens were more wear resistant. They were all prepared the same way so it has to be some metallurgical factor of those specific specimens.

I-5.1.3 Coal Ash

The loads from the coal ash tests started with a higher load, decreased to a low point past the middle point of the total run and then increased to a high load to finish the testing. The volume loss for the 30 minute tests was larger than the 20 minute tests. This was the pattern that was observed with the smooth glass spheres. Analysis of the wear rates and wear coefficients showed that the numbers from the 20 and 30 minute tests were approximately equal. This tends to lead one to believe that the tests progressed almost exactly the same. This was the only set of test results that behaved in this manner. A look at the wear equation shows that the resultant K and WR values become almost the same. This leads one to believe that the wear-in process was minimal with the coal ash.

I-5.1.4 Comparison of Results Between the Tests

In comparing results between the tests it is necessary

to note that all the tests were run in the same manner so that the comparison will be valid. The first comparison is for the sliding distance of the tests. The 20 and 30 minute tests all correlate very well with each other.

The loads of the tests showed great variation between the three particle types. The aluminum oxide particles showed the largest loads, approximately 1.6 lbf. The smooth glass spheres were next with averages of approximately .6 lbf for the 20 minute tests and .85 lbf for the 30 minute tests, both using the aluminum wear disk, and .6 lbf for the brass wear disk. There is no apparent answer as to why the averages between the 20 and 30 minute tests are so different. This author would say the answer is that the wear becomes more severe as the testing continues, the surface becomes more marked by troughs and indentations and the average load is increases likewise. This is a division factor of 3 to 5 less than the loads experienced by the aluminum oxide particles. This illustrates the severity of wear brought about by the highly angular particles. The coal ash tests showed loads a factor of 10 less than the smooth glass spheres, 20-50 times less than the aluminum oxide particles. Even though the coal ash is very angular it is also flat and does not do as much damage. The gap between the specimens may be a factor here. With a smaller (or larger) gap, there may be

more load subjected to the surfaces. Research is under way to verify this.

Volume loss was also markedly different between the three particle types. The aluminum oxide tests showed a total volume loss of 0.007 in^3 . The smooth glass spheres showed a total loss of 0.0003 and 0.0005 in^3 , somewhere between 12-20 times less than that found for the aluminum oxide particles. This also illustrates that the angular particles remove more material. The smooth glass sphere test with the brass disk showed a loss of 0.00016 in^3 . This is 40 times less than the aluminum oxide tests. It is believed that the softer brass disk is the primary reason for the difference in volume loss. The coal ash particles showed losses of 0.000045 and 0.000067 in^3 . This is 100 times less than the aluminum oxide particles. The coal ash does not wear as severe in a three-body wear situation as does the aluminum oxide. The reason for this is that the coal ash particles, though being very sharp, tend to fracture under load more readily than the aluminum oxide particles. This would cause a smaller load to act on the system. Again, the gap may be a factor here and it is being researched.

The wear coefficient for the aluminum oxide tests is 0.01 in/in . The smooth glass spheres show a wear

coefficient of 0.002 in/in and 0.001 in/in with 0.0007 in/in for the brass disk tests. The coal ash gives 0.002 in/in. As was expected the aluminum oxide particles gave the highest coefficient. The smooth glass spheres with the brass disk had the lowest because of the low volume loss and near average normal load.

The specific wear rate followed the same pattern as the wear coefficient. The aluminum oxide particles again showed the highest wear rate. The coal ash and smooth glass spheres were approximately the same. The smooth glass spheres with the brass disk was still lower than the other tests. The specific wear rate does not take into account the wear specimen's hardness so it is an empirical value. With the brass disk wear rate so much lower than the other tests it is obvious that the disk plays an important part in the test results.

I-5.1.5 Particle Shape Comparison

The particle shape characteristics used in this research were found using shape algorithms developed in research that is being conducted in conjunction with this work. Six different variables are used from a variety of algorithms. The variables are P2, P3, P4, 2DASP, FD, and NR. The P2, P3, and P4 variables are found using polygonal

harmonic analysis and represent the persistence of the 2nd, 3rd, and 4th harmonics which can represent the image. The persistence is the largest step length of a particular harmonic which can fit in an image divided by the smallest step length for the same harmonic. P2 is a line laid upon itself (a measure of elongation), P3 represents triangularity, and P4 represents closeness to a rhombus.

Most of the algorithms used for these shape factors were developed by Shuker (1989). The variable 2DASP is the two-dimensional aspect ratio of the image using the two-dimensional aspect ratio algorithm. The ratio is the longest diameter of the image divided by the longest chord orthogonal to the longest diameter. The variable FD represents the fractal dimension of the image. The fractal dimension is found using a Richardson log-log plot correlating step lengths of the sides of a polygon and the perimeter of the polygon. The fractal dimension is equal to one minus the slope of this plot. The last variable, NR, is the "Not-Roundness" of a particle.

A sample of 40 particles for each particle type was used for analysis. From this analysis an average value was calculated for each particle type. The results are presented in table 5.3.

In the testing, it was quite evident that the aluminum oxide and coal ash particles were "rough" when compared to the smooth glass spheres. The shape factors confirmed this because the numbers for the smooth glass spheres were considerably smaller for all six variables meaning it was very smooth. The aluminum oxide particles had lower P2, 2DASP, FD, and NR values than the coal ash. These numbers helped to confirm the statement that the coal ash was an elongated particle because P2 and 2DASP values were higher.

When comparing the wear rates of the three particles, the aluminum oxide was the most severe, followed by the coal ash then the smooth glass spheres. If the coal ash is elongated it stands to reason that it will do its maximum damage when the particle "stands-up" in the gap between the specimens and if the gap is large enough when the particle lays back down it will not react with the other surfaces. In the same sense, the aluminum oxide particles and smooth glass spheres would have more contacts with the surface over a period of time than the coal ash and have the ability to cause more damage. It is easy to see that the severity of wear should have the aluminum oxide particles ranked first, the small glass spheres second, and the coal ash last. The aluminum oxide is actually the most severe, so it remains first. The coal ash comes in second and the small glass spheres third because of the type of wear that

occurs. The spheres wear the surface by the delamination-fatigue process which takes longer and is not as severe as the gouging which is the process for the other particle types. The results of the tests and shape analysis help to confirm the discussion which was presented earlier and also help to prove that the rougher particles will help to produce a more severe wear process.

1-5.2 Uncertainty of Test Results

The accuracy of the numbers is the purpose of this section. The main analysis of the research deals with the wear equation

$$V = \frac{K \times W \times L}{3 \times H} \quad (5.3)$$

which gives the wear coefficient

$$K = \frac{3 \times V \times H}{W \times L} \quad (5.1)$$

To find the total uncertainty of K it is necessary to find the uncertainty of the variables in the equation.

The variable V represents the volume lost from the specimen in the equation. The balance that was used for

testing gives an uncertainty of ± 0.0005 grams, one half the least significant bit which is 0.001 gram, which translates to $\pm 3.57 \times 10^{-6} \text{ in}^3$. H is the hardness of the wear specimen. It is assumed constant for this analysis so no uncertainty will be ascribed to it. W is the normal load experienced by the wear specimen. It is given by the equation

$$F_n = \left(\frac{\frac{V_1}{a_{12} + a_{13}} - \frac{V_2}{a_{22} + a_{23}}}{\frac{a_{11}}{a_{12} + a_{13}} - \frac{a_{12}}{a_{22} + a_{23}}} \right) \quad (5.4)$$

which can be presented as

$$F_n = \frac{(A - B)}{(C - D)} \quad (5.5)$$

where

$$A = \frac{V_1}{a_{12} + a_{13}} \quad (5.6a)$$

$$B = \frac{V_2}{a_{22} + a_{23}} \quad (5.6b)$$

$$C = \frac{a_{11}}{a_{12} + a_{13}} \quad (5.6c)$$

$$D = \frac{a_{12}}{a_{22} + a_{23}} \quad (5.6d)$$

and

$$V_1 = a_1 \times 10 / 4096 \quad w_{V_1} = 0.00244 \text{ volts} \quad (5.7a)$$

$$V_2 = a_2 \times 10 / 4096 \quad w_{V_2} = 0.00244 \text{ volts} \quad (5.7b)$$

In order to find the uncertainty of the normal force it is necessary to take the partial derivative of each of the unknowns in the equation. This gives an equation of the form

$$w_{F_n} = \left[\left(\frac{\partial F_n}{\partial A} w_A \right)^2 + \left(\frac{\partial F_n}{\partial B} w_B \right)^2 + \left(\frac{\partial F_n}{\partial C} w_C \right)^2 + \left(\frac{\partial F_n}{\partial D} w_D \right)^2 \right]^{1/2} \quad (5.8)$$

where

$$\frac{\partial F_n}{\partial A} = \frac{1}{C - D} \quad (5.9a)$$

$$\frac{\partial F_n}{\partial B} = \frac{-1}{C - D} \quad (5.9b)$$

$$\frac{\partial F_n}{\partial C} = \frac{-(A - B)}{(C - D)^2} \quad (5.9c)$$

$$\frac{\partial F_n}{\partial D} = \frac{(A - B)}{(C - D)^2} \quad (5.9d)$$

The last task is to find the uncertainty of the variables A, B, C, and D. This is accomplished in the same manner as the normal force uncertainty equations which leads to the equations 5.10a through 5.10d

$$W_A = \left[\left(\frac{\partial A}{\partial V_1} W_{V_1} \right)^2 + \left(\frac{\partial A}{\partial a_{12}} W_{a_{12}} \right)^2 + \left(\frac{\partial A}{\partial a_{13}} W_{a_{13}} \right)^2 \right]^{1/2}$$

$$W_B = \left[\left(\frac{\partial B}{\partial V_2} W_{V_2} \right)^2 + \left(\frac{\partial B}{\partial a_{22}} W_{a_{22}} \right)^2 + \left(\frac{\partial B}{\partial a_{23}} W_{a_{23}} \right)^2 \right]^{1/2}$$

$$W_C = \left[\left(\frac{\partial C}{\partial a_{11}} W_{a_{11}} \right)^2 + \left(\frac{\partial C}{\partial a_{12}} W_{a_{12}} \right)^2 + \left(\frac{\partial C}{\partial a_{13}} W_{a_{13}} \right)^2 \right]^{1/2}$$

$$W_D = \left[\left(\frac{\partial D}{\partial a_{21}} W_{a_{21}} \right)^2 + \left(\frac{\partial D}{\partial a_{22}} W_{a_{22}} \right)^2 + \left(\frac{\partial D}{\partial a_{23}} W_{a_{23}} \right)^2 \right]^{1/2}$$

where

$$\frac{\partial A}{\partial V_1} = \frac{1}{a_{12} + a_{13}} \quad \frac{\partial A}{\partial a_{12}} = \frac{\partial A}{\partial a_{13}} = \frac{-V_1}{(a_{12} + a_{13})^2}$$

$$\begin{aligned}\frac{\partial B}{\partial V_2} &= \frac{1}{a_{22} + a_{23}} & \frac{\partial B}{\partial a_{22}} = \frac{\partial B}{\partial a_{23}} &= \frac{-V_2}{(a_{22} + a_{23})^2} \\ \frac{\partial C}{\partial a_{11}} &= \frac{1}{a_{12} + a_{13}} & \frac{\partial C}{\partial a_{12}} = \frac{\partial C}{\partial a_{13}} &= \frac{-a_{11}}{(a_{12} + a_{13})^2} \\ \frac{\partial D}{\partial a_{12}} &= \frac{1}{a_{22} + a_{23}} & \frac{\partial D}{\partial a_{22}} = \frac{\partial D}{\partial a_{23}} &= \frac{-a_{12}}{(a_{22} + a_{23})^2}\end{aligned}$$

(5.11a-d)

The values for a_{11} , a_{12} , a_{21} , a_{22} , a_{13} , a_{23} and the uncertainties for each are given below

$a_{11} = 0.066813$	$Wa_{11} = 0.00013528$
$a_{12} = -0.065458$	$Wa_{12} = 0.00005154$
$a_{21} = -0.020768$	$Wa_{21} = 0.00018526$
$a_{22} = -0.021431$	$Wa_{22} = 0.00020456$
$a_{13} = -0.001592$	$Wa_{13} = 0.00008524$
$a_{23} = 0.001598$	$Wa_{23} = 0.00008524$

The last variable needing analysis in the wear coefficient equation is L, or SD, the sliding distance. It is given by the equation

$$SD = rpm * \frac{1 \text{ min}}{60 \text{ sec}} * 2 * \pi * 1.5 * \text{time} \quad (5.12)$$

where

$$rpm = \frac{0.5}{\frac{PERIOD * 60}{3 * 2 * \pi}} \quad (5.13)$$

Period can be broken down to

$$PERIOD = \frac{PW * .41905}{1000000} \quad (5.14)$$

The term time in the SD equation is the absolute total time of the test, and PW is the average count returned by the A/D converter timer circuit of the pulse width of the signal returned from the slots on the light chopper disk. Substitution into the main equation gives

$$SD = \frac{\text{time} * 250000}{PW * .41905} \quad (5.15)$$

The uncertainty of SD can be found by using the same analysis that was performed on the normal force which in turn gives an equation of the form

$$W_{SD} = \left[\left(\frac{\partial SD}{\partial time} W_{time} \right)^2 + \left(\frac{\partial SD}{\partial PW} W_{PW} \right)^2 \right]^{1/2} \quad (5.16)$$

where

$$\frac{\partial SD}{\partial time} W_{time} = \frac{250000}{PW * .41905} \quad (5.17)$$

$$\frac{\partial SD}{\partial PW} W_{PW} = \frac{-time * 250000}{PW^2 * .41905} \quad (5.18)$$

and W_{time} and W_{PW} are the uncertainties of the variables time and PW. These values are

$$W_{time} = \pm 0.005 \text{ seconds}$$

$$W_{PW} = \pm 1 \text{ count}$$

Now that the uncertainties of all the variables are known the uncertainty equation for the wear coefficient equation can be developed. Using the same type of analysis as was used for the normal force and sliding distance, an equation is developed which is of the form

$$W_{K_3} = \left[\left(\frac{\partial K_3}{\partial V} W_V \right)^2 + \left(\frac{\partial K_3}{\partial W} W_W \right)^2 + \left(\frac{\partial K_3}{\partial L} W_L \right)^2 \right]^{1/2} \quad (5.19)$$

where

$$\frac{\partial K_3}{\partial V} W_V = \frac{1}{W * L} \quad (5.20)$$

$$\frac{\partial K_3}{\partial W} W_W = \frac{-V}{W^2 * L} \quad (5.21)$$

$$\frac{\partial K_3}{\partial L} W_L = \frac{-V}{W * L^2} \quad (5.22)$$

with W_V , W_W , and W_L being the uncertainties of V , W , and L respectively. The specific wear rate equation

$$WR = \frac{V}{W * L} \quad (5.2)$$

has the same style of uncertainty equation but of the form

$$W_{WR} = \left[\left(\frac{\partial WR}{\partial V} W_V \right)^2 + \left(\frac{\partial WR}{\partial W} W_W \right)^2 + \left(\frac{\partial WR}{\partial L} W_L \right)^2 \right]^{1/2} \quad (5.23)$$

where

$$\frac{\partial WR}{\partial V} W_V = \frac{1}{W * L} \quad (5.24)$$

$$\frac{\partial WR}{\partial W} W_W = \frac{-V}{W^2 * L} \quad (5.25)$$

$$\frac{\partial WR}{\partial L} W_L = \frac{-V}{W * L^2} \quad (5.26)$$

with W_V , W_W , and W_L remaining the same.

Table 5.3 gives a view of the values used for the uncertainty equations and table 5.4 gives a view of the actual numbers that resulted from the equations. The values used were from the first test run for each set of tests. The sliding distance equation shows the smallest error for the values used. The uncertainty of the force climbs as the magnitude of the force decreases. This is because the magnitude approaches that of the least significant bit of the A/D converter. This error, being the major one found in the equations, becomes the limiting factor for the rest of the analysis. The wear coefficients and specific wear rates both have higher uncertainty for the tests which have lower load.

For the test situations that were tried this higher error seems to be unavoidable. A quick look at the tables shows the highest error occurred during the ash tests. One way to correct this, or at least make the error lower, would be to induce a higher normal load on the test setup.

This requires closing the gap between the wear specimen and wear disk on the machine to bring about more loading of the surfaces. This would do two things; first, it would cause the normal load to rise, and second, it would cause more volume loss for the wear specimen. Research has been conducted to see if this approach works but no results are available at this time.

5.3 Wear Equation Development

Analysis has already been carried out using the Modified Archard Wear Equation

$$V = \frac{K \times W \times L}{3 \times H} \quad (5.3)$$

This equation functions independently of any test conditions and is used to quantify wear data. For instance, the hardness used in this equation is the hardness of the wear specimen. The equation disregards the hardness of the opposing metal and the abrasive. This is just one example of how the equation is lacking when it comes to a true representation of three-body wear.

The analysis which has been done so far has been to try to get results of three-body wear tests with different shape particles. This has been done to establish a

relationship between the results, such as wear coefficients and specific wear rates, and shape characteristics of the particles. This section discusses the redevelopment of the wear equation to include all the conditions of the tests and find where the shape factors should be introduced into the equation. The first thing to do is to discuss what conditions affect each of the variables in the wear equation.

Sliding distance is the easiest to visualize. It is dependent upon the velocity of the test and the total time. Sometimes the wear equation is presented using a velocity instead of a sliding distance to get a wear rate due to time, but for this analysis the sliding distance will be used.

Hardness, as was mentioned above is merely the hardness of the wear specimen in the wear equation. In actuality the hardness should be a function of the hardness of the wear specimen (H_{ws}), abrasive (H_a), and wear disk (H_{wd}). This gives

$$H = H (H_{ws}, H_a, H_{wd}) \quad (5.27)$$

where H is now an equivalent hardness taking into account all three bodies.

The volume for the equation is most often a measured

quantity, especially for testing purposes, but can be solved for to predict the volume loss. The volume is produced by measuring the mass loss of a specimen and converting this to a volume. In an actual test there is volume loss for the wear specimen, abrasive, and wear disk. This leads to an equation of the form

$$V = V (V_{ws}, V_a, V_{wd}) \quad (5.28)$$

which should appear as

$$V = V_{ws} + V_a + V_{wd} \quad (5.29)$$

where the volume loss is a function of the volume loss of the three bodies involved.

The load W involves the resistance of the materials to indentation of the abrasive into the respective surfaces. In the test situation there is a gap, h_{gap} , between the surfaces, and an effective particle size, D_{eff} , of the particles being used. In all three-body wear cases, $h_{gap} < D_{eff}$ to ensure that the wear process will occur. For ease of this theoretical analysis let the particle be spherical and undeformable. This means that if the particle is greater than the gap a spherical indentation will be placed into at least one of the surfaces. The load may now be

expressed as an equation of the form

$$W = W (D_{eff}, h_{gap}, E_1, E_2, E_3, \nu_1, \nu_2, \nu_3) \quad (5.30)$$

At this point a substitution is made of all the variables into the Modified Archard Wear equation and the equation is solved for the wear coefficient to give

$$K = \frac{3 V(V_{ws}, V_a, V_{wd}) H(H_{ws}, H_a, H_{wd})}{W(D_{eff}, h_{gap}, E_1, E_2, E_3, \gamma_1, \gamma_2, \gamma_3) L} \quad (5.31)$$

A few adjustments can now be made. The statement that the abrasive was undeformable leads to the assumption that it will not fracture to contribute to the wear debris. The spherical particles did not break apart so this assumption is seen to be valid. This lets the V_a term become zero. In the same manner, the H_a term can also be overlooked, because the particle is assumed to be undeformable so it has to be "infinitely" hard. The equation now appears as

$$K = \frac{3 V(V_{ws}, V_{wd}) H(H_{ws}, H_{wd})}{W(D_{eff}, h_{gap}, E_1, E_2, E_3, \gamma_1, \gamma_2, \gamma_3) L} \quad (5.32)$$

At this point a new three-body wear equation has been formulated which takes into account all the test parameters except the particle shape. In order to include the

particle shape factors in the equation it is important to find which variables are affected by the factors. It can be seen that the sliding distance, L , the wear specimen hardness, H_{ws} , and the wear disk hardness, H_{wd} , will not be affected by the particle shape as these variables are independent of the shape.

The volumes, V_{ws} and V_{wd} , will be affected indirectly in that the volumes may be greater/smaller due to the particle shape. For the load, all the variables in the equation would be the same and would not be affected "individually" by the shape factors. But the whole expression may be affected to give an equation of the form

$$K = \frac{3 V(V_{ws}, V_{wd}) H(H_{ws}, H_{wd})}{W(D_{eff}, h_{gap}, E_1, E_2, E_3, \gamma_1, \gamma_2, \gamma_3)^{s1} L} \quad (5.33)$$

Table I-51 Wear Test Results

	Time minutes	W lbs	hgap microns	L in	DV in ³	K	WR
ALOX20	20	1.697903	1000	12789.58	0.001789	0.011554	8.238367
	40	1.798488	1000	25859.75	0.003941	0.011884	8.473728
	60	1.821009	1000	38711.16	0.005881	0.011700	8.342628
	80	1.906326	1000	50011.85	0.00783	0.011518	8.212808
ALOX30	30	1.597038	1000	16753.3	0.001824	0.009562	6.817997
	60	1.632781	1000	32634.93	0.00369	0.009712	6.924935
	90	1.647357	1000	48541.02	0.005673	0.009950	7.094658
	120	1.62217	1000	64861.96	0.007748	0.010327	7.363820
QUSP20	20	0.244943	800	11654.89	0.000022	0.001123	0.800761
	40	0.237099	800	25257.2	0.000098	0.002308	1.646200
	60	0.323931	800	39151.93	0.000205	0.002273	1.620734
	80	0.39009	800	52216.72	0.000332	0.002289	1.632512
QUSP30	30	0.604471	800	15620.85	0.000038	0.000571	0.407737
	60	0.802786	800	31383.28	0.000162	0.000903	0.644001
	90	0.913474	800	47966	0.000325	0.001040	0.741743
	120	0.984036	800	63817.15	0.000507	0.001132	0.807743
ASH20	20	0.085395	300	10658.62	0.000012	0.001864	1.329388
	40	0.045141	300	21080.49	0.000021	0.003095	2.206822
	60	0.024155	300	32168.19	0.000037	0.006732	4.800374
	80	0.057036	300	43589.46	0.000045	0.002583	1.842192
ASH30	30	0.050278	300	15902.57	0.00001	0.001754	1.250704
	60	0.058616	300	31804.04	0.000025	0.001880	1.341039
	90	0.046584	300	48893.63	0.000045	0.002770	1.975711
	120	0.08551	300	65277.31	0.000067	0.001683	1.200316
QUSPBD20	20	0.530613	800	10388.64	0.000025	0.000636	0.453581
	40	0.568373	800	21013.43	0.000056	0.000660	0.471019
	60	0.604524	800	31879.35	0.000098	0.000718	0.512462
	80	0.629973	800	42540.86	0.000163	0.000855	0.609755
CASMGP20	20	0.191022	200	11958.38	0.000036	0.002214	1.579292
	40	0.159035	200	23168.94	0.000071	0.002712	1.933903
	60	0.164772	200	36320	0.000127	0.002980	2.124782
	80	0.143432	200	46749.82	0.000181	0.003787	2.700695
BLSND20	20	0.988323	400	10853.03	0.000496	0.006489	4.627038
	40	0.981909	400	25127.52	0.001052	0.005980	4.264105
	60	0.946216	400	37602.59	0.001691	0.006667	4.753911
	80	1.118361	400	48445	0.002617	0.006777	4.832093
CASMGP40	20	0.29267	100	11013.86	0.000086	0.003760	2.681587
	40	0.344399	100	21751.25	0.000189	0.003544	2.527089
	60	0.298619	100	32957.33	0.000290	0.004138	2.950612
	80	0.311187	100	44515.48	0.000415	0.004209	3.001327
ALOXBD20	20	1.129526	1000	11163.41	0.000859	0.009562	6.818343
	40	1.434648	1000	22060.90	0.002200	0.009749	6.951737
	60	1.523667	1000	32844.97	0.003543	0.009930	7.080456
	80	1.610687	1000	44119.97	0.005055	0.009978	7.114485

Table I-5.2 Shape Factors of the Test Particles

Shape Factors	Aluminum Oxide	Smooth Glass Spheres	Coal Ash
P2	1.363459	1.082357	1.681406
P3	1.160750	1.008608	0.876704
P4	1.099614	1.014876	1.082246
2DASP	1.280296	1.090985	1.630345
FD	1.017281	1.002226	1.060825
NR	0.085449	0	0.215569

P2 = Persistence of the 2nd harmonic

P3 = Persistence of the 3rd harmonic

P4 = Persistence of the 4th harmonic

2DASP = Two-dimensional aspect ratio

FD = Fractal dimension

NR = Not roundness

Table I-5.3 Values Used in the Error Analysis

	V1 volts	V2 volts	SD Sliding Distance	PULWID	TIME
1. ALOX20	0.124	-0.124	11755.38	61395	1209.75
2. ALOX30	0.102	-0.102	16487.99	63276	1748.77
3. QUSP20	0.0146	-0.0146	10708.85	60581	1087.44
4. QUSP30	0.0341	-0.0317	15718.82	63262	1666.82
5. ASH20	0.00732	-0.00488	10485.10	63228	1111.24
6. ASH30	0.00488	-0.00488	15860.95	63286	1682.53
7. QUSPBD20	0.0415	-0.0415	10282.76	63277	1090.64

	VOL	H
1.	0.001958	46750
2.	0.001977	46750
3.	0.000027	46750
4.	0.000035	46750
5.	0.000005	46750
6.	0.000010	46750
7.	0.000027	46750

Table 175.4 Error Analysis Results

	%Fn	%K	%WR
1. ALOX20	1.95	1.95	1.95
2. ALOX30	2.23	2.23	2.23
3. QUSP20	13.5	13.5	13.5
4. QUSP30	6.19	6.27	6.27
5. ASH20	36.1	36.6	36.6
6. ASH30	40.2	40.4	40.4
7. QUSPBD20	4.86	5.03	5.03

Chapter 1-6 Conclusions and Recommendations for Further Research

A three-body wear machine has been built and tested. The machine gives measurements of normal and frictional force loading upon a wear specimen. The forces that were measured were within $\pm 5\%$ experimental error with the higher load tests but this error increased as the intensity of the load decreased for different tests. This data, when combined with the hardness of the specimen, the sliding distance of the test, and the volume lost from the specimen, is used to calculate the wear coefficient K and the specific wear rate. The error of the wear coefficients and specific wear rates followed the errors found for the loads, i.e. varied from $\pm 5\%$ for the higher load tests to higher loads for the lighter load tests.

Three different particle types and two different test setups were used in the research. The particles used were aluminum oxide, smooth glass spheres, and coal ash from a hand fired furnace. Brass was used as the wear specimen and brass and aluminum were used as the wear disk materials. Results showed that the aluminum oxide particles were the most severe in wear of the specimen surface, followed by the coal ash then the smooth glass spheres. The aluminum oxide and coal ash wore the surface

via a gouging and rolling/scratching process but the coal ash damage was much less pronounced than the aluminum oxide damage. The smooth glass spheres wore the surface via a delamination fatigue process.

Shape characteristics were calculated using algorithms developed in the department. These factors showed that the aluminum oxide and coal ash could both be classified as "rough" with the aluminum oxide being "more round" and the coal ash "elongated". In testing the aluminum oxide and coal ash had higher wear coefficients and wear rates. This leads to the conclusion that the rougher the particle the more severe the wear will be.

The Modified Archard three-body wear equation was also re-evaluated. Factors uncommon to the original equation were included in this development equation. In addition this equation is presented with factors added that could act as the influence of the particle shape on the equation.

This initial research achieved its goals, but many factors can be improved. A new force sensing circuit must be constructed. The setup used was adequate but it allowed too much deflection of the system. A new setup with small deflections and a more accurate friction force sensing capability is feasible and has been discussed as an

alternative to the current setup.

Another suggestion is to use a 16-bit A/D converter board instead of the 12-bit board that was used for this research. This will increase the resolution in the load sensing circuit and make the load readings themselves more accurate which will in turn decrease the load error component, which is the limiting factor in the research.

The testing scheme can be restructured. A test matrix should be made where the height of the gap can be changed to see the affect on the test results. This matrix should be made for all the particle types, and also with two different disk materials being used. This data can be used in the re-Modified Archard equation to calculate the wear coefficient and the specific wear rate. At this point a regression analysis can be done to find out what affect the shape factors have on the equations and if it is possible to get one certain value for the wear coefficient K and have the test conditions affect its magnitude.

Appendix I-A

NOTE: All tests are run using an Aluminum Disk and Brass Specimens.

All test are run at room temperature and humidity.

Test #	Time	Weight Loss (grams)	Test Description	Results
1	60 min.	NA	1,11,31	1
2	65 min.	NA	1,11,31	1-4
3	90 min.	NA	1,11,31	1-5
4	30 min.	NA	4,14,31	1-5
5	NA	NA	1,12,13,31	6
6	NA	NA	2,12,32	7
7	NA	NA	3,12,13,32	7-9
8	NA	NA	3,12,13,32	7-9
9	NA	NA	3,12,13,32	7-9
10	30 min.	NA	1,15,16,11,31	1
11	30 min.	NA	4,11,31	1
12	30 min.	NA	5,17,11,32	10-12
13	15 min.	NA	1,22,32	12-14
14	20 min.	0.0379	1,23,32	12,13,15,16
15	20 min.	0.0711	1,23,32	12,13,15,16
16	20 min.	0.1600	1,23,32	12,13,15,16
17	20 min.	0.3428	1,23,32	12,13,15,16
18	33 min.	0.2024	1,24,32	12,13,15,16
19	33 min.	0.3141	1,24,32	12,13,15,16
20	33 min.	0.2734	1,24,32	12,13,15,16
21	33 min.	0.2365	1,24,32	12,13,15,16
22	20 min.	0.2734	1,23,32	12-14
23	20 min.	0.1743	1,23,32	12-14
24	20 min.	0.3456	1,23,32	12-14
25	20 min.	0.2083	1,23,32	12-14
26	20 min.	0.3944	1,23,32	12-14
27	20 min.	0.2335	1,23,32	12-14
28	20 min.	0.3164	1,23,32	12-14
29	20 min.	0.2611	1,23,32	12-14
30	20 min.	0.2551	1,23,32	12-14
31	20 min.	0.2863	1,23,32	12-14
32	20 min.	0.2785	1,23,32	12-14
33	20 min.	0.2661	1,23,32	12-14
34	20 min.	0.2670	1,23,32	12-14
35	20 min.	0.2324	1,23,32	12-14
36	20 min.	0.3507	1,23,32	12-14
37	20 min.	0.2413	1,23,32	12-14
38	20 min.	0.0038	6,23,31	17,1,3
39	20 min.	0.0044	6,23,31	17,1,3
40	20 min.	0.0028	6,23,31	17,1,3

41	20 min.	0.0018	6,23,31	17,1,3
42	20 min.	0.0108	6,23,31	17,1,3
43	20 min.	0.0204	6,23,31	17,1,3
44	20 min.	0.0044	6,23,31	17,1,3
45	20 min.	0.0068	6,23,31	17,1,3
46	20 min.	0.0175	6,23,31	14,1,3
47	20 min.	0.0175	6,23,31	18,1,3
48	20 min.	0.0142	6,23,31	14,1,3
49	20 min.	0.0107	6,23,31	14,1,3
50	20 min.	0.0265	6,23,31	14,1,3
51	20 min.	0.0193	6,23,31	18,1,3
52	20 min.	0.0101	6,23,31	14,1,3
53	20 min.	0.0152	6,23,31	14,1,3
54	30 min.	0.2768	1,24,32	15,12,13
55	30 min.	0.2905	1,24,32	15,12,13
56	30 min.	0.2604	1,24,32	15,12,13
57	30 min.	0.1939	1,24,32	15,12,13
58	30 min.	0.2109	1,24,32	12-14
59	30 min.	0.1898	1,24,32	12-14
60	30 min.	0.3595	1,24,32	12-14
61	30 min.	0.2844	1,24,32	12-14
62	30 min.	0.2542	1,24,32	12-14
63	30 min.	0.2780	1,24,32	12-14
64	30 min.	0.3067	1,24,32	12-14
65	30 min.	0.2718	1,24,32	12-14
66	30 min.	0.2976	1,24,32	12-14
67	30 min.	0.3395	1,24,32	12-14
68	30 min.	0.2779	1,24,32	12-14
69	30 min.	0.2467	1,24,32	12-14
70	30 min.	0.0049	6,24,31	17,1,3
71	30 min.	0.0071	6,24,31	17,1,3
72	30 min.	0.0051	6,24,31	17,1,3
73	30 min.	0.0047	6,24,31	17,1,3
74	30 min.	0.0178	6,24,31	18,1,3
75	30 min.	0.0170	6,24,31	18,1,3
76	30 min.	0.0199	6,24,31	18,1,3
77	30 min.	0.0145	6,24,31	18,1,3
78	30 min.	0.0159	6,24,31	18,1,3
79	30 min.	0.0230	6,24,31	14,1,3
80	30 min.	0.0280	6,24,31	14,1,3
81	30 min.	0.0241	6,24,31	14,1,3
82	30 min.	0.0211	6,24,31	18,1,3
83	30 min.	0.0246	6,24,31	14,1,3
84	30 min.	0.0268	6,24,31	14,1,3
85	30 min.	0.0297	6,24,31	14,1,3
86	20 min.	0.0008	7,23,33	16,13,19
87	20 min.	0.0020	7,23,33	16,13,19
88	20 min.	0.0015	7,23,33	16,13,19
89	20 min.	0.0025	7,23,33	16,13,19
90	20 min.	0.0007	7,23,33	16,13,19
91	20 min.	0.0009	7,23,33	16,13,19
92	20 min.	0.0009	7,23,33	16,13,19
93	20 min.	0.0025	7,23,33	16,13,19
94	20 min.	0.0013	7,23,33	16,13,19
95	20 min.	0.0030	7,23,33	16,13,19

96	20 min.	0.0017	7,23,33	16,13,19
97	20 min.	0.0031	7,23,33	16,13,19
98	20 min.	0.0016	7,23,33	16,13,19
99	20 min.	0.0017	7,23,33	16,13,19
100	20 min.	0.0004	7,23,33	16,13,19
101	20 min.	0.0011	7,23,33	16,13,19
102	30 min.	0.0014	7,24,33	16,13,19
103	30 min.	0.0016	7,24,33	16,13,19
104	30 min.	0.0009	7,24,33	16,13,19
105	30 min.	0.0022	7,24,33	16,13,19
106	30 min.	0.0020	7,24,33	16,13,19
107	30 min.	0.0022	7,24,33	16,13,19
108	30 min.	0.0017	7,24,33	16,13,19
109	30 min.	0.0021	7,24,33	16,13,19
110	30 min.	0.0024	7,24,33	16,13,19
111	30 min.	0.0027	7,24,33	16,13,19
112	30 min.	0.0036	7,24,33	16,13,19
113	30 min.	0.0027	7,24,33	16,13,19
114	30 min.	0.0026	7,24,33	16,13,19
115	30 min.	0.0029	7,24,33	16,13,19
116	30 min.	0.0036	7,24,33	16,13,19
117	30 min.	0.0032	7,24,33	16,13,19
118	20 min.	0.0039	6,23,31,34	18,1,3
119	20 min.	0.0032	6,23,31,34	18,1,3
120	20 min.	0.0042	6,23,31,34	18,1,3
121	20 min.	0.0027	6,23,31,34	18,1,3
122	20 min.	0.0035	6,23,31,34	18,1,3
123	20 min.	0.0038	6,23,31,34	18,1,3
124	20 min.	0.0063	6,23,31,34	18,1,3
125	20 min.	0.0039	6,23,31,34	18,1,3
126	20 min.	0.0067	6,23,31,34	18,1,3
127	20 min.	0.0052	6,23,31,34	18,1,3
128	20 min.	0.0067	6,23,31,34	18,1,3
129	20 min.	0.0052	6,23,31,34	18,1,3
130	20 min.	0.0077	6,23,31,34	18,1,3
131	20 min.	0.0092	6,23,31,34	18,1,3
132	20 min.	0.0100	6,23,31,34	18,1,3
133	20 min.	0.0093	6,23,31,34	18,1,3

Test Description Key

1. Start at 1000 microns.
2. Start at 600 microns.
3. Start at 850 microns.
4. Start at 1000 microns for 5 minutes.
5. Start at 2000 microns.
6. Start at 800 microns.
7. Start at 300 microns.

11. Move in 10 microns every 5 minutes.
12. Enter one particle at a time.
13. Lower the specimen as necessary.
14. Move to 850 microns.
15. Move to 850 microns for 5 minutes.
16. Move to 800 microns for 5 minutes.

17. Move to 1500 microns for 5 minutes.

21. Stay at 830 microns for 10 minutes.

22. Test for 4 cycles (A-D).

23. Test for 6 cycles (A-F).

24. Test for 9 cycles (A-I).

31. Used smooth glass spheres.

32. Used aluminum oxide particles.

33. Used coal ash.

34. Used brass wear disk

Results Description Key

1. Visible wear tracks and indentations.

2. Impacting of leading edges.

3. Visible platelets of brass in the wear debris.

4. No fracturing of test particles.

5. Wear mainly on the rear edge of the specimen.

6. Surface showed a pattern of divots along the path of travel of the particle.

7. Deep gouges were cut in both the disk and specimen.

8. Particle was found embedded in the brass specimen.

9. Particle fractured and traces could be seen in the brass specimen.

10. Severe wear of leading edge.

11. Very few visible tracks.

12. Broken particles visible.

13. Many directional scratches.

14. Entire surface worn.

15. Most of surface worn.

16. Large crescent with only minor indentations.

17. Large crescent unworn.

18. Small crescent still unworn.

19. Magnitude of wear appears small

Appendix 1-B

Wear7 program to find spindle rpm and read two strain gauges.

```

2      REM *** WEAR7.BAS
3      REM *** BY:  ROBERT JAMES
4      REM *** A/D AND POSITIONING PROGRAM
5      REM
6      REM
7      REM *** THIS SECTION SETS MEMORY AND BASE ADDRESS
8      REM
9      REM
10     CLEAR,49152
20     DEF SEG=0
30     SG=256*PEEK(&H511)+PEEK(&H510)
40     SG=SG+49152!/16
50     DEF SEG=SG
60     BLOAD"das8.bin",0
70     DEF SEG=SG
80     DAS8=0
81     REM
82     REM
83     REM *** THIS CALL WILL INITIALIZE THE ADC SYSTEM
84     REM
85     REM
90     MD%=0
100    D%=%H340
110    FLAG%=0
120    CALL DAS8(MD%,D%,FLAG%)
130    IF FLAG%<>0 THEN GOTO 60000
140    PRINT "THE ADC IS INITIALIZED"
150    REM
151    REM
152    REM *** THIS SECTION DIMENSIONS ALL USABLE ARRAYS
153    REM
154    REM
160    DIM LT%(2),D%(6),ARRAY%(1000),TRAN%(3),A(2000)
161    DIM A0(1000),A1(1000),X(20),FRQ%(2)
165    SCO=1
166    SCC=1
167    SCREEN 1,0
170    PRINT "ENTER A (1) TO MOVE THE NANOMOVER"
180    PRINT "ENTER A (2) TO TAKE DATA"
190    PRINT "ENTER A (3) TO QUIT"
200    INPUT Y
210    IF Y=1 THEN GOTO 50000
220    IF Y=2 THEN GOTO 500
230    IF Y=3 THEN GOTO 60000
240    GOTO 200
500    GOSUB 1000
510    GOSUB 5000
520    START=TIMER
530    FINISH=TIMER

```

```

540      DT=FINISH-START
550      IF DT<20 THEN GOTO 530
560      C$=INKEY$
570      IF C$="" THEN GOTO 500
580      INPUT "WISH TO CHANGE THE NANOMOVER POSITION";B$
590      IF B$="N" THEN GOTO 500
600      GOTO 210
978      REM
979      REM
980      REM *** THIS SECTION CALCULATES THE RPM OF THE
981      REM *** SPINDLE BY USING MODE 16 WHICH FINDS THE
982      REM *** PULSEWIDTH TO GET THE RPM.
983      REM
984      REM
1000     MD%=16
1010     PW%=0
1020     START1=TIMER
1021     START2=TIMER
1022     START3=TIMER
1023     START4=TIMER
1030     FLAG%=0
1040     CALL DAS8(MD%,PW%,FLAG%)
1050     IF FLAG%<>0 THEN GOTO 60000
1060     IF PW%<0 THEN PULWID=65536!+PW% ELSE PULWID=PW%
1070     IF PULWID<1000 THEN GOTO 1000
1080     PULWID=PULWID*.41905/1000000!
1090     PERIOD=PULWID
1100     VEL=((.5/PERIOD)/3)*60/6.28
1105     FINISH=TIMER
1110     PRINT PERIOD,VEL,FINISH-START
1120     START=TIMER
1150     RETURN
4978     REM
4979     REM
4980     REM *** THIS SECTION CONVERTS TWO CHANNELS ON A
4981     REM *** TRIGGER
4982     REM
5015     C=400
5020     LT%(0)=0
5030     LT%(1)=1
5040     GOSUB 11000
5050     GOSUB 15000
5060     CLS
5070     LINE(0,0)-(0,200),1
5080     LINE(0,100)-(350,100),1
5090     FOR T=1 TO C-1 STEP 2
5100     PSET(T*.5,100-ARRAY%(T)*1000/4096),2
5110     PSET(T*.5,100-ARRAY%(T+1)*1000/4096),3
5120     NEXT T
5125     FOR CO=1 TO 2000
5127     NEXT CO
5128     GOSUB 40000
5220     RETURN
10989    REM

```

```

10990      REM
10991      REM *** THIS SUBPROGRAM SETS CHANNEL SCAN LIMITS
10992      REM
10993      REM
11000      MD%=1
11010      FLAG%=0
11020      CALL DAS8(MD%,LT%(0),FLAG%)
11030      IF FLAG%<>0 THEN GOTO 60000
11040      RETURN
14989      REM
14990      REM
14991      REM *** THIS SUBPROGRAM READS THE A/D BOARD
14992      REM *** WHEN IT RECIEVES A TRIGGER, INCREMENTS
14993      REM *** THE CHANNEL, AND KEEPS READING UNTIL N
14994      REM *** COUNTS HAVE BEEN REACHED
14995      REM
15000      MD%=5
15010      TRAN%(0)=VARPTR(ARRAY%(0))
15020      TRAN%(1)=C
15030      FLAG%=0
15040      CALL DAS8(MD%,TRAN%(0),FLAG%)
15050      IF FLAG%<>0 THEN GOTO 60000
15180      RETURN
40000      IF SCO=1 THEN GOTO 40020
40010      GOTO 40040
40020      A$="A"
40030      SCO=SCO+1
40040      OPEN A$ FOR OUTPUT AS #1
40045      PRINT A$
40046      PRINT #1,VEL,TIMER
40050      FOR T=1 TO C-1 STEP 2
40060      PRINT#1,ARRAY%(T),ARRAY%(T+1)
40070      NEXT T
40080      CLOSE#1
40090      A$=A$+"Z"
40100      IF LEN(A$)<=8 THEN GOTO 40900
40110      IF SCO=2 THEN A$="B"
40120      IF SCO=3 THEN A$="C"
40130      IF SCO=4 THEN A$="D"
40140      IF SCO=5 THEN A$="E"
40150      IF SCO=6 THEN A$="F"
40160      IF SCO=7 THEN A$="G"
40170      IF SCO=8 THEN A$="H"
40180      IF SCO=9 THEN A$="I"
40190      IF SCO=10 THEN A$="J"
40200      IF SCO=11 THEN A$="K"
40210      IF SCO=12 THEN A$="L"
40220      IF SCO=13 THEN A$="M"
40230      IF SCO=14 THEN A$="N"
40240      IF SCO=15 THEN A$="O"
40250      IF SCO=16 THEN A$="P"
40260      IF SCO=17 THEN A$="Q"
40270      IF SCO=18 THEN A$="R"
40280      IF SCO=19 THEN A$="S"

```

```

40290      IF SCO=20 THEN A$="T"
40300      IF SCO=21 THEN A$="U"
40310      IF SCO=22 THEN A$="V"
40320      IF SCO=23 THEN A$="W"
40330      IF SCO=24 THEN A$="X"
40340      IF SCO=25 THEN A$="Y"
40350      IF SCO=26 THEN A$="Z"
40360      SCO=SCO+1
40900      RETURN
49988      REM
49989      REM
49990      REM
49991      REM *** THIS SUBPROGRAM CONTROLS THE POSITIONING
49992      REM *** SYSTEM, THE NANOMOVER MOTORS
49993      REM
49994      REM
50000      REM
50001      REM
50002      REM *** THESE LINES SET UP THE MEMORY AND
50003      REM *** ADDRESS SEGMENTS FOR THE NANOMOVER
50004      REM *** CONTROL SYSTEM
50005      REM
50008      Z=0
50010      CLS
50020      DEF SEG=0
50030      NANOMOVE=PEEK(320)+PEEK(321)*256
50040      NANOSEG=PEEK(322)+PEEK(323)*256
50050      NANOPOS=PEEK(324)+PEEK(325)*256
50060      NANOSTAT=PEEK(326)+PEEK(327)*256
50070      NANOPARM=PEEK(328)+PEEK(329)*256
50080      DEF SEG
50090      GOTO 50310
50094      REM
50095      REM
50096      REM *** THIS SUBROUTINE CHECKS THE POSITION OF
50097      REM *** THE NANOMOVER TRANSLATION STAGE
50098      REM
50099      REM
50100      GOSUB 50220
50110      IF (STATUS AND MOVING)=MOVING THEN GOTO 50100
50120      DEF SEG=NANOSEG
50130      CALL NANOPOS(AXIS,POSITION)
50140      DEF SEG
50150      RETURN
50154      REM
50155      REM
50156      REM *** THIS SUBROUTINE MOVES THE TRANSLATION
50157      REM *** STAGE
50158      REM
50159      REM
50160      GOSUB 50220
50170      IF (STATUS AND MOVING)=MOVING THEN GOTO 50160
50180      DEF SEG=NANOSEG
50190      CALL NANOMOVE(AXIS,DISTANCE)

```

```

50200 DEF SEG
50210 RETURN
50214 REM
50215 REM
50216 REM *** THIS SUBROUTINE CHECKS THE STATUS OF THE
50217 REM *** NANOMOVER TRANSLATION STAGE
50218 REM
50219 REM
50220 DEF SEG=NANOSEG
50230 CALL NANOSTAT(AXIS,STATUS)
50240 DEF SEG
50250 RETURN
50254 REM
50255 REM
50256 REM *** THIS SUBROUTINE IS USED TO STOP THE
50257 REM *** NANOMOVER MOTORS AND MODIFY PARAMETERS
50258 REM
50259 REM
50260 DEF SEG=NANOSEG
50270 CALL NANOPARM(AXIS2STOP,STOPMOTORS,STOPALL)
50280 DEF SEG
50290 PRINT "SPACEBAR HAS BEEN PRESSED: STOPPING MOTORS"
50300 END
50304 REM
50305 REM
50306 REM *** THESE LINES SET UP THE STATEMENTS NEEDED
50307 REM *** TO STOP THE NANOMOVER MOTORS
50308 REM
50309 REM
50310 AXIS2STOP=1
50320 STOPMOTORS=0
50330 STOPALL=0
50340 MOVING=1
50350 KEY 15,CHR$(0)+CHR$(57)
50360 ON KEY(15) GOSUB 60000
50370 KEY(15) ON
50374 REM
50375 REM
50376 REM *** THESE LINES ALLOW MOTION OF THE NANOMOVER
50377 REM *** AND THEN RETURNS TO THE BEGINNING OF THE
50378 REM *** PROGRAM
50379 REM
50380 AXIS=1
50390 INPUT "ENTER INITIAL MOVEMENT";X
50400 DISTANCE=X
50410 GOSUB 50160
50420 GOSUB 50100
50430 PRINT "POSITION=";POSITION
50440 INPUT Y
50450 GOTO 10
60000 END

```

Appendix I-C

FORCE3 program to find forces from voltage data of the load cell.

```
CLS
SCREEN 9
WINDOW (0,-240)-(640,240)

DIM A1(200),A2(200)

5   READ B$

    PRINT B$

    IF B$ = "END" THEN BEEP:END

    PRINT "          BEGINNING FIRST PART"

    A$ = "A"
    SCO = 1

10  OPEN "A:\WT" + B$ + "DAT\" + A$ FOR INPUT AS #1
    OPEN "C:\NAN" + A$ FOR OUTPUT AS #2

    INPUT #1, A, B

' READ DATA GIVING ADC CODES FOR GAUGE #1 AND GAUGE #2

    FOR T = 1 TO 200
        INPUT #1, A1(T) A2(T)
' CONVERT A1 AND A2 TO VOLTAGES AND THEN RESOLVE INTO FORCES
        V1 = A1(T) * 10 / 4096
        V2 = A2(T) * 10 / 4096
        A11 = 6.681377E-02
        A21 = -6.545844E-02
        A12 = -2.076866E-02
        A22 = -2.143152E-02
        A13 = -1.598472E-03
        A23 = 1.598472E-03
        FY = (V1/(A12+A13)-V2/(A22+A23)) /
              (A11/(A12+A13)-A21/(A22+A23))
        FX = (V1/A11-V2/A21) / ((A12+A13)/A11-(A22+A23)/A21)

15      PRINT #2, FY, FX
    NEXT T

    CLOSE #1
    CLOSE #2

' FILE NAME CHANGING SUB-ROUTINE

    V = LEN(A$)
```



```

    IF V = 8 THEN GOTO 20

    A$ = A$ + "Z"

    GOTO 10

20   SCO = SCO + 1
    IF SCO = 10 THEN GOTO 100
    IF SCO = 2 THEN A$ = "B"
    IF SCO = 3 THEN A$ = "C"
    IF SCO = 4 THEN A$ = "D"
    IF SCO = 5 THEN A$ = "E"
    IF SCO = 6 THEN A$ = "F"
    IF SCO = 7 THEN A$ = "G"
    IF SCO = 8 THEN A$ = "H"
    IF SCO = 9 THEN A$ = "I"

    GOTO 10

'SUB-ROUTINE FOR FINDING MAX., MIN., AND AVG. FORCE VALUES

100  DIM F1(200), F2(200)
    PRINT "                                BEGINNING SECOND PART"

    A$ = "A"
    SCO = 1

110  OPEN "D:\WT" + B$ + "1.DAT" FOR OUTPUT AS #2
    OPEN "D:\WT" + B$ + "2.DAT" FOR OUTPUT AS #3

115  OPEN "C:\NAN\" + A$ FOR INPUT AS #1

    FOR T = 1 TO 200
        INPUT #1, F1(T), F2(T)
    NEXT T

    CLOSE #1

    X1MIN = 100
    X1MAX = -100
    X2MIN = 100
    X2MAX = -100
    SUM1 = 0
    SUM2 = 0

    FOR T = 1 TO 200
        IF F1(T) < X1MIN THEN X1MIN = F1(T)
        IF F1(T) > X1MAX THEN X1MAX = F1(T)
        IF F2(T) < X2MIN THEN X2MIN = F2(T)
        IF F2(T) > X2MAX THEN X2MAX = F2(T)
        SUM1 = SUM1 + F1(T)

```

```

        SUM2 = SUM2 + F2(T)
NEXT T

AVG1 = SUM1 / 200
AVG2 = SUM2 / 200

PRINT #2, X1MAX, X1MIN, AVG1
PRINT #3, X2MAX, X2MIN, AVG2

V = LEN (A$)

IF V=8 THEN GOTO 120

A$ = A$ + "Z"

GOTO 115

'FILE NAME CHANGING SUB-ROUTINE

120  SCC = SCO + 1
      IF SCO = 10 THEN GOTO 200
      IF SCO = 2 THEN A$ = "B"
      IF SCO = 3 THEN A$ = "C"
      IF SCO = 4 THEN A$ = "D"
      IF SCO = 5 THEN A$ = "E"
      IF SCO = 6 THEN A$ = "F"
      IF SCO = 7 THEN A$ = "G"
      IF SCO = 8 THEN A$ = "H"
      IF SCO = 9 THEN A$ = "I"

      GOTO 115

200  CLOSE #2
      CLOSE #3

      GOTO 5
DATA  "192","193","194","195"
DATA  "END"

```

Appendix I-D

LOADGET program to find the average load of a test run.

```
CLS
SCREEN 9
WINDOW (0,0)-(640,480)

DIM F1(200), F2(200), F3(200), F4(200), F5(200), F6(200)

F1= 48

5   INPUT B$

OPEN "D:\WT" + B$ + "1.DAT" FOR INPUT AS #1
OPEN "D:\WT" + B$ + "2.DAT" FOR INPUT AS #2

'INPUT MAX., MIN., AND AVG. FORCE VALUES

FOR X = 1 TO F1
    INPUT #1, F1(X), F2(X), F3(X)
    INPUT #2, F4(X), F5(X), F6(X)
NEXT X

CLOSE #1
CLOSE #2

SUM1 = 0
SUM2 = 0

FOR X=1 TO F1
    SUM1 = SUM1 + F3(X)
    SUM2 = SUM2 + F6(X)
NEXT X

AVG1 = SUM1 / F1
AVG2 = SUM2 / F1

PRINT B$, AVG1, AVG2

GOTO 5
```

Appendix I-E

SLIDDIST program to find the sliding distance of a test run.

```
CLS
SCREEN 9
WINDOW (0,0)-(640,480)

DIM A1(200), A2(200)

PI = 3.141592654#

5   INPUT B$

SUM = 0

A$ = "A"
X = 0
SCO = 1

'INPUT AND SUM VELOCITY VALUES FROM FILE DATA

10  OPEN "D:\WT" + B$ + "DAT\" + A$ FOR INPUT AS #1

    INPUT #1, A, B
    X = X + 1
    SUM = SUM + A

    CLOSE #1

'FILE NAME CHANGE SUB-ROUTINE

15  V = LEN(A$)

    IF V = 8 THEN GOTO 20

    A$ = A$ + "Z"

    GOTO 10

20  SCO = SCO + 1
    IF SCO = 7 THEN GOTO 100
    IF SCO = 2 THEN A$ = "B"
    IF SCO = 3 THEN A$ = "C"
    IF SCO = 4 THEN A$ = "D"
    IF SCO = 5 THEN A$ = "E"
    IF SCO = 6 THEN A$ = "F"
    IF SCO = 7 THEN A$ = "G"
    IF SCO = 8 THEN A$ = "H"
    IF SCO = 9 THEN A$ = "I"

    GOTO 10
```

```

'SUB-ROUTINE TO FIND TOTAL TEST TIME AND TOTAL
' SLIDING DISTANCE

100 OPEN "D:\WT" + B$ + "DAT\A" FOR INPUT AS #1
    OPEN "D:\WT" + B$ + "DAT\FZZZZZZZ" FOR INPUT AS #2

    INPUT #1, A, B
    INPUT #2, C, D
    CLOSE #1
    CLOSE #2

    DTIME = D - B

    PRINT (SUM / 48), (SUM / 48) * DTIME / 60
    PRINT ((SUM / 48) * DTIME / 60) * 2 * PI * 1.5

    GOTO 5

```

References

1. J.F.Archard, Contact and Rubbing of Flat Surfaces, J. Appl. Phys., 24 (1953), pp. 981-988.
2. D.Weibull, M.A.Clerc, C.Ragues-Carnes, M.Barquins, Three-dimensional Quantification of Wear Tracks on Amorphous NiB Coatings, WEAR, 107 (1986), pp. 263-278.
3. J.Halling, Principles of Tribology, MacMillan Press Ltd. London, 1975, pp. 94-127.
4. J.Halling, Principles of Tribology,
Cited From -
I.V.Kragelskii, Friction and Wear, Butterworths, London, 1965.
5. I.V.Kragelskii, Friction and Wear, Butterworths, London, 1965, pp. 111-137,
Cited From -
P.A.Rebinder, Izd. Akad. Nauk SSSR, ser. khim. No. 5 (1936), p 637.
6. See #2
7. J.Halling, Principles of Tribology,
Cited From -
J.T.Burwell, Survey of Possible Wear Mechanisms, WEAR, 1 (1957), pp. 119-141.
8. I.V.Kragelskii, Friction and Wear,
Cited From -
J.T.Burwell, C.D.Strang, Metallic Wear, Proc. R. Soc. A212 (1952), p. 470.
9. I.V.Kragelskii, Friction and Wear,
Cited From -
V.A.Kislik, The Wear of Railway Engine Components, Trans-heldorizdat, 1948.
10. I.V.Kragelskii, Friction and Wear,
Cited From -
B.I.Kostetskii, Friction and Wear Phenomena in Machine Parts, Con. 'Friction and Wear in Machines' 4, Izd. Akad. Nauk SSSR (1957), p. 201.
11. K.H.Zum Gahr, Formation of Wear Debris Due to Abrasion, Wear of Materials Conference, April 1981, pp. 396-405.

12. A.Misra, I.Finnie, An Experimental Study of Three-Body Abrasive Wear, WEAR, 85 (1983), pp. 57-68.
13. M.M.Khrushchov, Principles of Abrasive Wear, WEAR, 28 (1974), pp. 69-88.
14. See #12
15. See #12
16. J.L.Xuan, I.T.Hong, E.C.Fitch, Hardness Effect on Three-Body Abrasive Wear Under Fluid Film Lubrication, Transactions of the ASME Journal of Tribology, vol. 111, January 1989, pp. 35-40.
17. J.I.McCool, Comparison of Models for the Contact of Rough Surfaces, WEAR, 107 (1986), pp. 37-60.
18. I.V.Kragelskii, Friction and Wear, Butterworths, London, 1965.
19. See #18
20. H.S.Avery, The Nature of Abrasive Wear, 1975.
21. M.J.Murray, P.J.Mutton, J.D.Watson, Abrasive Wear Mechanisms in Steel, Transactions of the ASME Journal of Lubrication Technology, vol. 104, January 1982, pp. 9-16.
22. E.Rabinowicz, L.A.Dunn, P.G.Russel, A Study of Abrasive Wear Under Three-Body Conditions, WEAR, 4 (1961), pp. 345-355.
23. J.F.Archard, Wear Theory and Mechanisms, Wear Control Handbook, Peterson and Winer (eds.), ASME, New York, 1980, pp. 35-80.
24. See #16
25. See #18
26. R.C.D.Richardson, The Maximum Hardness of Strained Surfaces and the Abrasive Wear of Metals and Alloys, WEAR, 10 (1967), pp. 353-382.
Cited From -
M.M.Kruschov, M.A.Babichev, Issled. Iznashivaniya Metallov, Izd. Akad. Nauk, USSR, Moscow, 1960, Chap. 18, N.E.L. Transl. No. 893.

27. I.Iliuc, Plate Like Wear Particle Formation in a Lubricated Ball-on-Plate Friction Pair, Tribology International, vol. 18, No. 4, August 1985, pp. 215-218.
28. R.C.D.Richardson, The Wear of Metals by Hard Abrasives, WEAR, 10 (1967), pp. 291-309.
29. See #27
30. See #12
31. Ji-yi Lin, H.S.Cheng, An Analytical Model for Dynamic Wear, Transactions of the ASME Journal of Tribology, vol. 111, July 1989, pp. 468-474.
32. H.Sin, N.Saka, P.Suh, Abrasive Wear Mechanisms and the Grit Size Effect, WEAR, 10 (1979), pp. 163-190.
33. N.P.Suh, The Delamination Theory of Wear, WEAR, 25 (1973), pp. 111-124.

FINAL REPORT

for

**A STUDY OF COAL PARTICLE SHAPE
AND THREE-BODY WEAR**

PART II. PARTICLE SHAPE AND THREE-BODY WEAR

**DOE/PETC GRANT No.
DE-FG22-88PC88941**

**N.N. Clark and K.H. Means
Principal Investigators**

**R. James and T. Thompson
Graduate Research Assistants**

II-1 PARTICLE SHAPE CHARACTERIZATION: IMAGE ANALYSIS TECHNIQUES

Generally, particle shape is characterized using behavioral methods, qualitative descriptors, or image analysis techniques. Behavioral shape analysis methods focus on the properties or response of a particle under particular physical conditions. Although these methods can analyze several particles quickly, they do not result in parameters that describe the shapes of the particles but, generally, separate particles into spherical and non-spherical. Qualitative shape descriptors describe the gross shape of a particle using terms such as elongated, blocky, or angular. These descriptors ignore the finer surface details of the particle and are subject to confusion. That is, there is no universal standard used by all researchers to classify a particle as blocky, for example. Existing image analysis techniques begin with a digitized outline of a particle and result in quantitative shape parameters. Image analysis methods include Fourier analysis, polygonal harmonics, fractal analysis, aspect ratio, and not-roundness, all of which were used in this research to correlate three-body wear to shape. Intuitively, it is obvious that abrasive, rough particles would result in more severe wearing of components than if the intrusive particles were smooth and round. Even so, there have been very few attempts to correlate macroscopic particle shape to three-body wear.

In order to utilize image analysis techniques to characterize particle shape, the particle must first be digitized and stored as a two-dimensional image in a computer. An edge follower algorithm is then used to define the edge as a set of (x,y) points. From this set of edge points, shape descriptors are found using algorithms written in QuickBasic (see Appendices II-A through II-H for listings). The equipment and algorithms used in this process are discussed below.

Particle Digitization

A Pulnix TM-540 video camera, a CCD (charge-coupled device) camera with a resolution of 512 x 480 pixels, was mounted to one eyepiece of an Olympus POM microscope to take pictures of particles. The microscope provided backlighting, enhancing the gradient between the particle outline and the microscope slide background. Once the particle was placed under the microscope, a Quickbasic program was run to snap a picture. This program first activates a PCVISIONplus frame grabber board, installed in a Zenith computer, so that the particle image appeared on a TV monitor as seen through the camera. Figure II-1 illustrates the equipment setup. The particle was then positioned so that it was in focus in the center of the monitor's screen, and the program was directed to take a picture. The frame grabber board then stores the picture as a 512 x 480 pixel array of gray-scale values ranging from 0 (black) to 255 (white). The frame-grabber was then accessed to retrieve this array and manipulate it to define the edge of the particle. From this edge, shape descriptors were found using algorithms that are independent of particle size.

The edge follower algorithm begins by checking the gray-scale value every ten pixels in ten row intervals over the whole screen. The deviation between gray-scale values at these intervals and a point five pixels away is checked. A large deviation indicates the edge of the particle image because the image is dark (having low gray-scale values) and the background is white (having high gray-scale values). When the deviation is large enough to indicate the edge, the algorithm searches in one pixel steps for the largest deviation five pixels in each direction vertically and twenty pixels in each direction horizontally. Once the largest deviation between two neighboring pixels is found, the pixel with the lower gray-scale value (indicating that it is dark and, thus, part of the particle image) is chosen as the starting point for the edge follower.

The edge follower algorithm then searches for the largest gray-scale gradient in seven directions around the starting point, and follows the largest gradient as it steps

around the image. Although there are eight possible directions, shown in Figure II-2 , the algorithm does not check the deviation in the direction that it just stepped from to ensure that it does not backtrack to the starting point.

The algorithm continues stepping around the particle image, following the largest gradient, until closure is achieved. To achieve closure, at least twenty edge points must be found and the distance between the last edge point found and the starting point must be less than four pixels. The edge following is then complete and the result is a set of discrete (x,y) points defining the particle's edge. This set of coordinates is then saved in the computer for use in several shape descriptor algorithms.

II-3

Shape Descriptor Algorithms

Several shape descriptors were used in this research to characterize particles, including a two-dimensional aspect ratio, persistences of polygonal harmonics, Fourier coefficients, fractal dimension, and not-roundness.

Polygonal Harmonics

Polygonal harmonics use a structured walk around the particle's edge that continues until it converges to repeatedly trace out a polygon with its vertices on the image edge. The resulting harmonic is defined as the number of sides in the polygon created, as illustrated in Figure II-3, and is a function of the step length. For example, a harmonic of three is indicated by the formation of a triangle while a harmonic of four is indicated by the formation of a rhombus. A harmonic formed by tracing the image edge more than once is termed a deviant harmonic. The persistence of a harmonic is defined as the ratio of the longest to shortest step lengths which both result in the same harmonic. The persistence of a harmonic is zero if that harmonic does not exist in an image and one if that harmonic exists for only one step length. The second, third, and fourth harmonic persistences (P₂,

P3, and P4, respectively) were used in this research and are measures of elongation, triangularity, and blockiness.

The polygonal harmonics algorithm begins by finding the longest diameter, d_{max} , of the particle image, which is the greatest step length possible in the structured walk. Distances are calculated between an arbitrary initial edge point and every tenth edge point along the particle image using the following formula:

$$\text{distance} = \sqrt{(\text{start } x - \text{edge } x)^2 + (\text{start } y - \text{edge } y)^2} \quad (1)$$

The starting point is then incremented by ten and distances again calculated between this new starting point and every tenth edge point. This process is repeated until the edge is traversed, with the longest diameter for each different starting point saved. The longest diameter of all the searches is then found and the coordinates of the two edge points making up this diameter are selected for the start of a more accurate search. The step length is cut from ten to one, and the distances calculated between all possible pairs of edge points within ten edge points of each of the two coordinates of the diameter. The longest distance is then found using a bubble sort and the (x,y) coordinates making up d_{max} are stored. The starting point for the structured walk is then chosen as the endpoint of d_{max} with the lower y-value. By selecting this as the starting point, the largest step length possible is guaranteed to be the longest diameter and not some smaller length that would result in a lower P2.

The structured walk used in the polygonal harmonics algorithm is a hybrid method. Distances are calculated using equation (1) between the starting point and successive edge points until the calculated distance exceeds the specified step length at a point, m. The distances between the starting point and point m and the starting point and point (m-1) are compared; whichever distance is closest to the step length determines the second path point, m or (m-1) (see Figure II-4). The second path point is then taken as the new starting point and the process repeated to determine the third path point, and so on. These path points

make up the vertices of a polygon which the algorithm continually traces. The walk proceeds clockwise although there is usually little difference in the resulting harmonic when stepping counterclockwise. It is simply a matter of protocol to maintain consistency.

The persistences of the harmonics are found by varying the step length of the hybrid walk from 5 pixels to the length of the maximum diameter. A step length of 5 pixels results in an acceptable error of no greater than 2%. However, smaller step lengths would result in greater error and require much more computer time and were, therefore, not used.

Fractal Dimension

Fractal dimension analysis uses the same hybrid structured walk around the particle edge as polygonal harmonics. However, in fractal dimension analysis the walk traverses the edge only one time and stops when the point being tested is the initial starting point. The polygon formed within the image may not be equilateral as it always is in polygonal harmonics, since the walk always stops at the initial starting point. The perimeter of the polygon formed is then calculated as:

$$P = (n - 1) SL + D_e, \quad (2)$$

where n is the number of equilateral sides of the polygon, SL is the step length, and D_e is the length of the chord drawn from the last path point and the starting point. In this research, the step length of the walk is varied from 5 pixels to 20% of the maximum diameter and for each step length the perimeter is calculated. A logarithmic plot of perimeter versus step length (a Richardson plot) is constructed. The slope, S , of a best fit line is always negative since smaller step lengths will account for finer details in the particle image and, thus, increase the perimeter. The fractal dimension of a particle is defined as $(1-S)$ and for one-dimensional images, always lies between one and two.

Whereas polygonal harmonics analysis results in macroscopic shape descriptors, fractal dimension analysis results in a descriptor which is a measure of the surface roughness of a particle as represented by the roughness of the image edge.

Two-Dimensional Aspect Ratio

The two-dimensional aspect ratio, R_{2D} , is defined by the ratio of the maximum particle diameter, d_{max} , to the maximum diameter orthogonal to d_{max} , d_m . Figure II-5 shows these two diameters of a particle. The algorithm used to find R_{2D} first determines the maximum diameter of the particle in the same manner as previously discussed. The angle between d_{max} and the horizontal is then calculated; if this angle is less than 45° , the following procedure is used to determine d_m . Beginning at the left endpoint of d_{max} , the algorithm marches along the horizontal (x-axis) in one pixel increments, calculating the corresponding y-value along d_{max} at each increment as such,

$$y = \left(\frac{y_2 - y_1}{x_2 - x_1} \right) (x - x_1) + y_1, \quad (3)$$

where (x_1, y_1) and (x_2, y_2) are the endpoints of d_{max} . The algorithm continues marching until the right endpoint of d_{max} is reached, resulting in a set of (x, y) values along d_{max} . Every point in this set is then tested against every edge point starting from the left endpoint of d_{max} and continuing clockwise until the right endpoint of d_{max} is reached. Those edge points that result in a slope of $-(1/\text{slope of } d_{max})$, the slope of d_m , with respect to d_{max} , are stored. The process is then repeated for every edge point in a counter-clockwise direction, once again starting at the left endpoint and ending at the right endpoint of d_{max} . The lengths of orthogonal diameters are then calculated using the two previously stored edge points corresponding to the same position along d_{max} . The longest of these diameters, d_m , is found using a bubble sort and, thus, the two-dimensional aspect ratio can be calculated.

In the case where the maximum diameter makes an angle greater than 45° with the horizontal, the (x,y) values along $d_{\max}$ are found by stepping vertically (along the y-axis) instead of horizontally and using equation (3) to find the x-values.

Fourier Analysis

There are two algorithms necessary to complete a (R, θ) Fourier analysis; the first algorithm computes a set of equally-spaced radii [(R, θ) values] for a particle (see Figure II-6) which are then used in a Fourier transform algorithm, resulting in Fourier coefficients describing that particle.

The first algorithm begins by finding the centroid of a particle image, from which the equally-spaced radii will be constructed. The QuickBasic PAINT command is used to make all points within the particle image, including the edge points, a specific color (i.e., numerical value at each x,y location). A box is then constructed, enclosing the image, with vertices at the maximum and minimum x-values and the maximum and minimum y-values of the edge points. Every pixel within this box is then tested for color. If a pixel is part of the particle image (not black), its x-value and y-value are summed, separately. The centroid is then the (x and y) sums divided by the number of pixels within the image.

The next step in this algorithm is to find the radii, or the (R, θ) values, for the particle. For reasons that will be explained below, 64 radii are constructed at 5.6° (i.e., $360/64$) intervals. Figure II-6 illustrate these radii on a coal ash particle. The first radius (at $\theta=0^\circ$) is consistently defined as the chord drawn from the centroid to the endpoint of the image's longest diameter with the lower y-value. The angles between this first chord and successive edge points are then calculated, proceeding in a clockwise direction, until the starting point is again reached. When the angles calculated between two successive edge points bound one of the desired angles (any multiple of 5.6° up to 360°), the edge point possessing the angle closest to the desired angle is chosen as the endpoint of a radius as shown in Figure II-7. The distances between these edgepoints and the centroid are saved

along with their corresponding angles, making a set of 64 (R,θ) values. The only flaw in this method occurs when the particle image is re-entrant, or when a radius at a certain angle could pass through more than one edge point of the image. In this case, the longest of the radii at that angle is chosen for the list of (R,θ) values because the longest radius gives more information on the overall shape of the particle. A re-entrant coal ash particle is shown in Figure II-8 with both sets of radii (long and short) to illustrate the difference.

A Fourier transform can either be fast or slow, where the slow transform results in phase angle information as well as the Fourier coefficients. In either case, the number of (R,θ) values needed to perform an efficient Fourier transform is of the form 2^n . In this research, a commercially available fast Fourier transform (FFT) was used since no phase angle information was desired and n was consistently chosen as 6. The FFT uses the previously found (R,θ) values and constructs a Fourier series of the form

$$R(\theta) = A_0 + \sum A_n \cos(n\theta - \phi_n), \quad (4)$$

Although 64 Fourier coefficients are returned for each particle, only A_0 through A_6 were examined in this research. The zeroth and first coefficients, A_0 and A_1 , are measures of the average radius around the centroid and the error involved in calculating the centroid, respectively. They were analyzed to ensure that the results were acceptable. The second, third, and fourth coefficients yield information on the fit of an ellipse (A_2), a triangle (A_3) and a rhombus (A_4) to a particle, while the higher order coefficients (A_5 and A_6) are measures of surface roughness and irregularity of a particle.

Not-Roundness

The algorithm developed to determine not-roundness is very similar to the (R,θ) Fourier analysis algorithm. This is not surprising since not-roundness was developed through Fourier analysis. The variables needed to calculate not-roundness are the equivalent

circular radius of the particle, R_o , and a set of radii, R_i , at angles θ_i . The equivalent circular radius is found by evoking the PAINT command, constructing the box around the particle image, and counting the total number of pixels within that box that belong to the particle, as described in the previous section. The equivalent circular radius is then calculated using

$$R_o = \sqrt{\frac{\text{Area}}{\pi}} = \sqrt{\frac{\text{total number of pixels within particle}}{\pi}} \quad (5)$$

The set of radii, R_i , is simply the same 64 radii found using the (R,θ) Fourier analysis. Not-roundness was then calculated using

$$NR = \frac{1}{nR_o^2} \sum (R_i - R_o)^2, \quad (6)$$

where $n = 64$.

Reproducibility of Algorithms

The shape descriptor algorithms discussed above were tested for their reliability to ensure that identical values would be returned for several executions using the same particle. Ten different views of the same side of a rock were photographed using the same equipment setup shown in Figure II-1 with the exception of the microscope. The microscope was not needed since the rock was large enough to be viewed using only the camera. After each photograph was taken, the rock was rotated to provide the different views of the same side shown in Figure II-9. It should be noted that a rock was used instead of a microscopic particle to ensure that the same side of the object was being photographed.

Results of the reproducibility test are illustrated in Figures II-10 through II-20. Although there is some data scatter, this can be partially attributed to the irregularity of the

rock surface. When the rock was rotated, it tended to shift slightly due to small protuberances on the side it was resting upon. Figure II-9 illustrates the variance between the ten views due to this shifting motion. Another source of data scatter occurs in the scaling of the particle image. Since the particle is photographed and stored as a 512 x 480 pixel array, the image must be scaled to obtain a square array, which should then be the true particle image. However, this scaling process often leads to slight distortions of the true image. Nevertheless, data scatter is minimal and standard deviations for the shape descriptors are much lower than for particles analyzed for the next section. Obviously, values returned by the algorithms would be much closer for ten pictures taken without rotating the rock. However, this would not be a true test of the reliability of the algorithms which was essential to this research.

Figure II-1: Experimental set-up for particle digitization

Figure II-2: Gradient directions for edge follower routine

Second Polygonal harmonic

Third Polygonal Harmonic

Fourth Polygonal Harmonic

Figure II-3: Illustration of the Polygonal Harmonics of different images

Figure II-4: Hybrid structured walk used by algorithms

Figure II-5: Diameters used to calculate two-dimensional aspect ratio

Figure II-6: The 64 radii of a particle found using Fourier Analysis

Figure II-7: Illustration of the selection of radii for Fourier analysis algorithm

Figure II-8: Illustration of the 64 longest and shortest radii of a re-entrant coal ash particle

Figure II-9: Ten different views of the same side of a rock used to test reliability of shape descriptor algorithms

Figure II-10: Distribution of the second harmonic persistence for ten views of the same side of a rock

Figure II-11: Distribution of the third harmonic persistence for ten views of the same side of a rock

Figure II-12: Distribution of the fourth harmonic persistence for ten views of the same side of a rock

Figure II-13: Distribution of aspect ratio for ten views of the same side of a rock

Figure II-14: Distribution of not-roundness for ten views of the same side of a rock

Figure II-15: Distribution of fractal dimension for ten views of the same side of a rock

Figure II-16: Distribution of the second Fourier coefficient for ten views of the same side of a rock

Figure II-17: Distribution of the third Fourier coefficient for ten views of the same side of a rock

Figure II-18: Distribution of the fourth Fourier coefficient for ten views of the same side of a rock

Figure II-19: Distribution of the fifth Fourier Coefficient for ten views of the same side of a rock

Figure II-20: Distribution of the sixth Fourier Coefficient for ten views of the same side of a rock

DATA AND CONCLUSIONS:

II-4 PARTICLE SHAPE AND THREE-BODY WEAR

II-5

Effect of Shape on Wear

Wear tests were run in four twenty minute intervals, as well as four thirty minute intervals, for each type of particle. In each case, fresh particles were used for each test interval, however, the same disk and specimen was used for the duration of testing. Table II-1 lists results from each test interval including the volume loss of the wear specimen, the wear coefficient, and the specific wear rate. The volume loss was found by weighing the specimen after each test interval while the wear coefficient and wear rates were calculated using the following two equations:

$$K_3 = \frac{3VH}{WL}, \quad (7)$$

and

$$WR = \frac{V}{WL}, \quad (8)$$

where K_3 is the wear coefficient, WR is the specific wear rate (in in^2/lb), V is the volume loss of the wear specimen (in in^3), H is the hardness of the wear specimen (in lb/in^2), W is the applied load to the specimen (in lbs) and L is the sliding distance (in in.).

To then establish what effect shape has on the wear parameters, forty fresh, random samples each of aluminum oxide particles, smooth glass spheres, and coal ash were image analyzed for this research. Average shape descriptors for each sample group was then determined using the algorithms discussed above. Table II-2 lists the average shape descriptors found for each particle type along with the total volume loss and the average wear rate and wear coefficient for both 20 minute and 30 minute test intervals.

The glass spheres exhibit low values of all shape descriptors as expected. Note, in particular, the low values given in Table II-2 for fractal dimension and the higher order

Fourier coefficients (A_5 and A_6); since these shape descriptors measure surface roughness and irregularity, it is evident that the spheres are indeed, smooth. A sphere in two-dimensions reduces to a circle, and not-roundness (NR) for a circle is defined as zero. As seen in Table II-2, the value of NR for the spheres is essentially zero.

The aluminum oxide particles, when viewed under the microscope, were, in general, blocky with a rough surface. Relatively high values of A_5 , A_6 , and the fractal dimension support this observation, while the value of the fourth polygonal harmonic persistence (P4) indicates that the particles were somewhat rectangular. However, the higher values of the second (P2) and third (P3) polygonal harmonic persistences suggest that they were more elongated and slightly more triangular than blocky.

The coal ash particles were very flat and flaky in nature and, when viewed under the microscope, were highly elongated and irregular. The high value of P2 in Table II-2 represents the elongation of the particles and since they are so elongated, values of P3 and P4 remain low. It should be noted that any one particle cannot have a value of P3 equal to 0.88 since the persistences must either be zero or greater than one by definition. However, since several of the forty sample particles had a value of $P3=0$ (i.e., no third harmonic), the average P3 of the sample group fell between zero and one. The coal ash had the highest values of the three particle types for all the descriptors that indicate roughness and irregularity, namely A_5 , A_6 and fractal dimension. Not-roundness for the ash was also the highest value for the particles, also suggesting a highly elongated and irregular particle.

In this research, the two-dimensional aspect ratio, R_{2D} , was calculated to justify the reliability of P2 as a measure of elongation. In Table II-2, both values are listed for the different particles. Although R_{2D} and P2 are very close in value for each of the different particle types, they are almost identical for the glass spheres. This is due to the fact that the particles analyzed were all spheres and, ideally, should have been identical, with values of R_{2D} and P2 equal to exactly one. However, perfect spherical particles, having all diameters exactly equal, would be difficult to obtain.

The volume loss from the wear specimen increases with test duration and test interval time (see Table II-1), as expected, with the exception of the aluminum oxide particles. Surprisingly, the total volume loss for both the 20 minute and 30 minute test intervals was the same at 0.007 in³. However, when comparing the volume loss between particle types, the aluminum oxide particles resulted in the greatest volume loss, while the glass spheres produced volume losses of 0.0003 in³ for the 20 minute intervals and 0.0005 in³ for the 30 minute intervals. Volume losses were smallest using the coal ash particles at 0.000045 in³ and 0.000067 in³ for 20 and 30 minute tests, respectively.

Since the coal ash particles are the most irregular of the particles based on the shape descriptors, it would be fair to assume at first glance that they would cause the greatest amount of wear. However, the ash particles, unlike the aluminum oxide and spheres, are highly elongated and very friable (i.e., they break up easily). Therefore, the time that they will do the greatest damage to the wear specimen is when they stand up during a test in which case they may be crushed and be unable to do subsequent damage. Otherwise, they may not be wearing the surface at all. On the other hand, the aluminum oxide particles possess relatively high shape descriptors in roughness and cause the highest volume loss of the three while the glass spheres have very low values of roughness and result in more volume loss than the coal ash. Generally, rougher, more abrasive particles will lead to higher volume loss as is the case with aluminum oxide compared to spheres, but these two particle types are comparable in hardness whereas the coal ash is very brittle and fragile. Although shape descriptors are helpful in predicting the trend in volume loss, there are other factors, mainly the hardness of the particles, that need to be considered also. Shape descriptors alone are, therefore, not a reliable means of predicting volume loss from a wear specimen.

Wear rates and wear coefficients are less for 30 minute test intervals than for 20 minute test intervals for all the particles as shown in Table II-2. This can be attributed to

the sliding distance, L , in equations (7) and (8). It is the only variable in the two equations that changes considerably due to the difference in test interval time.

The wear rates and wear coefficients are far greater for the aluminum oxide particles while the values for the coal ash are slightly greater than those for the spheres. The shape descriptors for the spheres indicate their smoothness and roundness so it stands to reason that they would have the lowest values of WR and K_3 . Although the coal ash is more irregular than the aluminum oxide, it is elongated and, as stated earlier, will do its greatest damage when standing on end. The aluminum oxide is not only irregular, it has a greater surface area in contact with the wear surfaces and, therefore, has a higher wear rate.

Shape descriptors can be useful in predicting wear rates, wear coefficients, and volume losses. However, the hardness of the particles must also be taken into account. This can be seen from the three types of particles analyzed. When comparing the spheres and aluminum oxide particles, which have similar hardnesses, the more irregular aluminum oxide had greater volume losses, wear rates, and wear coefficients. The coal ash, on the other hand, although highly irregular, was very brittle and produced low wear rates, wear coefficients, and even lower volume losses.

II-6

Effect of Wear on Shape

Forty samples each of aluminum oxide particles were analyzed after 0, 10, 20, and 30 minutes of wear to determine their shape descriptors using the image analysis techniques discussed above. Average values for each descriptor were calculated and are shown in Table II-3. Figures II-21 through II-31 show both histograms and cumulative frequency plots of the distribution of shape descriptor values for the particles. These plots show that the majority of particles analyzed in each group fall close to the average values of the shape parameter for that group. Figures II-32 through II-42 illustrate the mean value and standard deviation (shown as error bars) of the shape descriptors for each group of particles. Comparing the average value set of plots to the cumulative frequency plots, it can

be seen that, in almost every case, at least 75% of the particles had shape descriptors within one standard deviation of the mean for that descriptor.

Figures II-21 through II-31 as well as Table II-3 suggest that the shape descriptors for the different groups of particles, in general, do not significantly change in value with respect to wear time. The one exception to this is the third harmonic persistence, P3, which decreases between particles worn for 10 minutes and those worn for 20 minutes. This suggests that the particles become less triangular after an initial wear period of 10 minutes and then reach a nearly constant level of triangularity. Although the second harmonic persistence and two-dimensional aspect ratio increased slightly with wear time up to 30 minutes, where it decreased, the changes in values were not significant enough to suggest any elongation or shortening of the particles. Similarly, the fourth harmonic persistence increased only slightly with wear time. The fractal dimension values remain nearly constant with wear duration, indicating that the surface roughness of the particles was not affected by wear.

Although the values of not-roundness more than doubled for the worn particles compared to the fresh particles, the standard deviation of NR for the worn particles is so large, it leads to inconclusiveness about the circularity of the particles. The same can be said for the Fourier coefficients where the standard deviation is of the same order as the coefficients.

Conclusions

Results indicate that the aluminum oxide particles produced the greatest overall wear followed by the coal ash and then the spheres. According to the shape descriptor values, the aluminum oxide could be classified as rough, the coal ash as elongated and irregular, and the glass spheres smooth and round. A definite relationship exists between the particle shape and the amount of wear: the more rough and irregular the particle, the higher the

wear rate and wear coefficient. However, results also suggest that the hardness of the particles, as well as the shape, plays an important role in wear.

In addition, resulting shape descriptors suggest that wear affects only the triangularity of the particles. The third harmonic persistence shows a slight decrease between particles worn for 10 minutes and those worn for 20 minutes and then becomes constant again.

Particle	Time (min)	Load (lbs)	Gap (microns)	L (in)	Vol loss (in ³)	K	WR $\times 10^{-8}$
Aluminum Oxide 20 minute tests	20	1.6979	1000	12789.6	0.001789	0.011554	8.23837
	40	1.7985	1000	25859.7	0.003941	0.011884	8.47373
	60	1.8210	1000	38711.2	0.005881	0.011700	8.34263
	80	1.9063	1000	50011.8	0.007830	0.011518	8.21281
Aluminum Oxide 30 minute tests	30	1.5970	1000	16753.3	0.001824	0.009562	6.81799
	60	1.6328	1000	32634.9	0.003690	0.009712	6.92493
	90	1.6474	1000	48541.0	0.005673	0.009950	7.09466
	120	1.62217	1000	64861.9	0.007748	0.010327	7.36382
Glass Spheres 20 minute tests	20	0.24494	800	11654.9	0.000022	0.001123	0.800761
	40	0.23710	800	25257.2	0.000098	0.002308	1.64620
	60	0.32393	800	39151.9	0.000205	0.002273	1.62073
	80	0.39009	800	52216.7	0.000332	0.002289	1.63251
Glass Spheres 30 minute tests	30	0.60447	800	15620.8	0.000038	0.000571	0.40774
	60	0.80279	800	31383.3	0.000162	0.000903	0.64400
	90	0.91347	800	47966.0	0.000325	0.001040	0.74174
	120	0.98404	800	63817.1	0.000507	0.001132	0.80774
Coal Ash 20 minute tests	20	0.08539	300	10658.6	0.000012	0.001864	1.32939
	40	0.04514	300	21080.5	0.000021	0.003095	2.20682
	60	0.02415	300	32168.2	0.000037	0.006732	4.80037
	80	0.05704	300	43589.5	0.000045	0.002583	1.84219
Coal Ash 30 minute tests	30	0.05028	300	15902.6	0.000010	0.001754	1.25070
	60	0.05862	300	31804.0	0.000025	0.001880	1.34104
	90	0.04658	300	48893.6	0.000045	0.002770	1.97571
	120	0.08551	300	65277.3	0.000067	0.001683	1.20032

Table II-1: Three-body wear data for aluminum oxide particles, glass spheres, and coal ash

Particle	P2	P3	P4	A2	A3	A4	A5	A6	FD	ASP	NR	WR	K	V
Aluminum Oxide	1.36	1.16	1.10	13.18	8.57	6.11	3.81	3.24	1.02	1.28	.0117			
	20 min											8.32	.012	.007
	30 min											7.05	.010	.007
Glass Spheres	1.08	1.01	1.01	18.04	0.195	1.45	0.126	0.198	1.00	1.07	.0060			
	20 min											1.425	.002	.0003
	30 min											.6503	.009	.0005
Coal Ash	1.68	0.88	1.08	24.82	8.93	9.10	4.92	4.29	1.06	1.63	.1605			
	20 min											2.55	.0036	.000045
	30 min											1.44	.002	.000067

Table II-2: Various shape descriptors for aluminum oxide particles, glass spheres, and coal ash along with average wear test results

Particle	P2	P3	P4	A2	A3	A4	A5	A6	FD	ASP	NR
Unworn	1.36	1.16	1.10	13.18	8.57	6.11	3.81	3.24	1.02	1.28	.0117
	.171	.083	.048	7.66	7.12	4.53	2.73	2.50	.009	.203	.008
Worn 10 min	1.39	1.16	1.10	19.65	10.11	6.49	4.49	2.81	1.01	1.35	.0262
	.185	.101	.049	12.3	8.26	4.13	2.76	2.24	.004	.265	.037
Worn 20 min	1.39	1.08	1.12	25.78	9.14	7.40	4.33	3.22	1.02	1.38	.0276
	.235	.325	.059	9.50	5.70	4.90	2.58	2.16	.004	.263	.013
Worn 30 min	1.37	1.08	1.13	22.54	7.59	5.57	3.73	3.11	1.02	1.33	.0246
	.225	.326	.070	9.66	5.41	3.91	2.75	2.15	.007	.270	.013

Table II-3: Average values of shape descriptors from sample groups of 40 aluminum oxide particles. Standard deviation for each shape descriptor is below the average.

Figure II-21: Distribution plots of aspect ratio for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-22: Distribution plots of second harmonic persistence for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-23: Distribution plots of third harmonic persistence for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-24: Distribution plots of fourth harmonic persistence for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-25: Distribution plots of Not-Roundness for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-26: Distribution plots of fractal dimension for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-27: Distribution plots of the second Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-28: Distribution plots of the third Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-29: Distribution plots of the fourth Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear

Figure II-30: Distribution plots of the fifth Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear

Figure II-31: Distribution plots of the sixth Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-32: Mean value within one standard deviation of the second harmonic persistence for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-33: Mean value within one standard deviation of the third harmonic persistence for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-34: Mean value within one standard deviation of the fourth harmonic persistence for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-35: Mean values within one standard deviation of aspect ratio for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-36: Mean values within one standard deviation of not-roundness for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-37: Mean values within one standard deviation of fractal dimension for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-38: Mean value withing one standard deviation of the second Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-39: Mean value withing one standard deviation of the third Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-40: Mean value withing one standard deviation of the fourth Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-41: Mean value within one standard deviation of the fifth Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Figure II-42: Mean value within one standard deviation of the sixth Fourier coefficient for aluminum oxide particles after 0, 10, 20, and 30 minutes of wear testing

Appendix II-A

Computer Code to Digitize Image

```

'-----Initializing-----
    DECLARE FUNCTION bpix& (i&, j&, memloc&)
    DEFINT A-W
    OPTION BASE 0
    n = 3000
    DIM spot(n, 2)
5   GOSUB initialize
    GOSUB choose
    GOTO 5
END
'-----
initialize:
    SCREEN 9, 0
    WINDOW SCREEN (0, 0)-(512, 384)
    regseg = &H300
    DEF SEG = &HD000
    RETURN
'-----
choose:
'   subroutine that allows user to take a picture or quit
    PRINT : PRINT
    PRINT : PRINT "ENTER A NUMBER:          (1)  TAKE A PICTURE"
    PRINT : PRINT "                        (2)  QUIT"
    INPUT ch1
    IF ch1 = 2 THEN END
    PRINT
    PRINT
    IF ch1 = 1 THEN GOSUB snap
5   RETURN
'-----
snap:
'   subroutine that commands camera to "grab" a picture, then snap

1000    OUT regseg + 5, 194                                'grab
        PRINT "  GET READY TO TAKE THE PICTURE.....": PRINT : PRINT
1010    INPUT " ENTER FILENAME IF YOU WISH TO SAVE PICTURE "; name$
1011    OUT regseg + 5, 130                                'snap
        b = 100                                           'wait

        WHILE b > 64
            b = INP(regseg + 5)
        WEND
        PRINT

        GOSUB findedge
        GOSUB follow

        INPUT "WANT TO SAVE THIS PICTURE? (1 - yes, 2 - no)"; ch3
        IF ch3 = 1 THEN
            GOSUB store
        ELSE
            RETURN
        END IF

```

RETURN

```
'-----  
findedge: 'subroutine searches for first edge point using gradients  
gmax = 0  
gsum = 0  
c = 0  
FOR j = 10 TO 460 STEP 10  
  FOR i = 20 TO 470 STEP 50  
    g = bpix(i - 5, j, ml) - bpix(i, j, ml)  
    gsum = gsum + bpix(i, j, ml)  
    c = c + 1  
    IF g > gmax THEN  
      gmi = i  
      gmj = j  
      gmax = g  
    END IF  
  NEXT i  
NEXT j  
FOR j = (gmj - 5) TO (gmj + 5)  
  FOR i = (gmi - 20) TO (gmi + 20)  
    g = bpix(i - 1, j, ml) - bpix(i, j, ml)  
    IF g > gmax THEN  
      gmi = i  
      gmj = j  
      gmax = g  
    END IF  
  NEXT i  
NEXT j  
  
bgl = gsum / c  
i = gmi  
j = gmj
```

RETURN

```
'-----  
follow:  
  'subroutine that follows greatest gradient around the image  
  'written by William Long, West Virginia University  
  
  id = i  
  jd = j  
  io = i  
  jo = j  
  dr$ = "rt"  
  edge = 0  
  w = wset  
  maxg = mset  
  SCREEN 2, 0  
  WINDOW SCREEN (0, 0)-(512, 480)  
  y = 2 * 1.414214  
  
100 IF dr$ <> "lt" THEN  
  A = bpix(i + 1, j - 1, ml)  
  IF A <> 0 THEN
```

```

    b = bpix(i + 1, j + 1, ml)
    IF b <> 0 THEN
        max = (A - b) / 2
        IF dr$ = "rt" THEN : max = max + w * 1
        IF max > maxg THEN
            maxg = max
            id = i + 1
            jd = j
            dir$ = "rt"
        END IF
    END IF
END IF
END IF
END IF

IF dr$ <> "dl" THEN
    A = bpix(i, j - 2, ml)
    IF A <> 0 THEN
        b = bpix(i + 2, j, ml)
        IF b <> 0 THEN
            max = (A - b) / y
            IF dr$ = "ur" THEN : max = max + w * 1
            IF max > maxg THEN
                maxg = max
                dir$ = "ur"
                id = i + 1
                jd = j - 1
            END IF
        END IF
    END IF
END IF
END IF
END IF

IF dr$ <> "dn" THEN
    A = bpix(i - 1, j - 1, ml)
    IF A <> 0 THEN
        b = bpix(i + 1, j - 1, ml)
        IF b <> 0 THEN
            max = (A - b) / 2
            IF dr$ = "up" THEN : max = max + w * 1
            IF max > maxg THEN
                maxg = max
                dir$ = "up"
                id = i
                jd = j - 1
            END IF
        END IF
    END IF
END IF
END IF
END IF

IF dr$ <> "dr" THEN
    A = bpix(i - 2, j, ml)
    IF A <> 0 THEN
        b = bpix(i, j - 2, ml)
        IF b <> 0 THEN
            max = (A - b) / y

```

```

        IF dr$ = "ul" THEN : max = max + w * 1
        IF max > maxg THEN
            maxg = max
            dir$ = "ul"
            id = i - 1
            jd = j - 1
        END IF
    END IF
END IF

END IF

IF dr$ <> "ur" THEN
    A = bpix(i, j + 2, ml)
    IF A <> 0 THEN
        b = bpix(i - 2, j, ml)
        IF b <> 0 THEN
            max = (A - b) / y
            IF dr$ = "dl" THEN : max = max + w * 1
            IF max > maxg THEN
                maxg = max
                dir$ = "dl"
                id = i - 1
                jd = j + 1
            END IF
        END IF
    END IF
END IF

END IF

END IF

IF dr$ <> "up" THEN
    A = bpix(i + 1, j + 1, ml)
    IF A <> 0 THEN
        b = bpix(i - 1, j + 1, ml)
        IF b <> 0 THEN
            max = (A - b) / 2
            IF dr$ = "dn" THEN : max = max + w * 1
            IF max > maxg THEN
                maxg = max
                dir$ = "dn"
                id = i
                jd = j + 1
            END IF
        END IF
    END IF
END IF

END IF

END IF

IF dr$ <> "ul" THEN
    A = bpix(i + 2, j, ml)
    IF A <> 0 THEN
        b = bpix(i, j + 2, ml)
        IF b <> 0 THEN
            max = (A - b) / y
            IF dr$ = "dr" THEN : max = max + w * 1
            IF max > maxg THEN
                maxg = max
            END IF
        END IF
    END IF
END IF

```

```

                dir$ = "dr"
                id = i + 1
                jd = j + 1
            END IF
        END IF
    END IF
END IF

IF dr$ <> "rt" THEN
    A = bpix(i - 1, j + 1, ml)
    IF A <> 0 THEN
        b = bpix(i - 1, j - 1, ml)
        IF b <> 0 THEN
            max = (A - b) / 2
            IF dr$ = "lt" THEN : max = max + w * 1
            IF max > maxg THEN
                maxg = max
                dir$ = "lt"
                id = i - 1
                jd = j
            END IF
        END IF
    END IF
END IF

IF i = id AND j = jd THEN w = w + .25: GOTO 100
dr$ = dir$

IF id = 0 AND jd = 0 THEN
    edge = edge
ELSE
    edge = edge + 1
    spot(edge, 1) = id
    spot(edge, 2) = jd
END IF

PSET (id, jd)

IF edge > 20 AND ((io - id) * (io - id) + (jo - jd) * (jo -
jd)) < 16 THEN GOTO 55
A = bpix(id, jd, ml)
w = wset
i = id
j = jd
maxg = mset
GOTO 100
55 RETURN
'-----
store:
'subroutine that stores the edge points in a data file
x$ = "A:\\" + name$ + ".dat"
OPEN x$ FOR OUTPUT AS #1
WRITE #1, edge

```

```
FOR i = 1 TO edge
  WRITE #1, spot(i, 1), spot(i, 2)
NEXT i
CLOSE #1
RETURN
'-----
```

Appendix II-B

Polygonal Harmonics algorithm


```

'-----Initializing and Dimensioning Arrays-----

    DEFLNG A-V
    DEFSNG Z
    DECLARE FUNCTION bpix& (i&, j&, ml&)
    n = 1500
    DIM pict(n), path(n, 2), spot(n, 5), old(n, 5), zanswer(n, 3)
    DIM save(n, 2), now(n, 2), zpersist(6)
    OPEN "d:\teresa\data\ash.PH" FOR APPEND AS #5
5  GOSUB clearvar

'-----Reading the edge points of the image from a data file---

    READ name$
    PRINT name$
    IF name$ = "stop" THEN GOTO 25
    OPEN "d:\teresa\data\" + name$ + ".DAT" FOR INPUT AS #1
    INPUT #1, edge
    FOR i = 1 TO edge
        INPUT #1, now(i, 1), now(i, 2)
    NEXT i
    CLOSE #1

'-----Finding the longest diameter and forcing the starting---
'-----point to be the longest diameter's upper endpoint-----

    GOSUB distance
    GOSUB switch

'-----Loop incrementing the step length starting-----
'-----with 5 pixels and ending with 500 pixels-----
    ians = 1
    istart = 5
    fin = 500
    FOR sl = istart TO fin
        GOSUB clearsome
        zanswer(ians, 1) = ians
        zanswer(ians, 2) = sl
        GOSUB harm      'performs hybrid structured walk of step
                        'length, sl
        GOSUB menu      'defines polygon mapped out for sl
        IF zanswer(ians, 3) = 1 THEN GOTO 34
        ians = ians + 1
    NEXT sl

'-----
34 GOSUB persist
    GOTO 5
25 CLOSE #5
    STOP
    END

'-----
DATA "sph1", "sph2", "sph3", "sph4", "sph5", "stop"
'-----

```

```

persist:
' This subroutine will find persistences of harmonics 2 through 6
  FOR j = 2 TO 6
    ok = 0
    num = 0
    FOR i = 1 TO ians
      save(i, 1) = 0
      save(i, 2) = 0
    NEXT i
    FOR i = 1 TO ians
      IF zanswer(i, 3) = j THEN
        ok = 1
        num = num + 1
        save(num, 1) = zanswer(i, 2)
        save(num, 2) = zanswer(i, 3)
      END IF
    NEXT i
    pairs = num - 1
    done = 0
    WHILE done = 0
      done = 1
      FOR i = 1 TO pairs
        IF save(i, 1) > save(i + 1, 1) THEN
          temp1 = save(i, 1)
          temp2 = save(i, 2)
          save(i, 1) = save(i + 1, 1)
          save(i, 2) = save(i + 1, 2)
          save(i + 1, 1) = temp1
          save(i + 1, 2) = temp2
          done = 0
        END IF
      NEXT i
      pairs = pairs - 1
    WEND
    now the list of sl's with harmonic=j are in ascending order

    IF ok = 1 THEN 'meaning there are some harmonics=j
      wpers = save(num, 1) / save(1, 1)
    ELSE
      wpers = 0
    END IF
    zpersist(j) = wpers
  NEXT j
  WRITE #5, name$, dmax, zpersist(2), zpersist(3), zpersist(4)
RETURN
'-----
distance:
' This subroutine finds the length and position of the longest
' diameter

' rough search for longest diameter
dmax = 0
FOR i = 1 TO edge STEP 10
  FOR j = (i + 10) TO edge STEP 10

```

```

    deltx = now(i, 1) - now(j, 1)
    delty = now(i, 2) - now(j, 2)
    delty = delty * 3 / 4
    dist = deltx * deltx + delty * delty
    IF dist > dmax THEN
        dmax = dist
        pxmax1 = now(i, 1)
        pymax1 = now(i, 2)
        pxmax2 = now(j, 1)
        pymax2 = now(j, 2)
        edgloc1 = i
        edgloc2 = j
    END IF
NEXT j
NEXT i

```

```

low1 = edgloc1 - 10
IF low1 < 0 THEN low1 = 1
high1 = edgloc1 + 10
IF high1 > edge THEN high1 = edge
low2 = edgloc2 - 10
IF low2 < 0 THEN low2 = 1
high2 = edgloc2 + 10
IF high2 > edge THEN high2 = edge

```

```

converging to maximum diameter
FOR i = low1 TO high1
    FOR j = low2 TO high2
        deltx = now(i, 1) - now(j, 1)
        delty = now(i, 2) - now(j, 2)
        delty = delty * 3 / 4
        dist = deltx * deltx + delty * delty
        IF dist > dmax THEN
            dmax = dist
            pxmax1 = now(i, 1)
            pymax1 = now(i, 2)
            pxmax2 = now(j, 1)
            pymax2 = now(j, 2)
        END IF
    NEXT j
NEXT i

```

```

calculating maximum diameter (dmax), slope of dmax (zm)
slope of orthogonal maximum diameter (zms), and midpoint of dmax
dmax = SQR(dmax)
zm = -(pymax2 - pymax1) / (pxmax2 - pxmax1)
b = -pymax2 - zm * pxmax2
zms = -1 / zm
midi = (pxmax2 + pxmax1) / 2
midj = (pymax2 + pymax1) / 2

```

```

finding upper edgepoint of maximum diameter
IF pymax2 < pymax1 THEN
    starty = pymax2

```

```

        startx = pxmax2
ELSE
        starty = pymax1
        startx = pxmax1
END IF

RETURN
'-----
switch:
'   This subroutine makes the endpoint of the longest axis the
'   starting point for the harmonics work
num = 0
FOR i = 1 TO edge
    IF now(i, 1) = startx AND now(i, 2) = starty THEN
        isave = i
        GOTO 43
    END IF
NEXT i
43  FOR i = isave TO edge
        num = num + 1
        spot(num, 1) = now(i, 1)
        spot(num, 2) = now(i, 2)
    NEXT i
    FOR i = 1 TO (isave - 1)
        num = num + 1
        spot(num, 1) = now(i, 1)
        spot(num, 2) = now(i, 2)
    NEXT i

RETURN
'-----
clearvar:
'   This subroutine clears the variables for a new picture
FOR i = 0 TO n
    spot(i, 1) = 0
    spot(i, 2) = 0
    spot(i, 3) = 0
    path(i, 1) = 0
    path(i, 2) = 0
    old(i, 1) = 0
    old(i, 2) = 0
NEXT i
deviant = 0
change = 0
FOR j = 2 TO 6
    zpersist(j) = 0
NEXT j
RETURN
'-----
clearsome:
'   This subroutine clears some of the variables for a new
'   steplength
FOR i = 0 TO n

```

```

        spot(i, 3) = 0
        path(i, 1) = 0
        path(i, 2) = 0
        old(i, 1) = 0
        old(i, 2) = 0
    NEXT i
    deviant = 0
    change = 0
RETURN

```

```

'-----
harm:
    'This subroutine performs the hybrid structured walk with
    'steplength, sl
    savei = 1
    num = 0
    change = 0
    path(0, 1) = spot(0, 1)
    path(0, 2) = spot(0, 2)
10  FOR i = 1 TO edge
        deltx = spot(savei, 1) - spot(i, 1)
        delty = spot(savei, 2) - spot(i, 2)
        delty = delty * 3 / 4
        dist2 = deltx * deltx + delty * delty
        IF dist2 > sl * sl THEN
            change = 1
            'choosing point m or point (m-1) as the next path point
            IF ABS((dist1 - sl)) > ABS((dist2 - sl)) THEN
                savei = i - 1
            ELSE
                savei = i
            END IF
            path(num, 1) = spot(savei, 1)
            path(num, 2) = spot(savei, 2)
            spot(savei, 3) = spot(savei, 3) + 100
            IF spot(savei, 3) > 400 THEN GOTO 115
            spot(savei, 4) = num
            spot(savei, 5) = i
            num = num + 1
            dist1 = 0
            dist2 = 0

            END IF
            dist1 = dist2
            IF i = edge AND change = 0 THEN GOTO 115
        NEXT i
        IF change = 0 THEN
            GOTO 115
        ELSE
            GOTO 10
        END IF
115 RETURN
'-----

```

menu:

```
'This subroutine defines the polygon mapped out by the
'steplength arcs
ct = 0
FOR i = 1 TO edge
    IF spot(i, 3) >= 400 THEN
        ct = ct + 1
        old(ct, 1) = spot(i, 1)
        old(ct, 2) = spot(i, 2)
        old(ct, 3) = spot(i, 3)
        old(ct, 4) = spot(i, 4)
        old(ct, 5) = spot(i, 5)
    END IF
NEXT i
IF ct = 2 THEN
    zanswer(ians, 3) = 2
    GOTO 60
END IF
IF change = 0 THEN
    zanswer(ians, 3) = 1
    GOTO 60
END IF
pairs = ct - 1
done = 0
WHILE done = 0
    done = 1
    FOR i = 1 TO pairs
        IF old(i, 4) > old(i + 1, 4) THEN
            temp1 = old(i, 1)
            temp2 = old(i, 2)
            temp3 = old(i, 3)
            temp4 = old(i, 4)
            temp5 = old(i, 5)
            old(i, 1) = old(i + 1, 1)
            old(i, 2) = old(i + 1, 2)
            old(i, 3) = old(i + 1, 3)
            old(i, 4) = old(i + 1, 4)
            old(i, 5) = old(i + 1, 5)
            old(i + 1, 1) = temp1
            old(i + 1, 2) = temp2
            old(i + 1, 3) = temp3
            old(i + 1, 4) = temp4
            old(i + 1, 5) = temp5
            done = 0
        END IF
    NEXT i
    pairs = pairs - 1
WEND

GOSUB chdev      'checks to see if harmonic formed is deviant

IF deviant = 1 THEN
    zanswer(ians, 3) = ct / trav
ELSE
```

```

        zanswer(ians, 3) = ct
    END IF
60 RETURN
'-----
chdev:
    'this subroutine checks if the structured walk produced a
    'deviant harmonic
    trav = 0
    FOR i = 1 TO ct - 1
        IF old(i, 5) > old(i + 1, 5) THEN
            'has crossed the initial point
            trav = trav + 1
            'increase number of traverses
        END IF
    NEXT i
    IF old(ct, 5) > old(1, 5) THEN trav = trav + 1
    IF trav > 1 THEN
        deviant = 1
        zsides = ct / trav
    ELSE
        deviant = 0
    END IF
RETURN
'-----

```

Appendix II-C

Fractal Dimension algorithm


```

'-----Initializing and Dimensioning Arrays-----
  DEFINT A-Y
  DEFDBL Z
  DECLARE FUNCTION bpix& (i&, j&, ml&)
  n = 1500
  DIM pict(n), path(n, 2), spot(n, 3), old(n, 4), now(n, 2)
  DIM perim(n), p2(n)
  OPEN "d:\teresa\data\ash.fra" FOR APPEND AS #5

5  GOSUB clearvar

  READ name$
  IF name$ = "xxxx" THEN GOTO 25

'-----Loop allowing for four different starting points-----
  FOR trun = 1 TO 4

    IF trun = 1 THEN a$ = "a"
    IF trun = 2 THEN a$ = "b"
    IF trun = 3 THEN a$ = "c"
    IF trun = 4 THEN a$ = "d"

    OPEN "d:\teresa\data\" + name$ + a$ + a$ + ".fra" FOR OUTPUT AS #2

12  OPEN "d:\teresa\data\" + name$ + ".dat" FOR INPUT AS #1
    INPUT #1, edge
    FOR i = 1 TO edge
      INPUT #1, now(i, 1), now(i, 2)
    NEXT i
    CLOSE #1

    GOSUB distance      'finds dmax and sets starting point
    GOSUB switch        'forces edge point #1 to be starting point

4   GOSUB clearsoma
    datnum = 0
    sli = 5
    sle = INT(dmax / 5)

    FOR sl = sli TO sle      'loop incrementing step length from 5
                                'pixels to one-fifth of dmax
      datnum = datnum + 1
      perim(sl) = 0
      IF sl > 50 THEN size = 5
      IF sl > 150 THEN size = 10
      IF sl > INT(dmax) THEN
        sle = sl - 1
        GOTO 14
      END IF

      GOSUB clearsoma
      GOSUB fract          'calc perimeter for each step length
    NEXT sl

```

```

17    WRITE #2, trun, name$, datnum
      FOR sl = sli TO sle
        WRITE #2, sl, perim(sl)
      NEXT sl
      CLOSE #2

      NEXT trun
'-----
      GOSUB regress 'Calculating the fractal dimension

      GOTO 5

25 CLOSE #5
      STOP
      END
'-----
clearsome: 'see Appendix B for listing
'-----
switch:
  num = 0
  FOR i = 1 TO edge
    IF now(i, 1) = pxmax1 AND now(i, 2) = pymax1 THEN
      isave = i
      GOTO 43
    END IF
  NEXT i
43 FOR i = isave TO edge
  num = num + 1
  spot(num, 1) = now(i, 1)
  spot(num, 2) = now(i, 2)
NEXT i
  FOR i = 1 TO (isave - 1)
    num = num + 1
    spot(num, 1) = now(i, 1)
    spot(num, 2) = now(i, 2)
  NEXT i
RETURN
'-----
fract:

  perim(sl) = 0
  sum = 0
  savei = 1
  num = 0
  change = 0
  path(0, 1) = spot(1, 1)
  path(0, 2) = spot(1, 2)
  sides = 0

10 FOR i = 1 TO edge
  deltx = spot(savei, 1) - spot(i, 1)
  delty = spot(savei, 2) - spot(i, 2)
  dist2 = deltx * deltx + delty * delty

```

```

IF i = edge THEN
    extradist = SQR(dist2)
    GOTO 18
END IF

IF dist2 > s1 * s1 THEN
    change = 1
    sides = sides + 1
    IF ABS((dist1 - s1 * s1)) < ABS((dist2 - s1 * s1)) THEN
        savei = i - 1
        sum = sum + SQR(dist1)
    ELSE
        savei = i
        sum = sum + SQR(dist2)
    END IF
    path(num, 1) = spot(savei, 1)
    path(num, 2) = spot(savei, 2)
    IF num = 0 THEN
        END IF
    IF num > 0 THEN
        END IF
    num = num + 1
    dist1 = 0
    dist2 = 0
END IF

dist1 = dist2
NEXT i

IF change = 0 THEN
    extradist = 0
    perim(s1) = 0
    GOTO 15
END IF

18 perim(s1) = sum + extradist
p2(s1) = sides * s1 + extradist

15 RETURN
'-----
distance:
dmax = 0
FOR i = 1 TO edge STEP 10
    FOR j = (i + 10) TO edge STEP 10
        dist = ((now(i, 1) - now(j, 1)) ^ 2
            + ((now(i, 2) - now(j, 2)) ^ 2))
        IF dist > dmax THEN
            dmax = dist
            pxmax1 = now(i, 1)
            pymax1 = now(i, 2)
            pxmax2 = now(j, 1)
            pymax2 = now(j, 2)
            edgloc1 = i
            edgloc2 = j
        END IF
    NEXT j
NEXT i

```

```

        END IF
    NEXT j
NEXT i

low1 = edgloc1 - 10
IF low1 < 0 THEN low1 = 1
high1 = edgloc1 + 10
IF high1 > edge THEN high1 = edge
low2 = edgloc2 - 10
IF low2 < 0 THEN low2 = 1
high2 = edgloc2 + 10
IF high2 > edge THEN high2 = edge

FOR i = low1 TO high1
    FOR j = low2 TO high2
        dist = ((now(i, 1) - now(j, 1)) ^ 2
                + ((now(i, 2) - now(j, 2)) ^ 2))
        IF dist > dmax THEN
            dmax = dist
            pxmax1 = now(i, 1)
            pymax1 = now(i, 2)
            pxmax2 = now(j, 1)
            pymax2 = now(j, 2)
            ep1x = pxmax1
            ep1y = pymax1
            ep2x = pxmax2
            ep2y = pymax2
        END IF
    NEXT j
NEXT i

dmax = SQR(dmax) 'length of longest diameter

IF trun = 1 THEN
    IF ep1y < ep2y THEN
        pymax1 = ep2y
        'this sets the starting point as the
        'higher end point of the two
        pxmax1 = ep2x
    ELSE
        pymax1 = ep1y
        pxmax1 = ep1x
    END IF
END IF

IF trun = 2 THEN
    IF ep1y > ep2y THEN
        pymax1 = ep2y
        'this sets the starting point as the
        'lower end point of the two
        pxmax1 = ep2x
    ELSE
        pymax1 = ep1y
        pxmax1 = ep1x
    END IF
END IF

```

```

IF trun = 3 OR trun = 4 THEN
  FOR i = 1 TO edge
    IF now(i, 1) = pxmax1 AND now(i, 2) = pymax1
      THEN edgnum1 = i
    IF now(i, 1) = pxmax2 AND now(i, 2) = pymax2
      THEN edgnum2 = i
  NEXT i

  difference = ABS(edgnum1 - edgnum2)
  edgnum3 = edgnum1 + .5 * difference
  IF edgnum3 > edge THEN edgnum3 = (edgnum3 - edge)
  edgnum4 = edgnum2 + .5 * difference
  IF edgnum4 > edge THEN edgnum4 = (edgnum4 - edge)

  IF trun = 3 THEN
    pxmax1 = now(edgnum3, 1)
    pymax1 = now(edgnum3, 2)
  END IF

  IF trun = 4 THEN
    pxmax1 = now(edgnum4, 1)
    pymax1 = now(edgnum4, 2)
  END IF
END IF

midi = (pxmax2 + pxmax1) / 2
midj = (pymax2 + pymax1) / 2

RETURN
'-----
DATA "sph1","sph2","sph3","sph4","sph5","xxxx"
'-----
regress:

  'This subroutine calculates the linear fit of the just
  'compiled data - using all four runs of the program. It
  'calculates the slope, intercept, and fit correlation
  'coefficient. These values are stored in one separate file.

zsumx = 0
zsumy = 0
zsumxy = 0
zsumx2 = 0
zsumy2 = 0
totalnum = 0

FOR trun = 1 TO 4

  IF trun = 1 THEN a$ = "a"
  IF trun = 2 THEN a$ = "b"
  IF trun = 3 THEN a$ = "c"
  IF trun = 4 THEN a$ = "d"

```

```

OPEN "d:\teresa\data\" + name$+a$+a$+ ".fra" FOR INPUT AS #4

13 INPUT #4, trun, name$, datnum
totalnum = totalnum + datnum
FOR i = 1 TO datnum
    INPUT #4, sl, perim(sl)
    zx = LOG(sl) / LOG(10)
    zy = LOG(perim(sl)) / LOG(10)
    zsumx = zsumx + zx
    zsumy = zsumy + zy
    zsumx2 = zsumx2 + zx * zx
    zsumy2 = zsumy2 + zy * zy
    zsumxy = zsumxy + zx * zy
NEXT i
CLOSE #4
NEXT trun

zm = (totalnum * zsumxy - zsumx * zsumy) /
      (totalnum * zsumx2 - zsumx * zsumx)
zb = zsumy / totalnum - zm * zsumx / totalnum

WRITE #5, name$, zm, zb

RETURN
'-----

```

Appendix II-D

Two-Dimensional Aspect Ratio algorithm

'-----Initializing and Dimensioning Arrays-----

```

DEFING A-V
DECLARE FUNCTION bpix& (i&, j&, ml&)
n = 1500
DIM pict(n), path(n, 2), spot(n, 4), old(n, 4), now(n, 2)
DIM name$(40), dmin(40), dmax(40)
prnt = 0

```

5 CLS : GOSUB clearvar 'clears variables for new data

'-----Reading edge point data file-----

```

READ name$
PRINT name$
IF name$ = "xxxx" THEN GOTO 25
OPEN "d:\teresa\data\" + name$ + ".dat" FOR INPUT AS #1
INPUT #1, edge
FOR i = 1 TO edge
    INPUT #1, now(i, 1), now(i, 2)
    now(i, 2) = 3 / 4 * now(i, 2)
NEXT i
CLOSE #1

```

```

-----
        GOSUB distance    'finds longest diameter (dmax)
        GOSUB switch      'forces upper edge point of dmax to be
                           'starting point
        GOSUB ortho       'finds longest orthogonal diameter (dmin)
                           'to dmax
        GOTO 5
25      GOSUB outpt       'writes aspect ratio to data file
        END

```

DATA "sph1","sph2","sph3","sph4","sph5","xxxx"

clearvar:

'found in Appendix B

switch:

'found in Appendix B

distance:

'found in Appendix B

ortho:

```

IF pymax1 > pymax2 THEN
    max2i = pxmax1
    max2j = pymax1
    max1i = pxmax2
    max1j = pymax2
ELSE

```



```

        max2i = pxmax2
        max2j = pymax2
        max1i = pxmax1
        max1j = pymax1
END IF

distmax = 0
zminslope = -1 / zm
zminb = -pymax1 - zminslope * pxmax1

IF zm < 0 THEN
    GOTO 200
ELSE
    GOTO 400
END IF

200     i1 = max2i - 2
        j1 = -zm * i1 - zb

210     FOR a = 1 TO numsave
            IF spot(a, 1) = i1 THEN
                ztempslope = 0
                check = 1
                GOTO 213
            END IF

            IF check = 1 THEN
                zold = zminslope + .5
                ztempslope = zminslope + 1
                check = 0
                GOTO 213
            END IF

            ztempslope = -(spot(a, 2) - j1) * 1 /
                        (spot(a, 1) - i1)
213     IF a = 1 THEN zold = ztempslope
            yes = 0
            IF zminslope < ztempslope AND zminslope > zold THEN
                yes = 1
            IF zminslope > ztempslope AND zminslope < zold THEN
                yes = 1
            IF yes = 1 THEN
                ztempslope = zminslope
            ELSE
                zold = ztempslope
            END IF

            IF ztempslope = zminslope THEN
                delty = spot(a, 2) - j1
                deltx = spot(a, 1) - i1
                delty = delty * 1
                dist = delty * delty + deltx * deltx
                halfldist = SQR(dist)
                GOTO 220

```

```

                END IF
211      NEXT a
          GOTO 500

220      FOR b = edge TO numsave STEP -1
          IF spot(b, 1) = i1 THEN
            ztempslope = 0
            check = 1
            GOTO 203
          END IF

          IF check = 1 THEN
            zold = zminslope + .5
            ztempslope = zminslope + 1
            check = 0
            GOTO 203
          END IF

          ztempslope = -(spot(b, 2) - j1) * 1 /
                        (spot(b, 1) - i1)
203      IF b = edge THEN zold = ztempslope

          IF zminslope < ztempslope AND zminslope > zold OR
            zminslope > ztempslope AND zminslope < zold THEN
            ztempslope = zminslope
          ELSE
            zold = ztempslope
          END IF

          IF ztempslope = zminslope THEN
            delty = spot(b, 2) - j1
            deltx = spot(b, 1) - i1
            delty = delty * 1
            dist = delty * delty + deltx * deltx
            half2dist = SQR(dist)
            dist = half1dist + half2dist

            IF dist > distmax THEN
              min2i = spot(a, 1)
              min2j = spot(a, 2)
              min1i = spot(b, 1)
              min1j = spot(b, 2)
              distmax = dist
            END IF

            i1 = i1 - 1
            IF i1 <= max1i THEN GOTO 500
            j1 = -zm * i1 - zb
            GOTO 210
          END IF

221      NEXT b
        GOTO 500

400      i2 = max2i + 2

```

```

j2 = -zm * i2 - zb
410  FOR a = 1 TO numsave
      IF spot(a, 1) = i2 THEN
          zold = -100
          GOTO 411
      END IF

      dy = spot(a, 2) - j2
      dx = spot(a, 1) - i2
      ztempslope = -dy * 1 / dx
      IF a = 1 THEN zold = ztempslope
      IF zminslope < ztempslope AND zminslope > zold
          OR zminslope > ztempslope
          AND zminslope < zold THEN
          ztempslope = zminslope
      ELSE
          zold = ztempslope
      END IF

      IF ztempslope = zminslope THEN
          delty = spot(a, 2) - j2
          deltx = spot(a, 1) - i2
          delty = delty * 1
          dist = delty * delty + deltx * deltx
          half1dist = SQR(dist)
          GOTO 420
      END IF
411  NEXT a
      GOTO 500

420  FOR b = edge TO numsave STEP -1
      IF spot(b, 1) = i2 THEN
          zold = -100
          GOTO 421
      END IF

      ztempslope = -(spot(b, 2) - j2) * 1 /
                    (spot(b, 1) - i2)
403  IF b = edge THEN zold = ztempslope
      IF zminslope < ztempslope AND zminslope > zold
          OR zminslope > ztempslope
          AND zminslope < zold THEN
          ztempslope = zminslope
      ELSE
          zold = ztempslope
      END IF

      IF ztempslope = zminslope THEN
          delty = spot(b, 2) - j2
          deltx = spot(b, 1) - i2
          delty = delty * 1
          dist = delty * delty + deltx * deltx
          half2dist = SQR(dist)

```

```

        dist = half1dist + half2dist

        IF dist > distmax THEN
            min2i = spot(a, 1)
            min2j = spot(a, 2)
            min1i = spot(b, 1)
            min1j = spot(b, 2)
            distmax = dist
        END IF

        i2 = i2 + 1
        IF i2 >= max1i THEN GOTO 500
        j2 = -zm * i2 - zb
        GOTO 410
    END IF
421     NEXT b

500     dmin = SQR((min1i - min2i) * (min1i - min2i) +
                (min1j - min2j) * (min1j - min2j))
        dmax(prnt) = dmax
        dmin(prnt) = dmin
        name$(prnt) = name$
        prnt = prnt + 1

RETURN
'-----
outpt:
    OPEN "d:\teresa\data\ash.ASP" FOR OUTPUT AS #2
    FOR i = 0 TO (prnt - 1)
        WRITE #2, name$(i), dmax(i), dmin(i), dmax(i) / dmin(i)
    NEXT i
    CLOSE #2

RETURN
'-----

```

Appendix II-E

Fourier Analysis algorithm

'-----Initializing and Dimensioning Arrays-----

DEFSNG A-Z

n = 1700

DIM edgx(1000), edgy(1000), radius(1000), now(n, 2), spot(n, 2),
temp(n, 2)

DIM radarray(n), angarray(n), radx(n), rady(n), rad(n)

DIM radxarray(n), radyarray(n)

DIM yreal(100), hreal(100)

SCREEN 9

WINDOW SCREEN (0, 0)-(512, 479)

OPEN "C:\teresa\data\RP.For" FOR APPEND AS #3

1 GOSUB start 'reads in edge points and initializes variables
GOSUB distance 'finds the longest diameter
GOSUB switch 'forces upper endpoint of dmax as starting point
GOSUB masscenter 'calculates centroid & equiv circular radius
GOSUB getrads 'calculates n radii about centroid
GOTO 1
STOP

21 CLOSE #3

STOP

END

'-----

start:

rad2deg = 180 / 3.1415

READ name\$

IF name\$ = "STOP" THEN GOTO 21

OPEN "C:\TERESA\DATA\" + name\$ + ".dat" FOR INPUT AS #1

INPUT #1, edge

FOR i = 1 TO edge

INPUT #1, now(i, 1), now(i, 2)

NEXT i

CLOSE #1

NU = 6

n = 2 ^ NU

FOR ij = 0 TO n

rad(ij) = 0

radx(ij) = 0

rady(ij) = 0

radarray(ij) = 0

radxarray(ij) = 0

radyarray(ij) = 0

angarray(ij) = 0

count = 0

yreal(ij) = 0

hreal(ij) = 0

NEXT ij

pi = 3.14159265#

RETURN

```

'-----
distance:  'see Appendix B for listing
'-----
switch:    'see Appendix B for listing
'-----
getrads:

'known:  cx,cy - coordinates of the mass center (centroid)
'        dmax - maximum diameter
'        sx,sy - starting point, edge point #1 after Switch
'        edge = number of edge points in the data file
'        n = number of angles desired

zerox = spot(1, 1)
zeroy = spot(1, 2)
zerotheta = rad2deg * ATN((cy - zeroy) / (zerox - cx))
IF (cy - zeroy) < 0 AND (zerox - cx) < 0
    THEN zerotheta = zerotheta + 180
IF (cy - zeroy) > 0 AND (zerox - cx) < 0
    THEN zerotheta = zerotheta + 180
IF (cy - zeroy) < 0 AND (zerox - cx) > 0
    THEN zerotheta = zerotheta + 360
count = 0

FOR edgpt = 1 TO edge - 1
    angle1 = rad2deg * ATN((cy - spot(edgpt, 2)) /
                          (spot(edgpt, 1) - cx))
    angle2 = rad2deg * ATN((cy - spot(edgpt + 1, 2)) /
                          (spot(edgpt + 1, 1) - cx))
    IF (cy - spot(edgpt + 1, 2)) < 0
        AND (spot(edgpt + 1, 1) - cx) < 0 THEN angle2 = angle2 - 180
    IF (cy - spot(edgpt + 1, 2)) > 0
        AND (spot(edgpt + 1, 1) - cx) < 0 THEN angle2 = angle2 + 180
    IF (cy - spot(edgpt + 1, 2)) < 0
        AND (spot(edgpt + 1, 1) - cx) > 0 THEN angle2 = angle2 + 360
    IF (cy - spot(edgpt, 2)) < 0
        AND (spot(edgpt, 1) - cx) < 0 THEN angle1 = angle1 - 180
    IF (cy - spot(edgpt, 2)) > 0 AND (spot(edgpt, 1) - cx) < 0
        THEN angle1 = angle1 + 180
    IF (cy - spot(edgpt, 2)) < 0 AND (spot(edgpt, 1) - cx) > 0
        THEN angle1 = angle1 + 360

    IF angle1 > zerotheta THEN
        deltheta1 = zerotheta - angle1 + 360
    ELSE
        deltheta1 = zerotheta - angle1
    END IF

    IF angle2 > zerotheta THEN
        deltheta2 = zerotheta - angle2 + 360
    ELSE
        deltheta2 = zerotheta - angle2
    END IF

```

```

FOR m = 0 TO n - 1
  IF m = 0 THEN
    IF deltheta1 < 2 AND deltheta2 < 358 THEN
      IF ABS((deltheta1 - 0)) > ABS((deltheta2 - 360)) THEN
        radarray(count) = SQR((cy - spot(edgpt + 1, 2)) *
                               (cy - spot(edgpt + 1, 2)) +
                               (cx - spot(edgpt + 1, 1)) *
                               (cx - spot(edgpt + 1, 1)))
        radxarray(count) = spot(edgpt + 1, 1)
        radyarray(count) = spot(edgpt + 1, 2)
        angarray(count) = m * 360 / n
        count = count + 1
        GOTO 16
      ELSE
        radarray(count) = SQR((cy - spot(edgpt, 2)) *
                               (cy - spot(edgpt, 2)) +
                               (cx - spot(edgpt, 1)) *
                               (cx - spot(edgpt, 1)))
        angarray(count) = m * 360 / n
        radxarray(count) = spot(edgpt, 1)
        radyarray(count) = spot(edgpt, 2)
        count = count + 1
        GOTO 16
      END IF
    END IF
  END IF
  IF deltheta1 < (m * 360 / n) AND deltheta2 > (m * 360 / n)
    THEN
      IF ABS((deltheta1 - (m * 360 / n))) >
        ABS((deltheta2 - (m * 360 / n))) THEN
        radarray(count) = SQR((cy - spot(edgpt + 1, 2)) *
                               (cy - spot(edgpt + 1, 2)) +
                               (cx - spot(edgpt + 1, 1)) *
                               (cx - spot(edgpt + 1, 1)))
        radxarray(count) = spot(edgpt + 1, 1)
        radyarray(count) = spot(edgpt + 1, 2)
        angarray(count) = m * 360 / n
        count = count + 1
        GOTO 16
      ELSE
        radarray(count) = SQR((cy - spot(edgpt, 2)) *
                               (cy - spot(edgpt, 2)) +
                               (cx - spot(edgpt, 1)) *
                               (cx - spot(edgpt, 1)))
        angarray(count) = m * 360 / n
        radxarray(count) = spot(edgpt, 1)
        radyarray(count) = spot(edgpt, 2)
        count = count + 1
        GOTO 16
      END IF
    END IF
  NEXT m
16 NEXT edgpt

```



```

FOR m = 0 TO (n - 1)      'bubble sort for longest radii
  FOR i = 0 TO (count - 1)
    IF angarray(i) = m * 360 / n THEN
      IF radarray(i) > rad(m) THEN
        rad(m) = radarray(i)
        radx(m) = radxarray(i)
        rady(m) = radyarray(i)
      END IF
    END IF
  NEXT i
NEXT m

OPEN "C:\TERESA\DATA\" + name$ + ".for" FOR OUTPUT AS #4

WRITE #3, name$, n, cx, cy, sum, egrad
FOR m = 0 TO (n - 1)
  WRITE #4, rad(m)
NEXT m
CLOSE #4

```

RETURN

masscenter:

```

xsum = 0
ysum = 0
sum = 0
minlx = 10000
maxlx = 0
minly = 10000
maxly = 0

```

'finding max and min xs and ys for vertice of box around
'image

```

FOR i = 1 TO num - 1
  IF spot(i, 2) < minly THEN minly = spot(i, 2)
  IF spot(i, 2) > maxly THEN maxly = spot(i, 2)
  IF spot(i, 1) < minlx THEN minlx = spot(i, 1)
  IF spot(i, 1) > maxlx THEN maxlx = spot(i, 1)
NEXT i
IF spot(num, 2) < minly THEN minly = spot(num, 2)
IF spot(num, 2) > maxly THEN maxly = spot(num, 2)
IF spot(num, 1) < minlx THEN minlx = spot(num, 1)
IF spot(num, 1) > maxlx THEN maxlx = spot(num, 1)
centery = (maxly - minly) / 2 + minly
centerx = (maxlx - minlx) / 2 + minlx

```

PAINT (centerx, centery), 2

```

FOR j = minly TO maxly
  FOR i = minlx TO maxlx
    test = POINT(i, j)
    IF test = 2 THEN
      xsum = xsum + i
      ysum = ysum + j
      sum = sum + 1
    END IF
  NEXT i
NEXT j

```

'testing points within box
'for color- if part of image
'(color=2) increment x and
'y sums separately

```

            END IF
        NEXT i
    NEXT j

    cx = xsum / sum
    cy = ysum / sum
    eqrad = SQR(sum / pi)
RETURN
'-----
DATA "RP1","RP2","RP3","RP4","RP5","RP6","RP7","RP8","RP9","RP10"
'-----

```

Appendix II-F

Fast Fourier Transform algorithm

'This program performs a Fast Fourier Transform on a
 'set of data consisting of N equally spaced samples.
 'The total number of data points (nd) must be a power of 2.
 'In this case, the total number was consistently 64

'-----
 'This section declares the sub programs SUB FFTCalc, and SUB
 'FFTSolve of the main module FFT.BAS for use.
 '-----

```
DECLARE SUB FFTCalc (xreal!(), yimag!(), numdat%)
DECLARE SUB FFTSolve (xreal!(), yimag!(), numdat%, flag%)
  DIM xreal(64), yimag(64), yreal(64)
  DIM nd AS INTEGER
  DIM i(64)
  nd% = 64
  SCREEN 9
  WINDOW (0, 0)-(2000, 1500)
```

'-----
 'This section inputs the data set of 64 points from the data's home
 'directory.
 '-----

```
1      CLS
      READ a$
      PRINT a$
      IF a$ = "stop" THEN GOTO 5
      OPEN "d:\TERESA\DATA\" + a$ + ".FOR" FOR INPUT AS #1
          FOR i = 0 TO (nd - 1)
              INPUT #1, xreal(i)
              LINE (i, 0)-(i, xreal(i))
              yimag(i) = 0
          NEXT i
      CLOSE #1
```

'-----
 'This section calls the sub program FFTCalc, and uses the sub
 'program FFTSolve to perform the actual Fourier Transform on the
 'data set.
 '-----

```
      CALL FFTCalc(xreal(), yimag(), nd%)
      OPEN "c:\teresa\data\" + a$ + ".fft" FOR OUTPUT AS #1
      WRITE #1, a$
          FOR i = 0 TO (nd - 1)
              WRITE #1, i + 1, xreal(i)
          NEXT i
      CLOSE #1
      GOTO 1
```

```
5      STOP
```

'-----
 'DATA"RP1F", "RP2F", "RP3F", "RP4F", "RP5F", "stop"
 '-----

'This section creates a quick plot of the Fourier Transform.

'-----

CLS

max = 0

FOR i = 1 TO 2047

xreal(i) = ABS(xreal(i))

IF xreal(i) > max THEN max = xreal(i)

NEXT i

FOR j = 1 TO 2047

LINE (j, 0)-(j, xreal(j) / max * 500), 13

NEXT j

a1\$ = ""

WHILE a1\$ = ""

a1\$ = INKEY\$

WEND

Appendix II-G

Not-Roundness algorithm

```

'-----Initializing and Dimensioning Arrays-----
CLS
n1 = 40
n2 = 64
DIM R(n2), REQ(n1), NR(n1), A$(n1), ND(n1), CX(n1), CY(n1), A(n1)
OPEN "D:\TERESA\DATA\ASH.NR" FOR APPEND AS #3

'-----Reading in equivalent radii (Ro) of n1 particles-----
OPEN "D:\TERESA\DATA\ASH.FOR" FOR INPUT AS #2
FOR J = 1 TO n1
    INPUT #2, A$(J), ND(J), CX(J), CY(J), A(J), REQ(J)
NEXT J
CLOSE #2
'-Reading the radii(Ri) of one particle at a time for n1 particles-
FOR K = 1 TO n1
    CLS
    READ name$
    PRINT name$
    IF name$ = "STOP" THEN GOTO 5
    OPEN "D:\TERESA\DATA\" + name$ + ".FOR" FOR INPUT AS #1
    FOR I = 1 TO n2
        INPUT #1, R(I)
    NEXT I
    CLOSE #1

'-----Calculating NR of one particle at a time for n1 particles---
    SUM = 0
    FOR L = 1 TO n2
        SUM = (R(L) - REQ(K)) * (R(L) - REQ(K)) + SUM
    NEXT L
    NR(K) = (1 / (n2 * REQ(K) * REQ(K))) * SUM
    WRITE #3, A$(K), SUM, REQ(K), NR(K)
NEXT K

5  CLOSE #3
    STOP

'-----Data File Listing-----
DATA "ash1","ash2","ash3","ash4","ash5","stop"
'-----

```

Appendix II-H

Electron Microscope Photographs

Appendix II-H: Electron Microscope Photographs

The wear specimens were photographed under the electron microscope in order to closely observe the wear mechanisms. The photographs confirmed the conclusions of the research and demonstrated that the wear mechanism is dependent on particle shape.

For the glass spheres the primary wear mechanism was fatigue of small platelets of wear specimen material. In the attached photographs the platelets of brass can be clearly seen at 1,000 magnification. In addition, the fatigue crack on a platelet was photographed at 10,000 times magnification. The wear particles generated by the glass spheres are the thin flake-like platelets.

The coal ash and the aluminum oxide wear particles caused a different wear mechanism. The shape of the particles resulted in a micro-cutting type of wear on the specimens. The wear specimen photography clearly shows the cutting process. In this type of mechanism wear particles often get stuck in the wearing surface as can be seen in the photograph of the Aluminum Oxide particles at a magnification of 2,200. At a magnification of 17,000 the surface of the wear specimen shows the cutting ruts as well as small debris.

The results from the electron microscope confirm the importance of particle shape on the three-body wear process.

Platelet Formation on a Brass Specimen Under Wear By Glass Beads 1,000 Magnification

Fatigue Crack on a Platelet on a Brass Wear Specimen Under Wear by Glass Beads 10,000 Magnification

Microcutting Grooves On A Brass Wear Specimen Under Wear By Aluminum Oxide Particles, 2,200 Magnification

Microcutting Grooves And Wear Debris On A Brass Wear Under Wear By Aluminum Oxide Particles, 17,000 Magnification

PROJECT SUMMARY

The tasks completed in this project provided new insight into the three-body wear process. The highlights of the research are summarized as follows:

1. A new type of three-body wear test machine was developed. The important features of the machine include the ability to accurately position the wear specimens to within ± 1 micron of each other. This feature allows the study of particle shape and its effect to take place because it allowed the wearing process to occur without destroying the wear particles.
2. A wide range of wear tests were conducted with several types of wear specimens and wear particles. These wear particles included aluminum oxide, glass spheres, coal ash and sand that were used on combinations of aluminum and brass wear specimens.
3. Accurate data was taken that described the normal and frictional forces in the wear process as well as the actual length and velocity traveled by the wear specimen.
4. To assess the relationships between three-body wear and particle shape, samples of the particle. were subjected to image analysis using an optical microscope and video camera connected to a "frame-grabber" board in a personal computer. Each two-dimensional particle image was analyzed to determine the sequence of points comprising the image edge. From this set of edge points quantitative shape descriptors such as fractal dimension, Fourier coefficients, aspect ratio and harmonic persistences were calculated for each particle, and distributions of shape descriptors were found for each particle sample. All of these descriptors, as expected, showed that the rate of three-body wear depended on particle shape.
5. It was found that in terms of these descriptors shape of particles changed little during the three body wear process.
6. The electron microscope revealed the wear process to be very dependent on particle shape.
7. The research done in this grant has developed an excellent test bed from which future wear research will be conducted.

END

**DATE
FILMED
03/2/92**