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The Effects of Layer Thickness on Dry-Sliding Wear of Binder Jet Additively Manufactured Stainless Steel and Bronze Composite

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By

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This thesis has been examined and approved by the following members of the student's committee.

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Abstract

Title: The Effects of Layer Thickness on Dry-Sliding Wear of 420 Stainless Steel and 90/10 Bronze Composite

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Pin on disk wear testing was used to compare additively manufactured binder jet metal matrix composites. The process parameters were changed. The layer thickness and applied forces were varied for the experimental study. Three different layer thicknesses used were, 50µm, 100µm, and 200µm. The pin used was a 420 stainless pin. The wear characteristics of the disk were examined using pin-on-disc method. The material tested was a composite of 420 stainless steel, and 90-10 bronze. Samples were weighed before, during, and after the test to determine differences in mass. Wear tracks were examined using a Scanning Electron Microscope. The results indicated increased wear for both thickness, and larger forces.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

In the past, automotive parts were manufactured with traditional methods. Parts were casted, pressed, molded, welded, and machined. As automobiles advance into the future, so must the methods of automobile manufacturing. Additive Manufacturing (AM), also known as 3D printing or Rapid Prototyping (RP), is making advances in the automotive field. From printing replacement parts to making custom one-off parts, AM is often cheaper and faster than traditional manufacturing methods for low volume production in the thousands. Additive manufacturing is being utilized in ways never imagined even a few years ago. One of the additive manufacturing technologies being used is binder jet. Binder jet technology utilizes powdered metal to create parts.

Changing the process parameters when manufacturing parts effects how the parts wear. The materials used were Stainless Steel 420 and 90/10 bronze. The process parameters that were changed were the layer thickness and the force. Samples were tested in order to rank the materials based on wear. Samples that had thinner layers wore less than those with thicker layers. The primary objective of this body of research was to examine the wear characteristics of AM materials.

Additive Manufacturing

Additive manufacturing is a relatively new manufacturing process, in the history of manufacturing. In the past for a part to be created, a larger raw piece of material was selected and was machined to achieve the desired finished result. Traditional manufacturing processes consisted of, turning, grinding, milling, planning, drilling, etc. This was referred to as subtractive machining, as material was removed to create the desired finished piece. Only recently have people been able to manufacture parts using an additive method instead of a subtractive method. The ability to additively manufacture products has opened up new possibilities for complex solid parts. The manufacture of small batch, or custom parts that were previously too expensive, too complicated, or nearly impossible to manufacture subtractively were now possible to produce relatively quickly and inexpensively.

Additive manufacturing is the overarching term to describe a manufacturing process where material is added instead of removed. Early systems were an extrusion type. Since then, additive manufacturing technologies have evolved into many different types. Some common technologies today are Photopolymerization, Selective Laser Sintering, Fused Deposition Modeling, Laminated Object Manufacturing, binder jet, etc. Each of these technologies has their own advantages and disadvantages.

Most additive manufacturing processes follow a similar cycle from concept to realization. The sequence follows the eight basic steps listed in Figure 1.

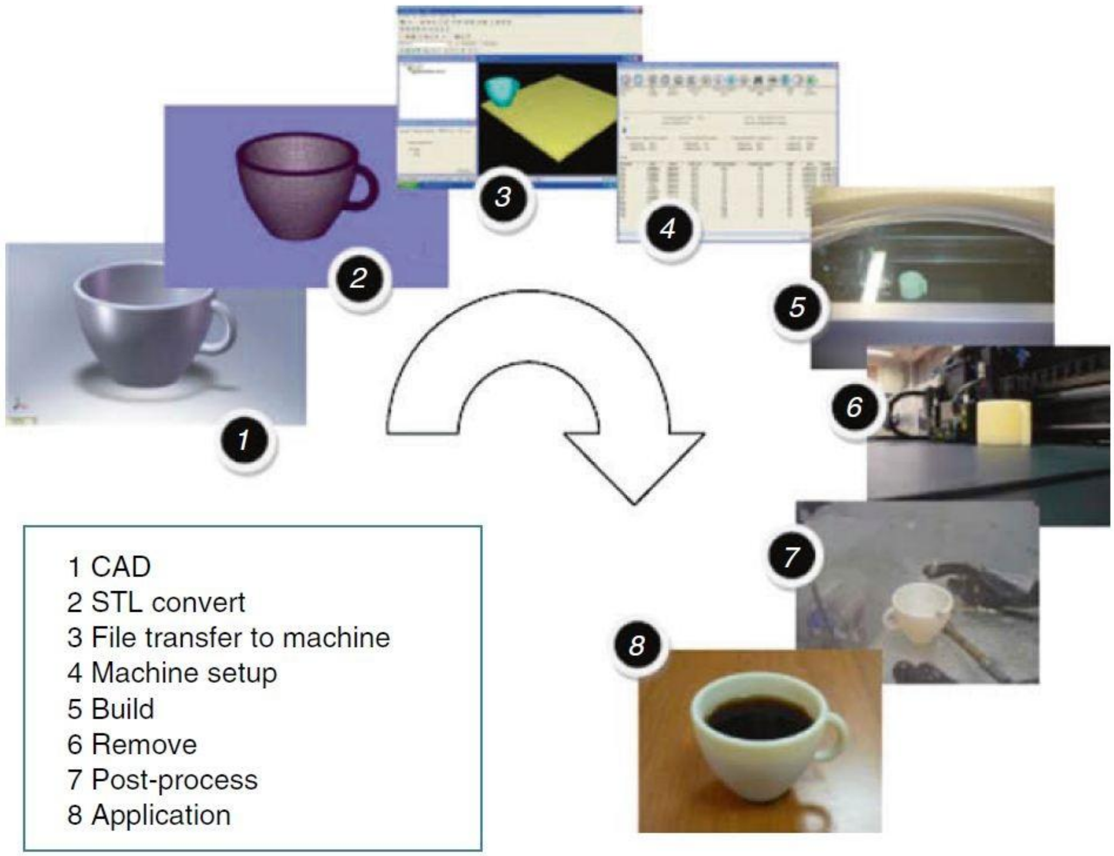

Figure 1 (Gibson, Rosen, & Stucker, 2010)

1. CAD

    All AM parts must start from a software model that fully describes the external geometry. This can involve the use of almost any professional CAD solid modeling software, but the output must be a 3D solid or surface representation. Reverse engineering equipment (e.g., laser scanning) can also be used to create this representation.

2. STL Convert

    Nearly every AM machine accepts the STL file format, which has become a defacto standard, and nearly every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.

3. File Transfer to Machine

   The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.

4. Machine Setup

   The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.

5. Build

   Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.

6. Remove

   Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.

7. Post-Process

   Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.

8. Application

   Parts may now be ready to be used. However, they may also require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish. Treatments may be laborious and lengthy if the finishing requirements are very demanding. They may also be required to be assembled together with other mechanical or electronic components to form a final model or product. (Gibson, Rosen, & Stucker, 2010)

Computer Aided Design

Before something can be additively manufactured, a digital representation must be created. Parts are digitally created using different methods. 3-Dimension models are constructed using Computer Aided Design (CAD) software. This software allows the part to be manipulated in 3-dimensions and examined virtually before being manufactured. 3-dimensonal models can also be created using reverse-engineering technology. (Gibson, Rosen, & Stucker, 2010) Once the part is created using CAD software it needs to be converted into a format that the additive manufacturing machine can utilize. Typically, the file type utilized by additive manufacturing machines is an STL file.

(Gibson, Rosen, & Stucker, 2010) STL is the file extension, and is an acronym for Standard Tessellation Language. (RapidToday, 2009) The STL file contains information about the part in a series of interconnected triangles. These triangles are what make up the part, Figure 3b. The more triangles in the part, the more accurately the part represents the original Figure 3a. The more accurate the STL file, the smaller, and more abundant the triangles.

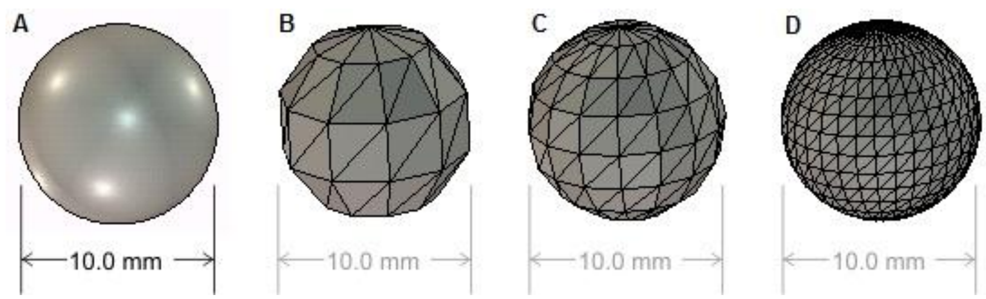

Figure 2 (InkBerry, 2014)

The part must also be converted into layers. The slicing of the part into layers is done in the additive manufacturing machine Figure 3c. Most machines have the ability to change the parameters of the part before printing such as layer thickness, print speed. (Gibson, Rosen, & Stucker, 2010)

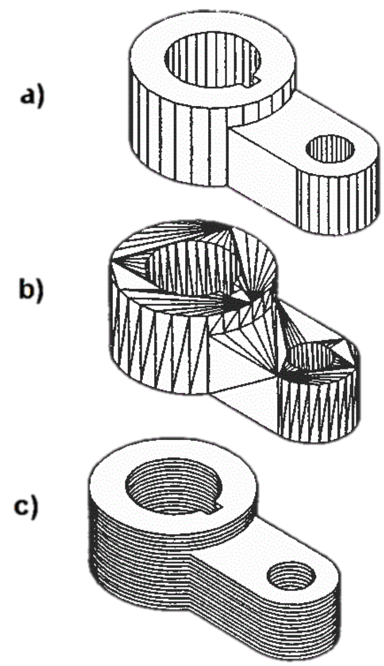

Figure 3 (University of Texas, Austin, 2000)

Types of Additive Manufacturing

There are many types of additive manufacturing technologies. Some of the commercially available types are photopolymerization, fused deposition modeling, selective laser sinter, and binder jet. Binder jet technology was used in for this research

Photopolymerization

Photopolymerization works by using liquid monomers. The process works by exposing the liquid polymer to radiation, a laser, or a light source (typically UV). The monomer changes state from a liquid to a solid. Parts are printed layer by layer.

The photopolymer is contained in a vat. Inside the vat of photopolymer is where the part is printed. The part rests on a bed, and a laser (typically) is used to trace the layer of the part, Figure 4. Each layer is added successively to the previous layer, in order to form a complete part. With photopolymerization, it is necessary to have support structures. These support structures maintain the desired shape of the part during manufacturing. Photopolymerization produced parts require some post processing. Support structures must be removed after the part is finished, also the part must be removed from the bed that it was printed.

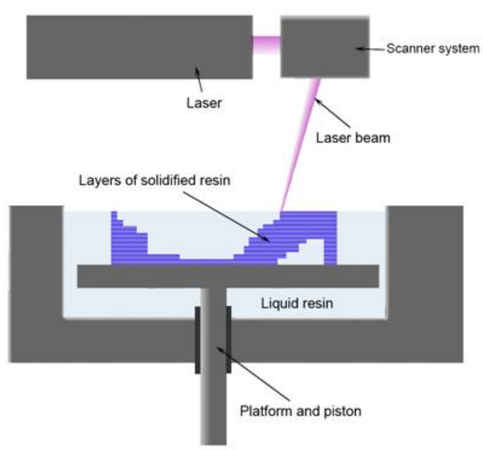

Figure 4 (Materialgeeza, 2008)

Fused Deposition Modeling

Fused Deposition Modeling (FDM) works by extruding material layer by layer, Figure 5. Material is extruded to create the part much like toothpaste from a tube. Plastic or wax filament is typically the medium for this technology, although other materials such as wood fibers can be used (Grunewald, 2014). The material is typically in a coiled filament, and is fed into the extruding nozzle as it is extruded. The nozzle is heated to facilitate extrusion. The heated nozzle causes the material to become molten. The extruded material hardens almost immediately after it leaves the extrusion nozzle. Typically, on these systems, the nozzle moves in the X and Y directions and the printing bed moves down incrementally as new layers are produced.

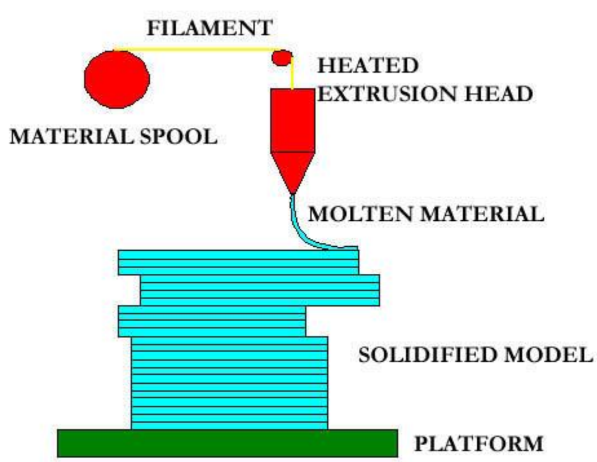

Figure 5 (Nithish, 2012)

Selective Laser Sintering

Selective Laser Sintering (SLS) is a technique that uses lasers and powdered material (typically metal) to create 3-dimensional parts (Figure 6). The technology uses high-powered lasers to sinter together powdered metal. The laser heats up the powdered metal in each layer causing it to sinter together. Parts are constructed layer by layer. The laser moves in two directions, the X and Y planes, and selectively sinters the areas defined by the CAD file. Once one layer has been sintered, the next is created. The next layer is created by adding another layer of powdered metal. Selective laser sintering machines typically have two platforms, or beds. One bed has all of the unsintered powdered metal. The other bed is the bed where the part is constructed. As a layer is completed, a new layer of unsintered powdered metal must be added. Once a layer of powdered metal has been sintered together, the bed containing the sintered part moves down in preparation for the next layer. The build bed moves down one increment in preparation for the next layer. After the printing bed has moved down for the next layer, the bed containing the unsintered powdered metal moves up one increment. When both beds are done moving up and down, a roller moves across the beds. The roller moves from the bed containing unsintered powdered metal toward the bed containing the sintered powdered metal. This roller will drag, and evenly distribute the next layer of unsintered powdered metal over the layer of powdered metal that has just been sintered. The roller ensures that each layer on the print bed is the same thickness as the previous layer. Once the new layer of powder has been rolled on top of the previous layer, the process begins again with another layer being sintered by the laser. When all layers have been completed the part is removed from the printing bed, and the loose material is removed. The part may require some post processing, but this is not always necessary.

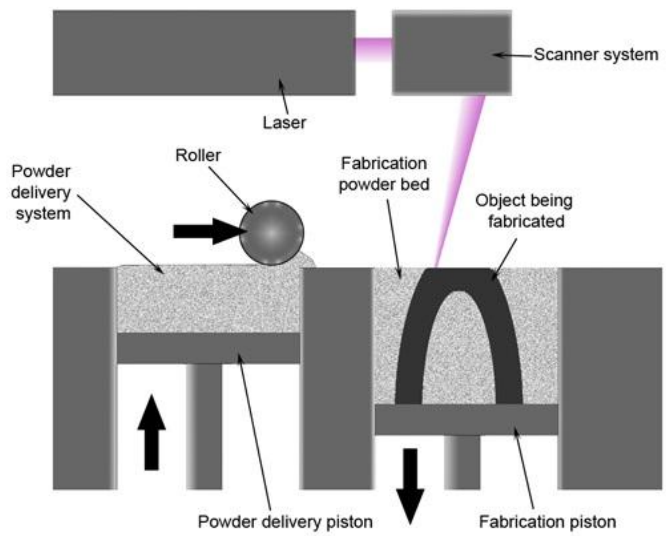

Figure 6 (Materialgeeza, 2008)

Binder Jet Technology

The technology used in this experiment is binder jet technology. This technology is, in some ways, similar to Selective Laser Sintering (SLS) type technology. Selective Laser Sintering uses high-powered lasers to bind powder together in layers. Binder jet technology uses an ink-jet type print head instead of a high-power laser to bind together areas of each layer. The print head sprays a binding agent and bind powder together.

ExOne M1-Lab

The technology utilized in this research was binder-jet technology. An ExOne M1-Lab machine was used to create the metal composite samples in this experiment. This machine is typically used for research, or education in a laboratory setting (ExOne, 2013). Powered metal, in addition to binding material and heat, are utilized to produce the part. Like other additive manufacturing processes, the samples were printed layer by layer. The machine contains two beds, a powder bed, and a build bed. The powder bed contains all of the powdered metal required for printing. Adjacent to the powder bed is the build bed, where the layered part was printed, Figure 7.

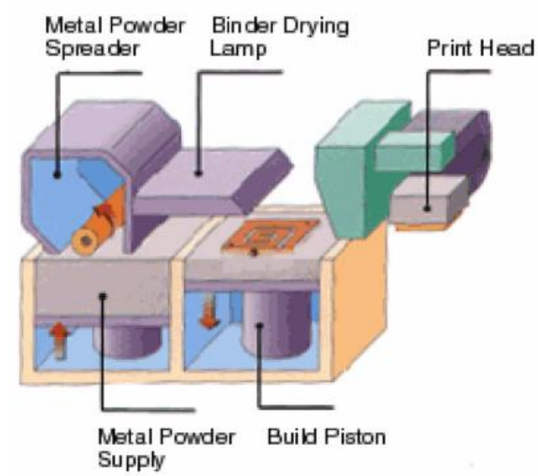

Figure 7 (ExOne, 2013)

A layer of powder is spread across the build bed, and binder is applied based on the predefined tool path. The binder is dried for a short time (≈10 sec) under a heater, and then then another layer is spread on top of the previous layer. The process continues until the part is printed. At this point, the printed part is encapsulated with loose powder. This loose powder acts as a temporary support material. The part is then removed from the printing machine, and the loose powder is removed. The part is then transferred into an oven. In the oven, the part is heated to fuse the metal particles together. The binder material is also burned away when the part is in the oven. Once the part has been removed from the oven, it has an approximate density of 50%. The density is somewhat variable depending on the layer thickness, and the size of the powdered metal. Using a scale, and the volume of the printed part, either from the CAD drawing or from measuring, the density of the part is derived. The density of the part determines how much material is required for infiltration. The bronze is measured out by weight, and placed in a container with the powered metal part. The container with the infiltration material and the printed part are then placed into a cup that contains ceramic grains, Figure 8.

Figure 8 Sintered Part and Powdered Bronze (ExOne, 2013)

This container is placed inside an electric furnace. Air is evacuated from the furnace, and replaced with argon at atmospheric pressure. The furnace gradually increases in temperature in stepped increments until it reaches the maximum temperature. Upon reaching maximum temperature, the temperature is slowly brought back down in stepped increments, until it reaches room temperature. At this point, the part is finished, and ready for secondary finishing. Figure 9 shows this process in a flow chart.

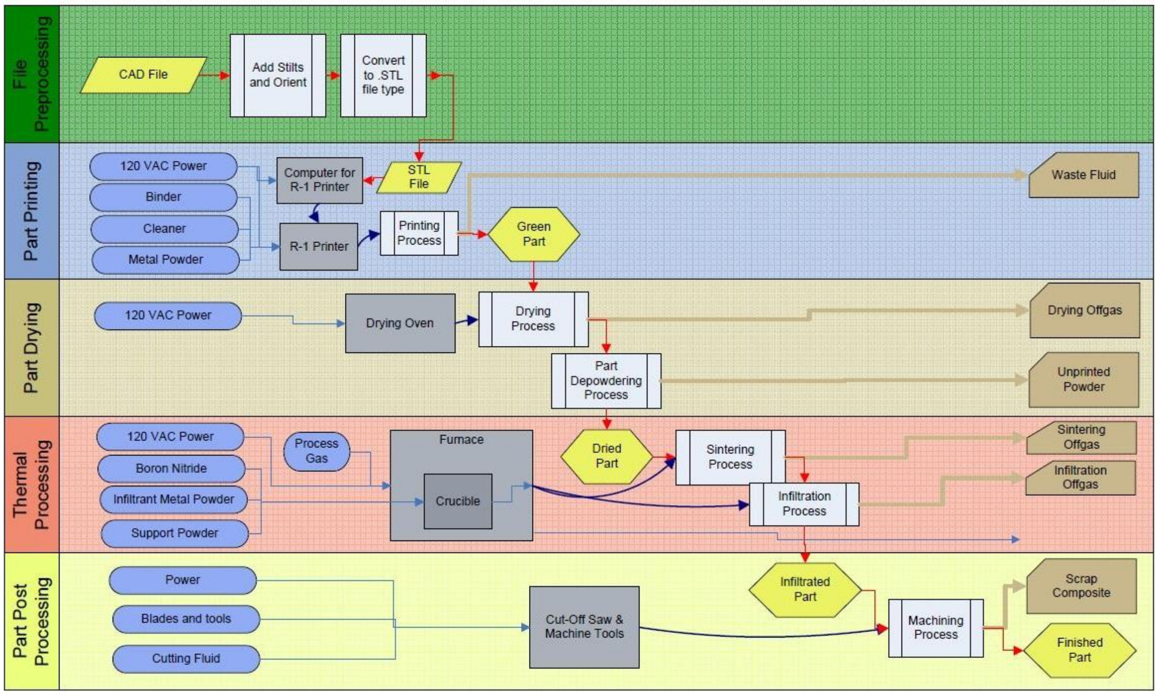

Figure 9 (ExOne, 2013)

Metal Matrix Composite

A metal matrix composite (MMC) is a composite that uses metal as the matrix, reinforcement, or both. SLS and binder jet are two examples of an AM process that create an MMC. In the case of the binder jet technology, metal is used as the matrix, and the reinforcement. The stainless steel is the reinforcement, and the bronze is the matrix.

Chapter 2

Material Wear

Wear is a common occurrence in everyday life. Wear occurs wherever two or more surfaces are in contact with each other. Shoes, engine parts, brakes, cutting tools, are all examples of things that wear. The American Society of Testing and Materials (ASTM) has defined wear as the "alteration of a solid surface by progressive loss or progressive displacement of material due to relative motion between that surface and a contacting substance or substances" (ASTM, Standard Terminology Relating to Wear and Erosion, 2013). The study of how surfaces in motion interact with each other is called tribology. Because of the complex nature of wear, and how surfaces interact, wear is typically broken down into different categories. Wear is often broken down into some common categories: adhesive wear, abrasive wear, surface fatigue, fretting wear, erosive wear, and tribochemical reaction. This study focuses primarily on the characteristics of adhesive wear, and abrasive wear.

Adhesive Wear

Adhesive wear occurs when material from one sliding surface is displaced onto the other surface which it slides against. ASTM defines adhesive wear as "wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or loss from either surface (ASTM, Standard Terminology Relating to Wear and Erosion, 2013).

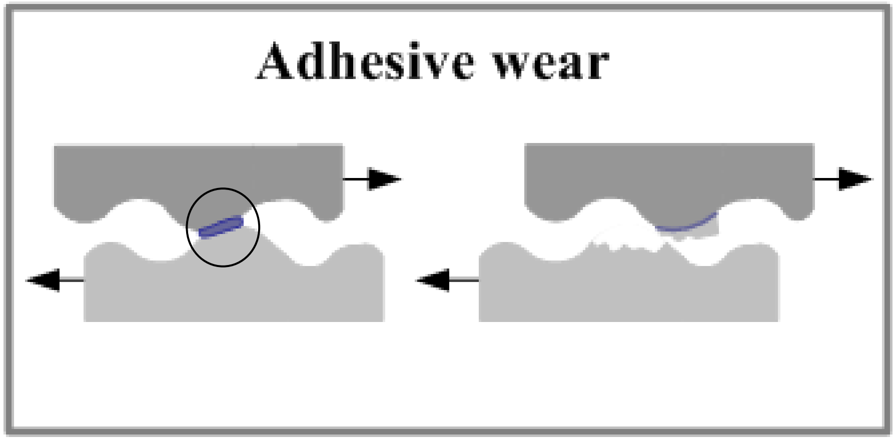

Figure 10 (Kopelovich, 2014)

Figure 10 shows the asperities in the two sliding surfaces. The circled area shows the collision of the asperities. Followed by the collision, material is removed from one surface, and displaced onto the other surface. Figure 11 is a scanning electron microscope (SEM) micrograph of material transfer that occurred during adhesive wear; softer steel is deposited on a hardened steel surface (Gahr, 1987).

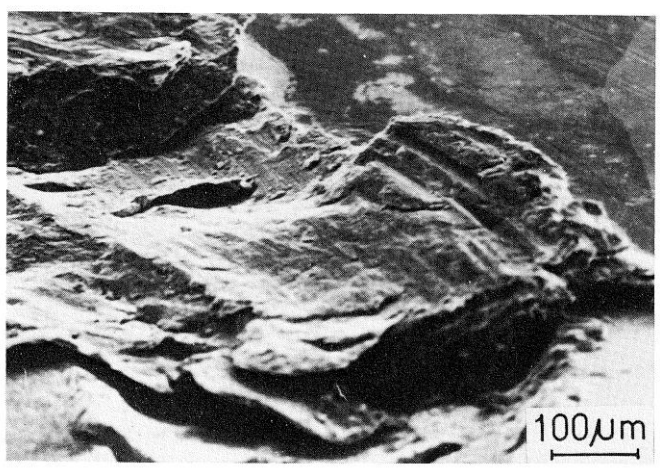

Figure 11 (Gahr, 1987)

Abrasive Wear

Abrasive wear is defined by the ASTM as “wear due to hard particles or hard protuberances forced against and moving along a solid surface” (ASTM, Standard Terminology Relating to Wear and Erosion, 2013). Abrasive wear can be classified by the different types. Abrasive wear has two modes: two-body, and three-body. With two-body wear, the hard surface removes material from the contact surface. The particles created are constrained. Three-body wear occurs when loose particles are introduced, or generated between the contacting surfaces (ASTM, Standard Terminology Relating to Wear and Erosion, 2013). These different modes of wear are shown in Figure 12 .

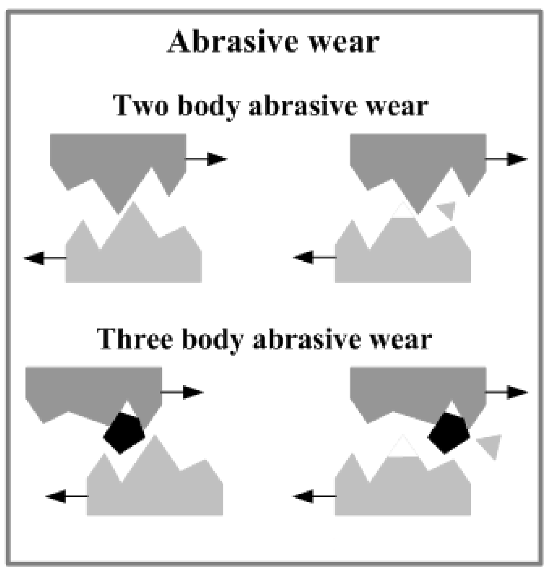

Figure 12 (Kopelovich, 2014)

Abrasive wear is further broken down by the type of mechanisms. Different examples of these mechanisms are microplowing, microcutting, microfatigue, and microcracking. These different mechanisms are shown in Figure 13

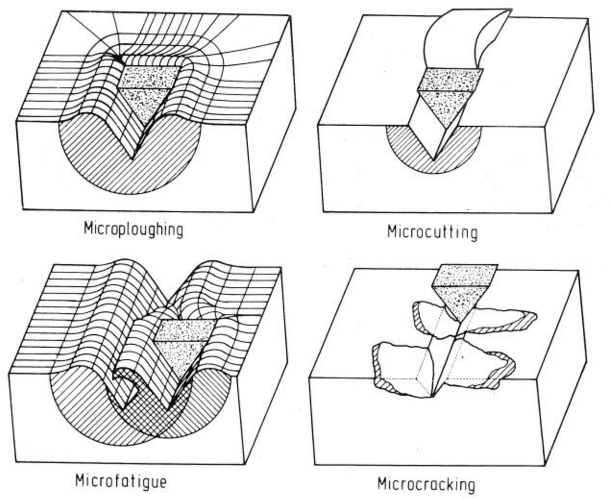

Figure 13 (Gahr, 1987)

Measuring Wear

The measurement of wear is complex issue. There are a number of different ways to measure wear. The ASTM, as well as the German Institute for Standardization (DIN) has developed test methods for measuring wear. Measuring wear is typically done with a tribometer, a device specifically made for measuring wear. Several different tribometers, and test methods exist. Some examples of tribometers are; block-on-ring, twin-disk, and pin on disk. This study will focus on the pin-on-disk method from the ASTM G99 test procedure.

ASTM Standards.

ASTM committee *G02* has created testing standards that deal with wear, and measuring wear. These standards are used to help compare wear of different materials, and ensure that testing is done in a controlled environment and all variables are accounted for. Volume is used because it provides a better picture of wear than the change in mass. Volume loss, due to the loss of material from wear, is used as a comparison due to the differing densities in materials. The ASTM cautions that information gleaned from wear testing should only be used for comparison purposes, and that wear cannot be predicted outside the specific conditions the in which the material originally tested.

Standard G99 is the Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. Figure 14 shows a diagram of the pin-on-disk test method. These standards state that wear should be expressed in volume (mm^3). As stated by the ASTM, “For the pin-on-disk wear test, two specimens are required. One, a pin with a radiused tip, is positioned perpendicular to the other, usually a flat circular disk. A ball, rigidly held, is often used as the pin specimen. The test machine causes either the disk specimen or the pin specimen to revolve about the disk center. In either case, the sliding path is a circle on the disk surface. The plane of the disk may be oriented either horizontally or vertically” (ASTM, Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus, 2013).

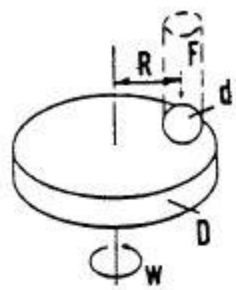

Figure 14 (ASTM, Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus, 2013)

Automotive Application

Understanding the interaction between contacting surfaces is of great concern to manufacturing, and engineering. Wear is present in almost every system in a modern automobile. From pistons, to camshafts, to axles, to brakes, all of these items are subject to high forces. These items are in contact with other surfaces. In addition to being subject to high forces, they are also in contact with surfaces of relative motion. This relative motion and contact creates wear. Understanding how these materials will wear is of great interest to engineers and manufacturers. Automotive components are expected to have a long life span, and provide the customer with a low-maintenance, long-lasting product. Additive manufacturing has been making its way into the automotive field. Currently additive manufacturing is utilized for sand-casting, and for rapid prototyping of parts. Manufacturers are now starting to utilize additive manufacturing processes to produce parts to be used on production cars. An example of an additively manufactured parts is the titanium exhaust tip on the Koenigsegg One:1. As additively manufactured components start making their way into engine, drivetrain, and suspension systems, the characteristics of wear become a great concern. Engine and drivetrain components are subject to some of the highest forces in an automobile. Engine components need to have a very high wear resistance. The development of materials, and the understanding of the wear characteristics of additively manufactured components is crucial to the further expansion of additive manufacturing into the automotive field.

Chapter 3

Experimental Plan

The parameters examined in this body of research were the layer thicknesses, and applied forces. Three different layer thickness were examined, 50µm, 100µm, and 200µm. In addition to layer thickness, three different pin forces were also examined. Forces of 89N (20 lbs), 178N (40 lbs), and 267N (60 lbs) were used. A modified version of the ASTM G99 standard was used to conduct pin-on-disk wear testing. The test was performed for 30 minutes at a speed of 0.0429 m/s (80 rpm) with a total sliding distance 77.19m. Tests were performed in 10-mintue intervals to give a better prediction of wear over time.

Material Selection

The materials examined in this study were stainless steel 420 (SS420), and 90/10 bronze. Stainless steel was printed from powered metal. The stainless steel had an average particle size of 30µm, with a density of 2.75 g/cm^3. The material composition is shown in Table 1.

Chemical Composition of Stainless Steel 420 by weight %					
Carbon	Manganese	Phosphorus	Sulfur	Silicon	Chromium
0.15 min	1.00 max	0.040 max	0.030 max	1.00 max	12.00 – 14.00

Table 1

The material chosen for the infiltrate was bronze. The bronze was 90% Copper and 10% Tin, by weight composition. Prior to any samples being produced, the metals were examined under an SEM. The micrographs for SS420 can be seen in Figure 15 and Figure 16, and bronze in Figure 17 and Figure 18.

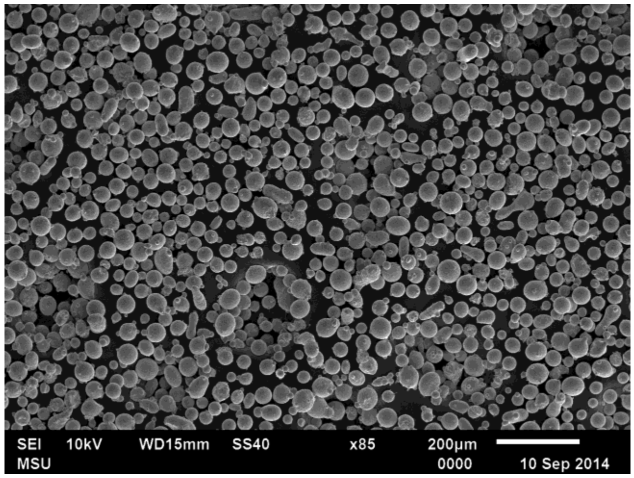

Figure 15 Powdered SS420

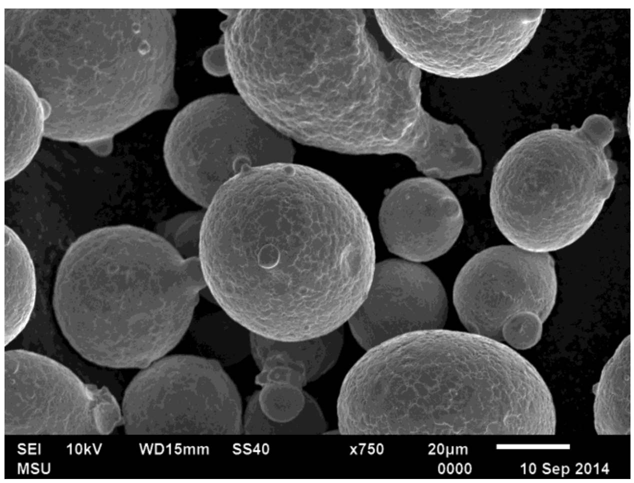

Figure 16 Powdered SS420

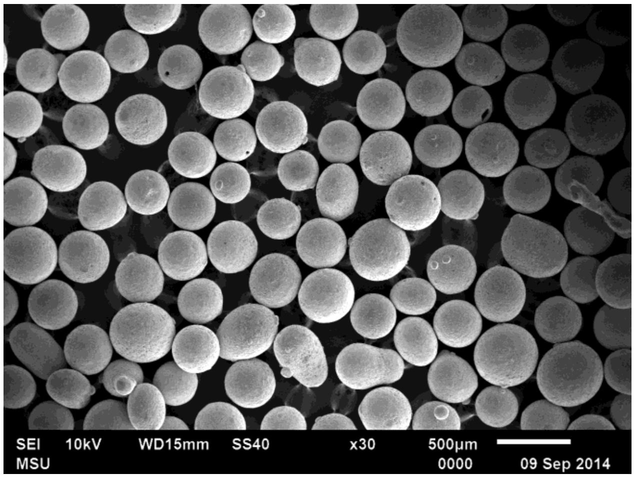

Figure 17 Powdered Bronze

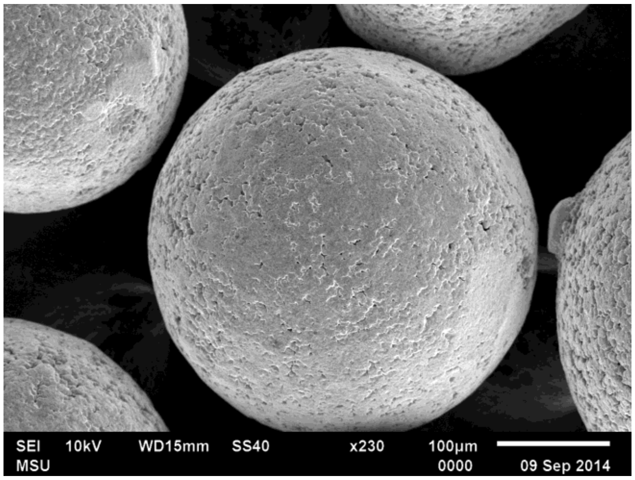

Figure 18 Powdered Bronze

For the pins, stainless steel 420 was also used. The SS420 pins were chosen because of the use of SS420 in the disks.

Material Preparation

The discs were printed using an M1 machine. The discs were 19mm in diameter, with a thickness of 8mm. The diameter of 19mm was chosen because it allowed multiple discs to be printed at once. A diagram of the disk can be seen in Figure 19.

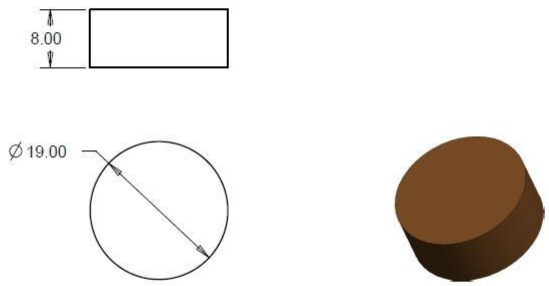

Figure 19 Drawing of Disk

The print bed has a maximum size of 60mm X 40mm. The 19mm discs allowed six discs to be printed at once. Three disks from each set of six were used for other experiments. Disks were printed with three different layer thicknesses. Sets were printed with a 50µm layer thickness, 100µm layer thickness, and a 200µm layer thickness. Figure 20 shows 6 of the disks that were used.

Figure 20 Disks Prior to Finish Machining

The pins were machined from 3/16" 420 stainless steel. The pins were cut down to 1" segments. One end of the each of the pins was turned down into a ball end using a lathe with a stop to ensure consistent results. Each disk and pin pair was grouped into pairs. The pins were color coded for identification. Colors were used to match the pin to the disc. After the disks were printed, they were machined down to a thickness of 8mm. The tops and bottoms were machined flat using an end-mill, as shown in Figure 21.

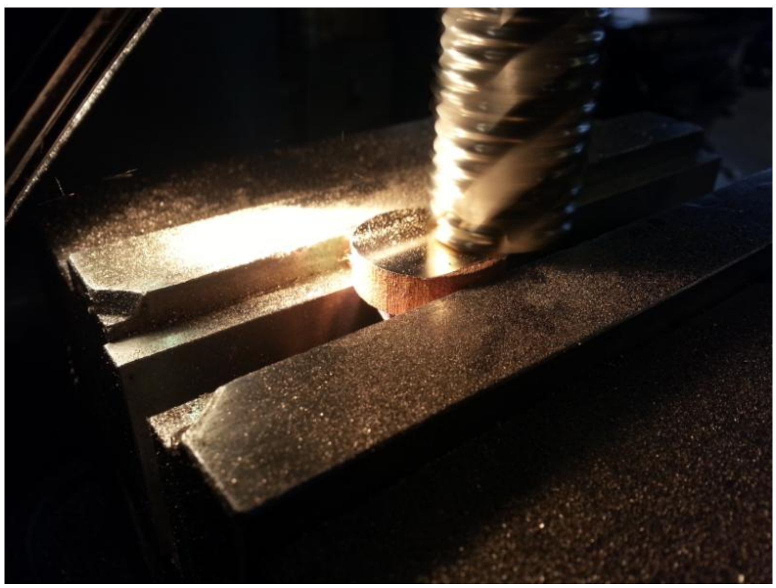

Figure 21 Finish Machining of Disk

The samples were then stamped with a number for identification purposes. After the samples had been given an identification number, the samples were then wet sanded to achieve the final surface finish. A four-stage wet-sanding process was used. Wet sanding was done using 120 grit, 240 grit, 400 grit, and 600 grit sanding discs. All discs were sanded until they had a surface roughness of 0.2 Ra or less. A micrograph of the polished surface can be seen in Figure 22. Figure 22 shows the stainless steel 420, and the bronze infiltrate. The darker colored circles are the stainless steel 420, and the lighter colored material surrounding, is the bronze infiltrate.

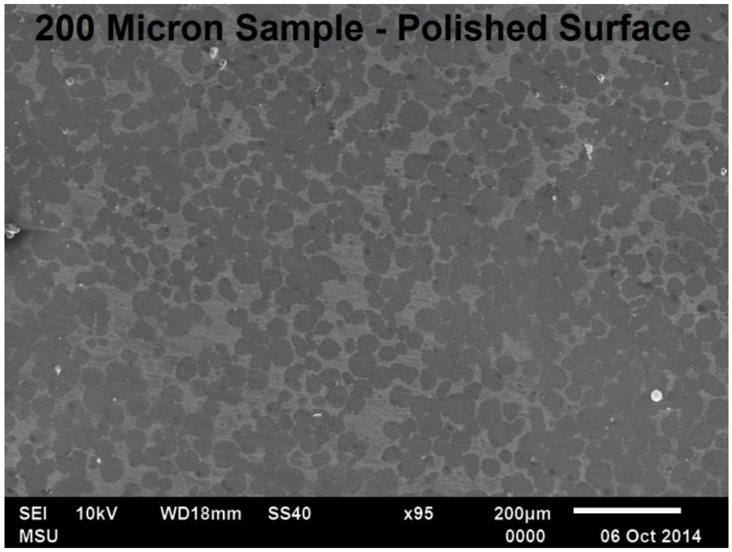

Figure 22 Polished Surface, 200 Micron

A TR200 Roughness meter was used to examine the surface roughness. A photo of this can be seen in Figure 23 and Figure 24.

Figure 23 TR200 Roughness Meter

Figure 24 TR200 Roughness Meter

A surface roughness of 0.2 Ra was chosen due to the recommendation in ASTM G99. The ASTM G99 test procedure calls for a surface roughness of less than 0.8 Ra.

Test Setup

The test performed was a modified version of the ASTM G99 Pin-on Disk wear test. Testing was performed on a Bridgeport milling machine. The discs were mounted in the vise on the milling machine bedplate. V-blocks were used in the vise to keep the discs perpendicular to the axis of rotation of the quill. 1¼"parallel bars were used to keep the discs at a consistent height throughout testing. The pin was secured by means of a specially built fixture (Figure 25).

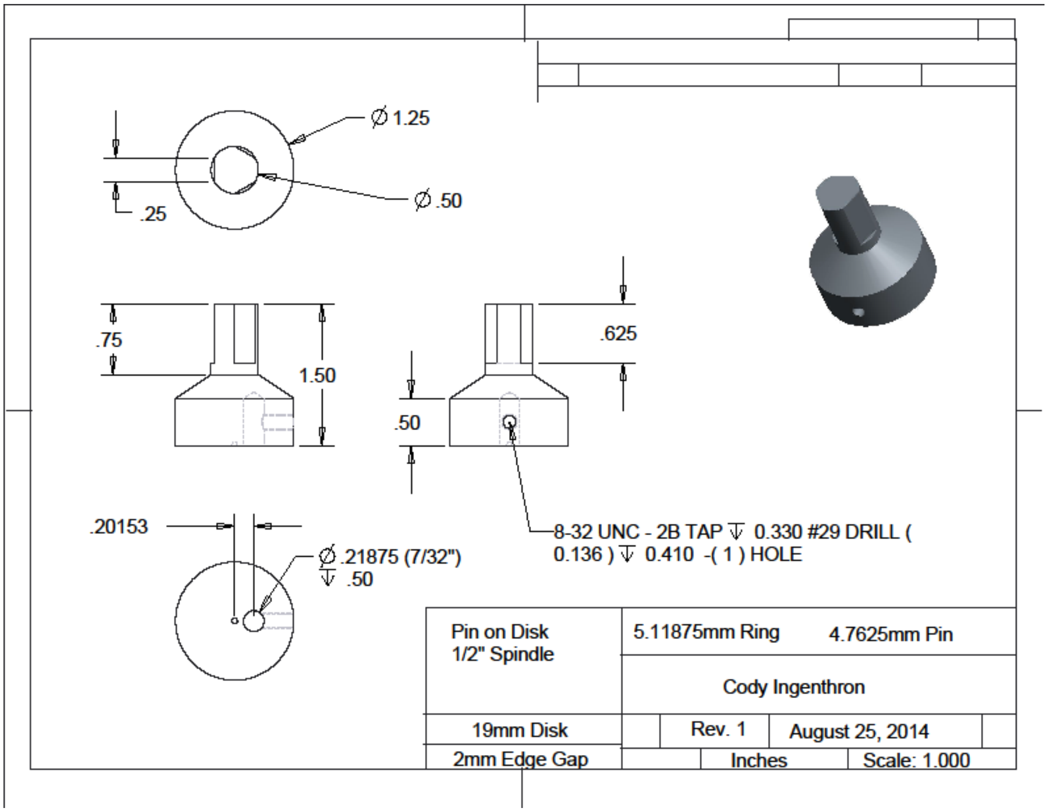

Figure 25 Spindle Drawing

The fixture held the pin parallel to the axis of rotation, with an offset of 5.119mm. The pin was secured into the fixture with a thumbscrew. The offset of 5.119mm was chosen to give a 2mm buffer from the outside of the wear-track to the edge of the disk in the event that the ball-end of the pin was worn completely flat. The fixture was secured into the quill of the milling machine with a ½" collet. To achieve varying down forces, a lever-arm was affixed to the rack-and-pinion of the quill. A scale was placed under the quill to measure the down force from the quill. A weight was attached to the lever-arm. The distance from the weight to the fulcrum varied to attain the correct down forces of 89N, 178N, and 267N. All down force measurements were taken with the lever arm in a level position to ensure consistent forces. Figure 26 shows a representation of the fixture with the pin and the disk.

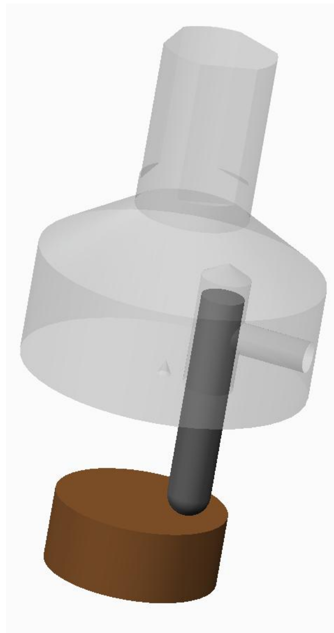

Figure 26 Pin Fixture

Test Procedure

Each pin and disk pair was tested for 30 minutes. The 30-minute intervals were divided into 10-minute intervals. The pin and fixture were rotated at a speed of 80rpm. Prior to start of each 30-minute test, the samples were cleaned with warm soapy water, and dried with a non-linting towel. At each 10-minute interval, the samples were weighed for mass change, and photographed for visual reference. The samples were weighed on an Ohaus EX124/AD scale, with a resolution of 0.0001g. Upon completion of the 30-minute test, the hardness was examined inside and outside of the wear tracks for comparison purposes. The hardness was measured using a Rockwell tester with a type “C” penetrator (Figure 27).

Figure 27 Rockwell Hardness Tester

Chapter 4

Results

All samples lasted the entirety of the test without failing (ex: fracturing, bending). All samples experienced some types of wear. The types of wear changed depending on the test parameters. All results were recorded in the form of volume lost. Micrographs are also included for visual reference.

50µm Layer Thickness Sample

The 50µm layer thickness disk experienced the least amount of volume loss when compared to the 100µm and the 200µm disks. The volume loss was very little for all three different forces. The disk tested with the 89N force did not lose any measureable volume during the 30-minute test. Figure 28 shows the volume lost for the 50µm layer thickness disk during the 30-minute test.

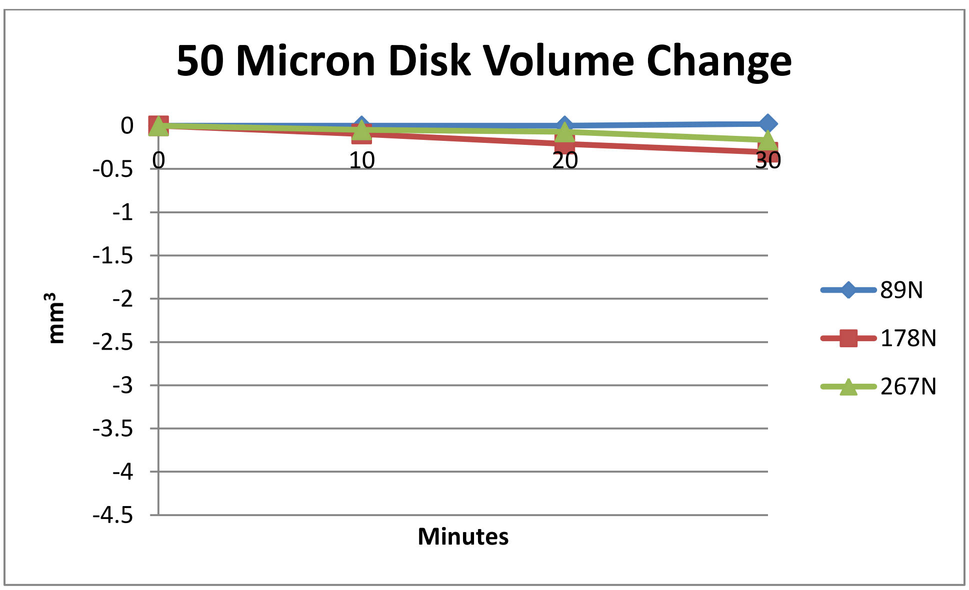

Figure 28 Disk Volume Change, 50 Micron

100µm Layer Thickness Sample

Figure 29 shows the volume lost for each of the forces over the 30-minute test period. The 100µm layer thickness sample had similar wear characteristics for the 89N and 178N forces. When the 267N force was initially applied, the disk wore in a similar manner to the disks tested with 267N and 178N down forces. After the initial 10-minute period, the mode of wear changed. Material lost during the 10-30-minute test periods experienced more plowing than adhesive wear, this is apparent in the SEM micrographs, Figure 32 and Figure 35. This wear pattern could be due to a “break-in” phase; where after, the wear rate stabilizes.

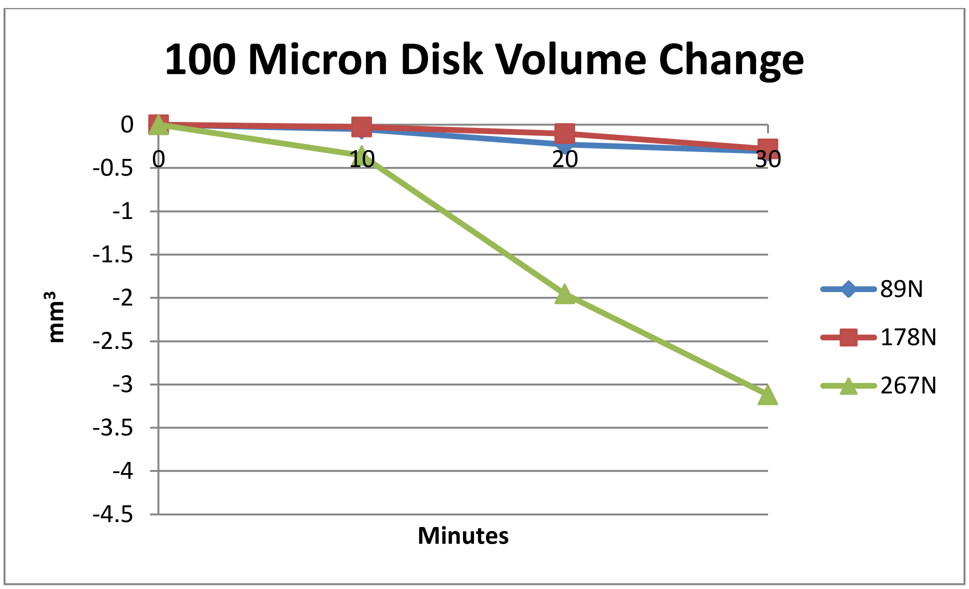

Figure 29 Disk Volume Change, 100 Micron

Figure 29 shows the changes in the disk volume over time, and with varying forces. The 267N force caused the greatest change in volume.

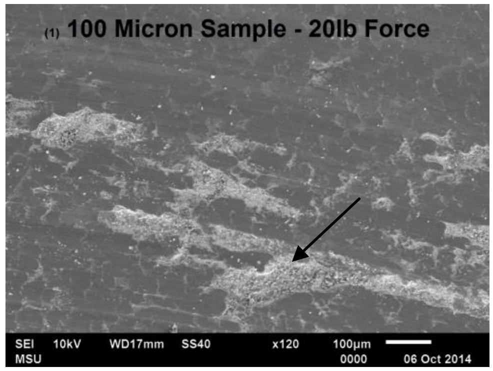

Figure 30 SEM Micrograph, 100 Micron

Figure 30 shows some adhesive wear. The adhesive wear is the lighter colored patches, shown with the arrow.

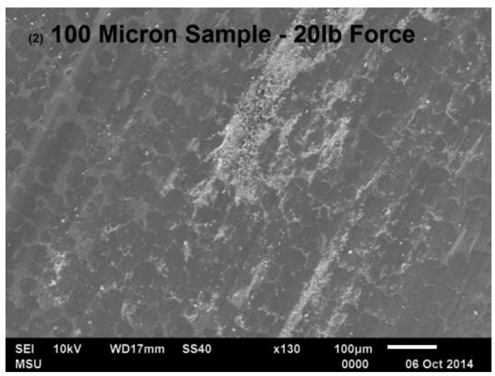

Figure 31 SEM Micrograph, 100 Micron

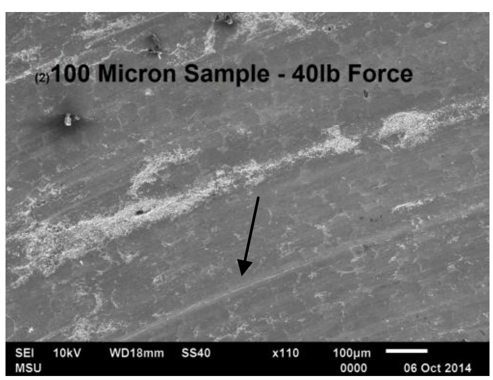

Figure 32 SEM Micrograph, 100 Micron

Figure 32 shows less adhesive wear, and an increase in abrasive wear. The abrasive wear is shown by the arrow. There is a shift from predominantly adhesive wear to abrasive wear. Plowing has begun to occur.

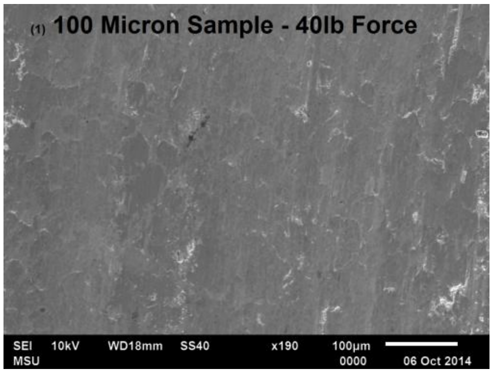

Figure 33 SEM Micrograph, 100 Micron

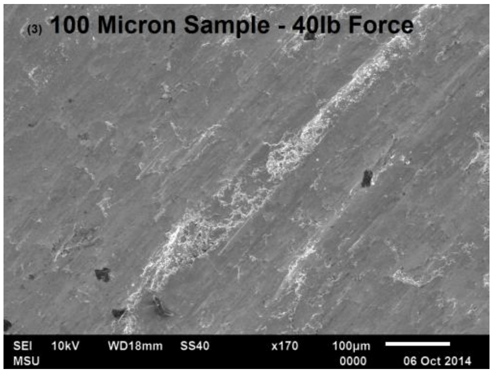

Figure 34 SEM Micrograph, 100 Micron

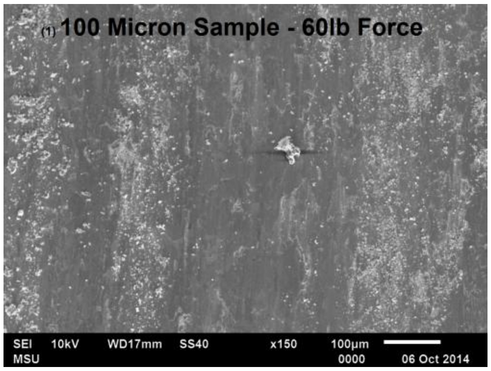

Figure 35 SEM Micrograph, 100 Micron

Figure 35 shows the wear occurring with the 267N force. Almost all of the wear is abrasive at this point. Some adhesive wear is still occurring on the outside of the wear track.

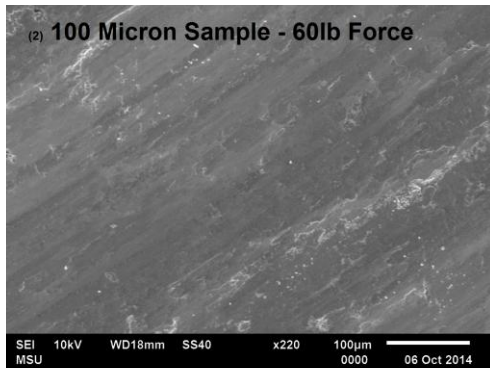

Figure 36 SEM Micrograph, 100 Micron

Figure 36 shows that almost all of the wear has become abrasive, in the form of plowing.

200µm Layer Thickness Sample

The 200µm layer thickness disk experienced the most wear of the other disks tested. The disks lost volume at a faster rate than any of the other samples tested. In addition to losing volume faster than any other samples tested, the amount of volume lost was also greater than any of the samples tested. The graph showing volume lost is shown in Figure 37.

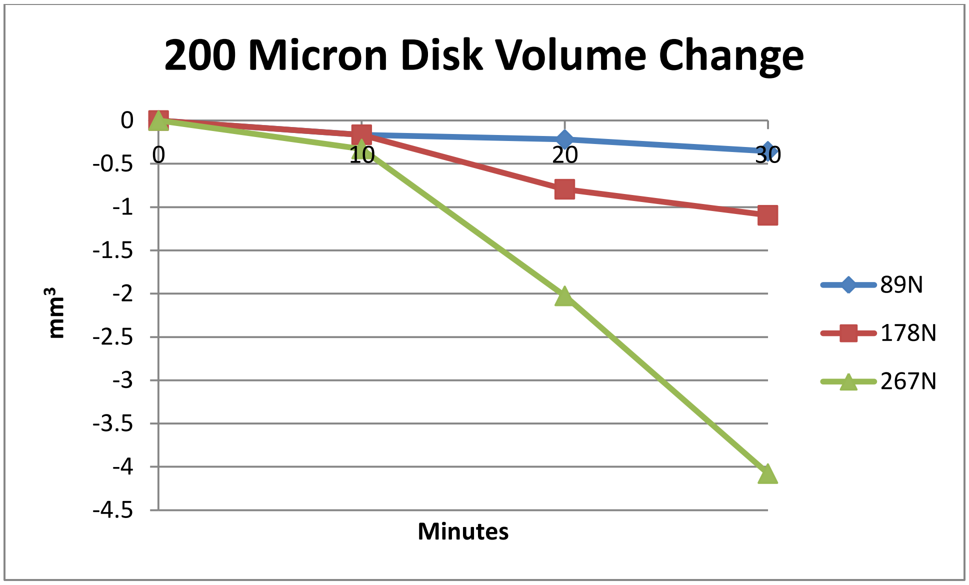

Figure 37 Disk Volume Change, 200 Micron

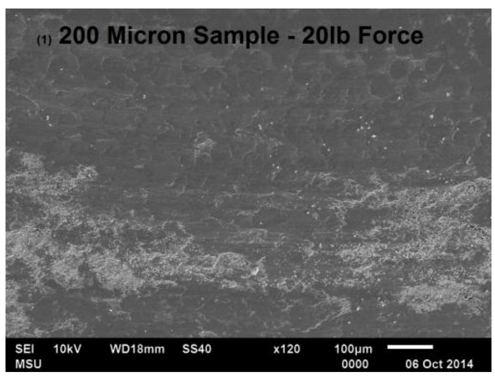

Figure 38 SEM Micrograph, 200 Micron

Figure 38 shows the 200µm layer thickness disk with the 89N force. Some adhesive and abrasive wear is present. The adhesive wear was localized to a few regions; however, the majority of the wear was abrasive.

Figure 39 SEM Micrograph, 200 Micron

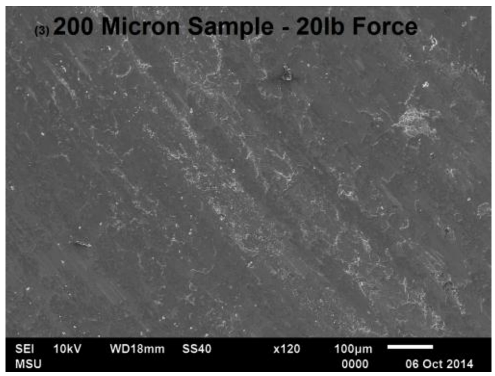

Figure 40 SEM Micrograph, 200 Micron

Figure 39 and Figure 40 are consistent in showing the abrasive wear. This is the type of wear that occurred most frequently with this disk, and 89N of force.

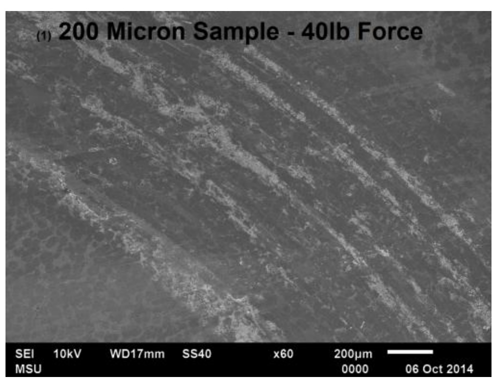

Figure 41 SEM Micrograph, 200 Micron

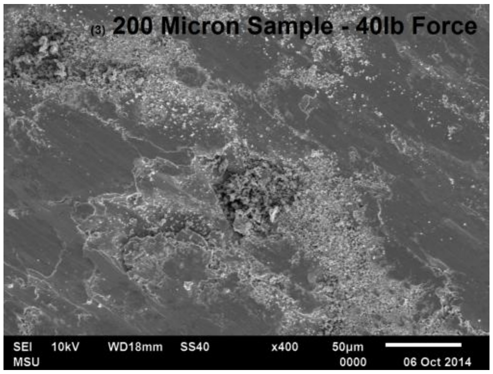

Figure 42 SEM Micrograph, 200 Micron

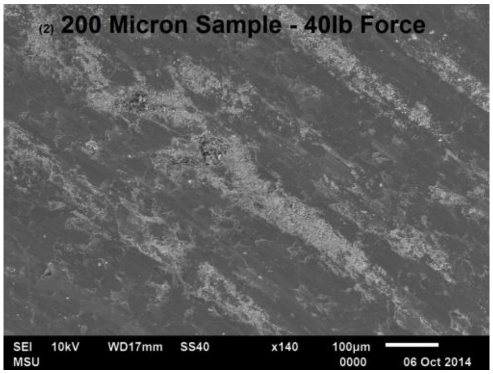

Figure 43 SEM Micrograph, 200 Micron

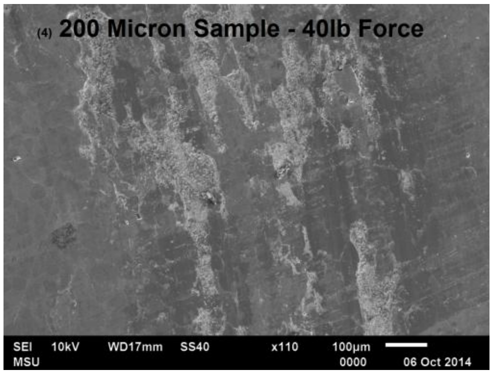

Figure 44 SEM Micrograph, 200 Micron

Figure 41, Figure 42, Figure 43, and Figure 44 show the adhesive wear that occurred during this test. Figure 42 shows a highly magnified view of material that has adhered to the disk. Some abrasive wear is also present in these figures.

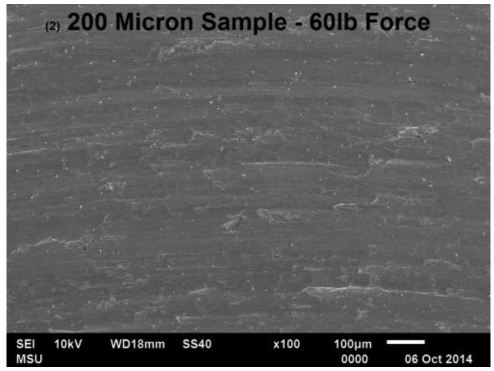

Figure 45 SEM Micrograph, 200 Micron

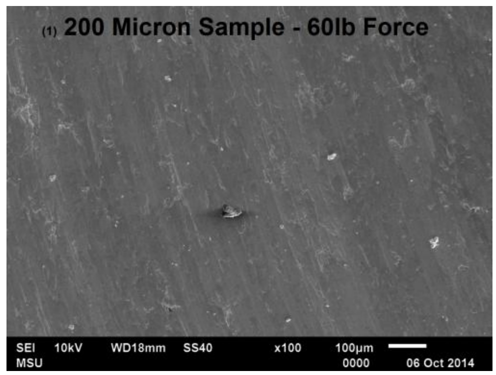

Figure 46 SEM Micrograph, 200 Micron

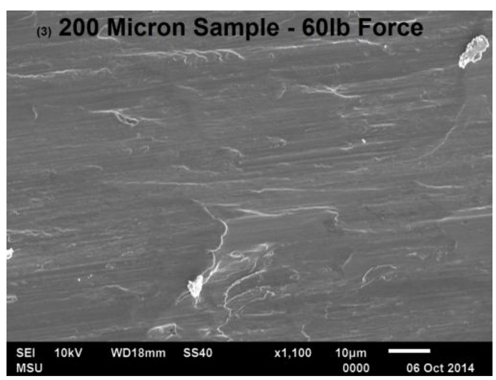

Figure 47 SEM Micrograph, 200 Micron

Figure 45, and Figure 46 show the wear that occurred with the 267N force. The wear is more substantial here than with lower forces. No adhesive wear is seen in these micrographs. The type of wear shown is an abrasive wear. Microplowing is taking place, and a highly magnified image of this can be seen in Figure 47.

Chapter 5

Discussion of Results

The graph in Figure 48 shows the change in volume for the samples tested. The 100µm layer thickness disks and the 200µm layer thickness disks have a similar trend. Both the 100µm and 200µm layer thickness disks lost volume slowly with lower forces and then the volume-loss increased more significantly after higher forces were applied.

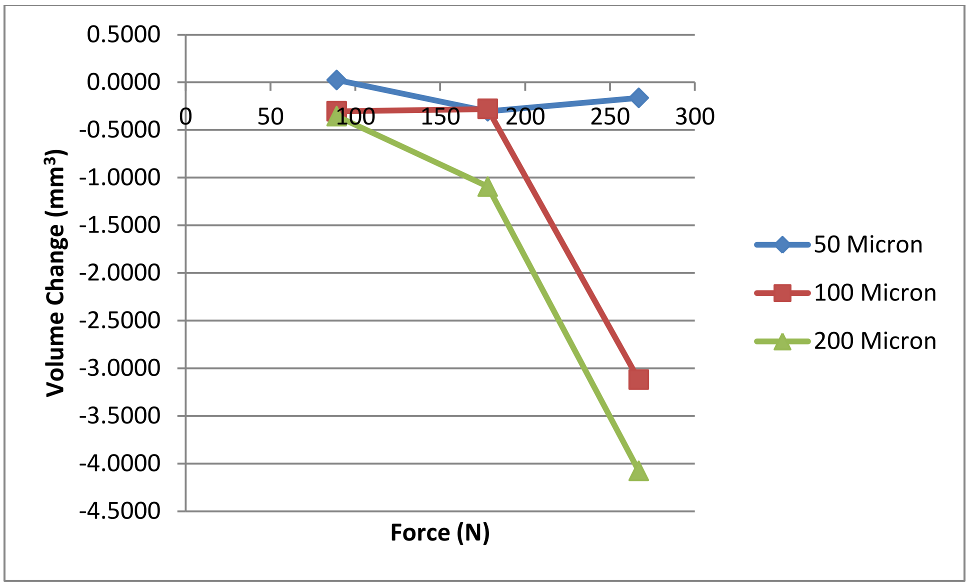

Figure 48 Volume Change Graph

Conclusions

When designing using AM materials, the process parameters affect the mechanical properties of the final product. In order to increase the wear resistance, the part must be in an environment with lower forces, or the layer thickness needs to be thinner. As the layer thickness decreases the concentration of stainless steel increases. because stainless steel 420 is more resistant to wear than the 90/10 bronze, the increased concentration of stainless steel leads to an increase in the wear resistance. As layer thickness increases, the stainless steel concentration is decreased. The decrease in stainless steel allows for more bronze to infiltrated, and in turn creates a part that has less wear resistance than one with thinner layers. The layer thickness is a significant factor in the wear resistance, the thinner the layers, the more wear resistance the part will be.

Future Research

Other areas outside of this experiment could be explored. The ExOne M1-Lab has many parameters that can be altered. One area that was not examined during the test was the wear effects of the pin. This could be another area to study. Other areas to consider would be changing the layer orientation, print speed, heater power, or other parameters to see the wear effects.

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Appendix

Spreadsheet Data

50µm Sample

			Disk Mass (g) After Minutes				Disk Mass (g) Change After Minutes			
	Ra after polishing	Downforce (lb)	0	10	20	30	0	10	20	30
5.2	0.107	20	17.7773	17.7773	17.7773	17.7774	0.0000	0.0000	0.0000	0.0001
5.1	0.054	40	17.6394	17.6390	17.6385	17.6381	0.0000	-0.0004	-0.0009	-0.0013
5.3	0.133	60	17.5567	17.5565	17.5564	17.5560	0.0000	-0.0002	-0.0003	-0.0007

Disk Volume Change After Minutes (mm3)				
	0	10	20	30
5.2	0	0	0	0.0234375
5.1	0	-0.09375	-0.2109375	-0.3046875
5.3	0	-0.046875	-0.0703125	-0.1640625

Pin Volume Change After Minutes (mm3)				
	0	10	20	30
5.2	0	0.0234375	-0.04687	-0.04687
5.1	0	-0.046875	-0.09375	-0.11719
5.3	0	0.0234375	-0.02344	-0.14063

100µm Sample

			Disk Mass (g) After Minutes				Disk Mass (g) Change After Minutes			
	Ra after polishing	Downforce (lb)	0	10	20	30	0	10	20	30
11.2	0.041	20	17.9577	17.9575	17.9568	17.9565	0.0000	-0.0002	-0.0009	-0.0012
11.1	0.105	40	17.1573	17.1572	17.1569	17.1562	0.0000	-0.0001	-0.0004	-0.0011
11.3	0.049	60	16.9289	16.9275	16.9212	16.9166	0.0000	-0.0014	-0.0077	-0.0123

	Hardness Outside Groove						Hardness Inside The Groove					
	Hardness 1	Hardness 2	Hardness 3	Hardness 4	Hardness 5	Average Hardness	Hardness 1	Hardness 2	Hardness 3	Hardness 4	Hardness 5	Average Hardness
11.2	12	15	12	16	17	14.4	11	17	11	17	16	14.4
11.1	16	15.5	15	13.5	14	14.8	16	19	18	12	15	16
11.3	16	14	20	17	18	17	16	19	19	15	13	16.4

Disk Volume Change After Minutes (mm3)				
	0	10	20	30
11.2	0	-0.050731707	-0.2282927	-0.3043902
11.1	0	-0.025365854	-0.1014634	-0.2790244
11.3	0	-0.355121951	-1.9531707	-3.12

Pin Volume Change After Minutes (mm3)				
	0	10	20	30
11.2	0	0.025365854	-0.076098	-0.177561
11.1	0	0.126829268	0.0507317	-0.050732
11.3	0	0.076097561	0	-0.380488

	Hardness Outside Groove						Hardness Inside The Groove					
	Hardness 1	Hardness 2	Hardness 3	Hardness 4	Hardness 5	Average Hardness	Hardness 1	Hardness 2	Hardness 3	Hardness 4	Hardness 5	Average Hardness
11.2	12	15	12	16	17	14.4	11	17	11	17	16	14.4
11.1	16	15.5	15	13.5	14	14.8	16	19	18	12	15	16
11.3	16	14	20	17	18	17	16	19	19	15	13	16.4

200μm Sample

			Disk Mass (g) After Minutes				Disk Mass (g) Change After Minutes			
	Ra after polishing	Downforce (lb)	0	10	20	30	0	10	20	30
7.2	0.175	20	16.2552	16.2546	16.2544	16.2539	0.0000	-0.0006	-0.0008	-0.0013
7.1	0.07	40	17.3229	17.3223	17.3200	17.3189	0.0000	-0.0006	-0.0029	-0.0040
7.3	0.044	60	16.3104	16.3092	16.3030	16.2955	0.0000	-0.0012	-0.0074	-0.0149

	Hardness Outside Groove						Hardness Inside The Groove					
	Hardness 1	Hardness 2	Hardness 3	Hardness 4	Hardness 5	Average Hardness	Hardness 1	Hardness 2	Hardness 3	Hardness 4	Hardness 5	Average Hardness
7.2	9	9	10	10	10	9.6	8	8	7	9	6	7.6
7.1	8	9	7.5	8	10	8.5	6	9	4	7	13	7.8
7.3	17	12	11	12	9	12.2	15	13	17	15	16	15.2

Disk Volume Change After Minutes (mm3)				
	0	10	20	30
7.2	0	-0.164210526	-0.2189474	-0.3557895
7.1	0	-0.164210526	-0.7936842	-1.0947368
7.3	0	-0.328421053	-2.0252632	-4.0778947

Pin Volume Change After Minutes (mm3)				
	0	10	20	30
7.2	0	0.027368421	0.0821053	0.0273684
7.1	0	0.136842105	0.0547368	-0.054737
7.3	0	0.082105263	0.1094737	-0.301053