

WEAR STUDIES IN BINDER JET ADDITIVE MANUFACTURED STAINLESS STEEL - BRONZE COMPOSITE

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Abstract

Additive Manufactured (AM) components can be used for form, fit or function. If these components have to replace the traditionally manufactured parts, they must be evaluated for their properties. One of the properties that are very important in many cases is the wear of material in service. The aim of this research is to study the wear behavior of additive manufactured components under dry sliding conditions.

Small cylindrical disks of stainless steel 420-bronze composite were made by binder jet AM process with layer thicknesses of 50 μm , 100 μm and 200 μm . These disks were subjected to varying wear rates using pin-on-disk test based on ASTM standards. Different sliding distances were used on samples to understand the wear phenomenon. The weight of samples before and after tests was recorded to calculate wear rates. Wear debris and samples after testing were evaluated under a scanning electron microscope (SEM) to reveal changes in microstructure. Testing results are presented in this paper along with a discussion on how the wear occurs in the SS420-Bronze composite. This information can be used for designing the products from this AM process to match the requirements in service.

Introduction

Additive Manufacturing (AM) technologies have gained tremendous popularity in the last few years. They have been used to produce parts in virtually every domain: ranging from Astronomy, Biology, Engineering, Sports, Theatre, and Music etc. The parts from AM technologies can serve one or more of the three basic purposes in any application: form, fit or function. The material, strength, dimensional and other requirements on an AM part vary depending on this purpose. For example, if AM part is being manufactured to fulfill the requirements of form of an actual steel part, it can be made from plastic or wax. On the other hand, if the AM part needs to replace a metal gear in service, it needs to fulfill the strength, wear and corrosion resistance requirements of the gear.

There are several methods currently available for additive manufacturing of metals. Some of the most widespread among them are the Powder Bed Fusion (PBF) methods (including Selective Laser Sintering, Selective Laser Melting, and Electron Beam Melting) (Wohlers, 2011) (Gibson, Rosen, & Stucker, 2010). All these methods typically create parts with polymers, metallic material (eg. stainless steel, titanium, cobalt chrome) or ceramics with varying densities and porosities. These methods have one or more energy sources, which cause fusion between

metallic powder particles, and the layers are deposited one on top of another by a spreading mechanism, typically rollers. The binding mechanisms in PBF can be solid state sintering, chemically induced bonding, liquid phase sintering and full melting. Depending on the material and the binding mechanisms, the properties of the part produced can vary (Noorani, 2006) (Kruth, Wang, Laoui, & Froyen, 2003) (Facchini, Magalini, Robotti, & Molinari, 2009).

One of the most prominent methods for additively manufacturing metals is called Binder Jet (BJ) by The ExOne Company. This method mainly works on the principle of chemical adhesion to create a green part that is subsequently sintered and infiltrated to create a fully dense part. Some of the common materials used in this process are SS420, SS316 or iron infiltrated with bronze. The applications of the parts produced by this technique include rotors, stators, impellers, and prosthetics. In all these applications, drastic reductions in time to manufacture from concept and significant weight and cost savings have been realized (ExOne Company).

Like with any other manufacturing process, it is important to understand the interaction between the process parameters and the correlated properties of the parts produced in additive manufacturing process too. This will help in design and manufacturing of parts with the best combination of strength, weight, cost and other performance functions. Unfortunately very little research has been done in BJ process and how it affects material properties.

This research aims to bridge that gap by studying how the various parameters during the Binder Jet process affect the wear properties of SS420 + Bronze parts. Small cylindrical disks of stainless steel 420-bronze composite were made by binder jet AM process with layer thicknesses of 50 μm , 100 μm and 200 μm . These disks were subjected to varying wear rates using pin-on-disk test based on ASTM standards. Different sliding distances were used on samples to understand the wear phenomenon. The weight of samples before and after tests was recorded to calculate wear rates. Wear debris and samples after testing were evaluated under a scanning electron microscope (SEM) to reveal changes in microstructure. Testing results are presented here along with a discussion on how the wear occurs in the SS420-Bronze composite. This information can be used for designing the products from this AM process to match the requirements in service.

Wear of Materials

Wear is a common occurrence in everyday life and 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: adhesive wear, abrasive wear, surface fatigue, fretting wear, erosive wear, and tribochemical reaction.

Adhesive Wear

Adhesive wear occurs when material from one sliding surface is displaced onto the other surface that 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).

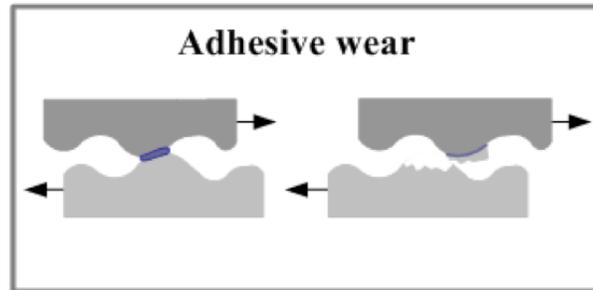


Figure 1 Mechanism of Adhesive Wear (Kopelovich, 2014)

Figure 1 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 2** 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).

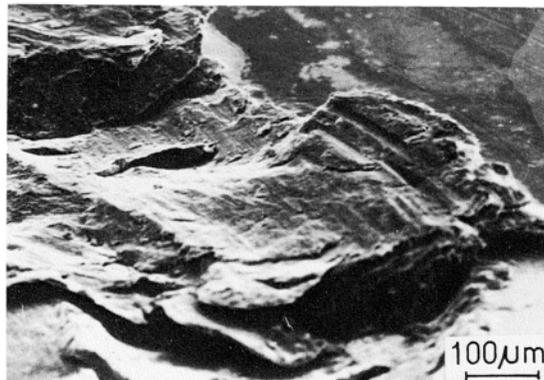


Figure 2 Material Transfer during adhesion (Gahr, 1987)

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). It has two modes: two-body, and three-body. With two-body wear, the hard surface removes material from the contact surface and the particles created are constrained. Three-body wear occurs when loose particles are introduced, or generated between the contacting surfaces. These different modes of wear are shown in **Figure 3** Mechanism of Abrasive Wear .

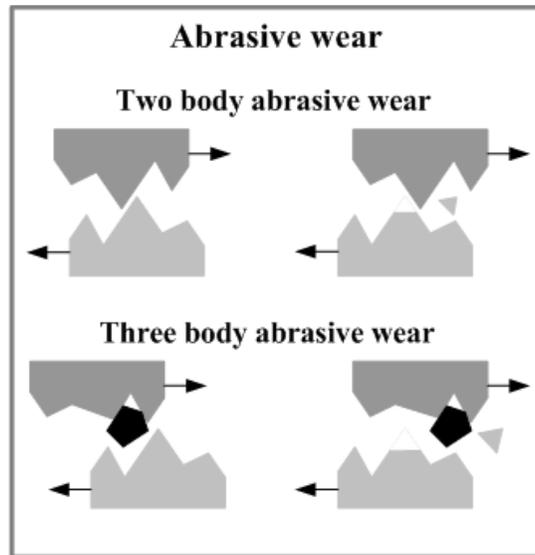


Figure 3 Mechanism of Abrasive Wear (Kopelovich, 2014)

Measuring Wear

The measurement of wear is a 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 in which the material was originally tested.

Standard G99 is the Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. **Figure 4** shows a diagram of the pin-on-disk test method. 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”. This is the same testing method which is used in this study to compare the different processing conditions of BJ method.

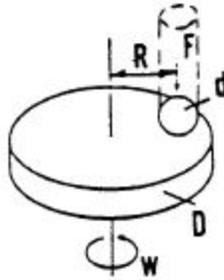


Figure 4 Pin on Disk wear test apparatus

Binder Jet-based Additive Manufacturing

The main technique of manufacture using the Binder Jet process is as follows: (a) The CAD file is sliced into layers and a STL file is generated, (b) Each layer begins with a thin distribution of powder spread over the surface of a powder bed, (c) Using a technology similar to ink-jet printing, a binder material selectively joins particles where the object is to be formed, (d) A piston that supports the powder bed and the part-in-progress lowers so that the next powder layer can be spread and selectively joined, (e) This layer-by-layer process repeats until the part is completed, (f) Following a heat treatment, unbound powder is removed and the metal powder is sintered together. (g) This sintered metal powder is then infiltrated with bronze to impart the strength and fill up the pores. **Figure 5** shows the details of the whole process.

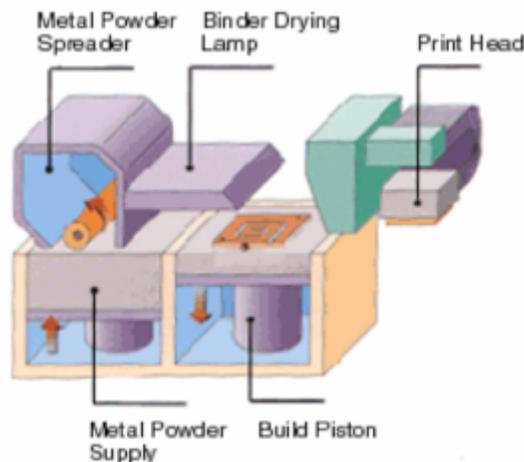


Figure 5: Schematic of the Binder Jet Process (Courtesy The ExOne Company)

Process parameters

The Binder Jet process described above can be divided into 3 basic steps: 1) Binding, 2) Curing and 3) Sintering + Infiltration. There are various process parameters that can be changed to obtain a customized part in each of these steps. These include powder size, layer thickness during binding, part orientation in bed, heater power, roller speed, curing temperature, curing time, sintering time, sintering temperature, and sintering atmosphere. To study the effect of each of these parameters and their interactions would require a huge experimental design and many

hundred samples and testing. To reduce the experimental space it was decided to study the effect of only the layer thickness in this study. Other parameters will be researched in future studies.

Experimental Plan

The material of the powder was stainless steel 420 (SS420), which has a mean particle size of 30 μ m and an apparent density of 2.75 g/cc. The chemical composition of SS420 is shown in Table 1. SS420 is a magnetic, martensitic stainless steel, and is typically used in cutlery and surgical instruments. The infiltrate was a Tin Bronze with 90% Cu / 10% Sn by weight composition.

C	Mn	P	S	Si	Cr
0.15 min	1.00 max	0.040 max	0.030 max	1.00 max	12.00 – 14.00

Table 1: Chemical composition of SS420 (wt %)

Scanning Electron Microscope (JEOL JSM-6510MV) was used to look at the sizes and distribution of the powders before the process. The images for SS420 are shown in Figure 6 and 7.

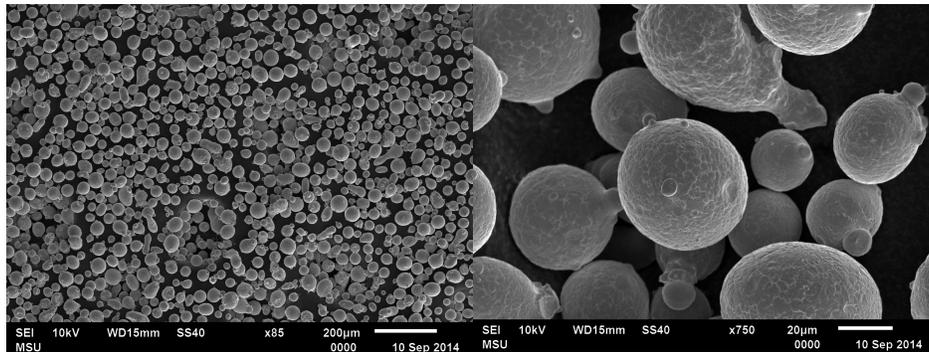


Figure 6: SEM Micrographs for SS420

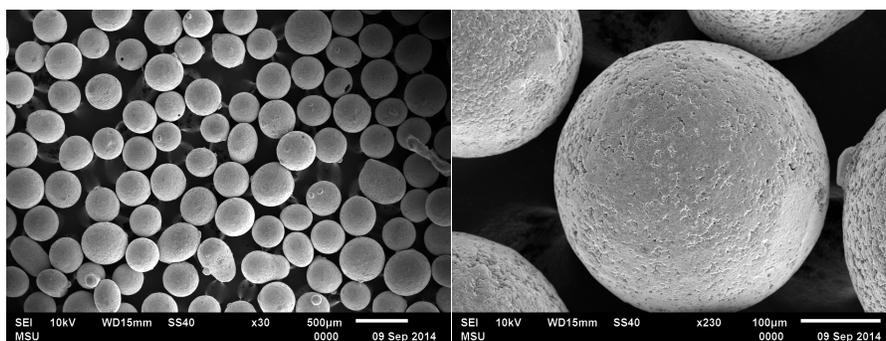


Figure 7: SEM Micrographs for Bronze

Wear test Details

The discs were printed using an ExOne MLab machine. The discs were 19mm in diameter, with a thickness of 8mm. Disks were printed with three different layer thicknesses.

Sets were printed with a 50 μm layer thickness, 100 μm layer thickness, and a 200 μm layer thickness. **Figure 8** shows 6 of the disks that were used.



Figure 8 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. The samples were then wet sanded to achieve the final surface finish. A four-stage wet-sanding process 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 9.

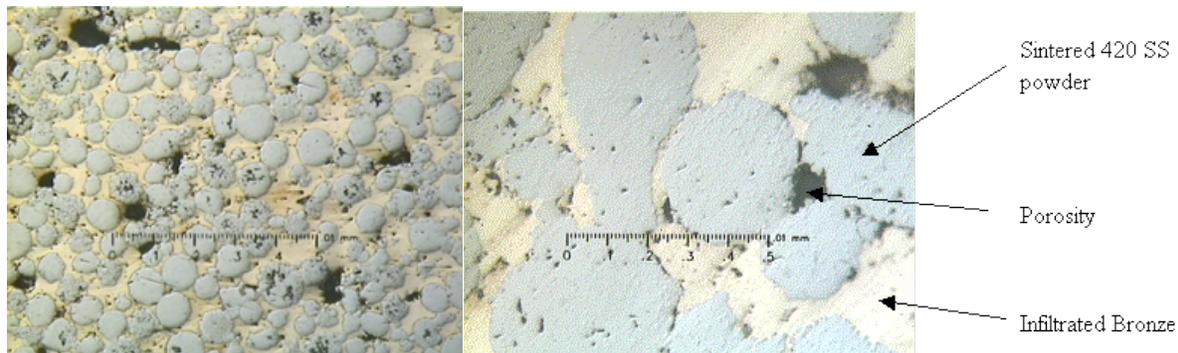
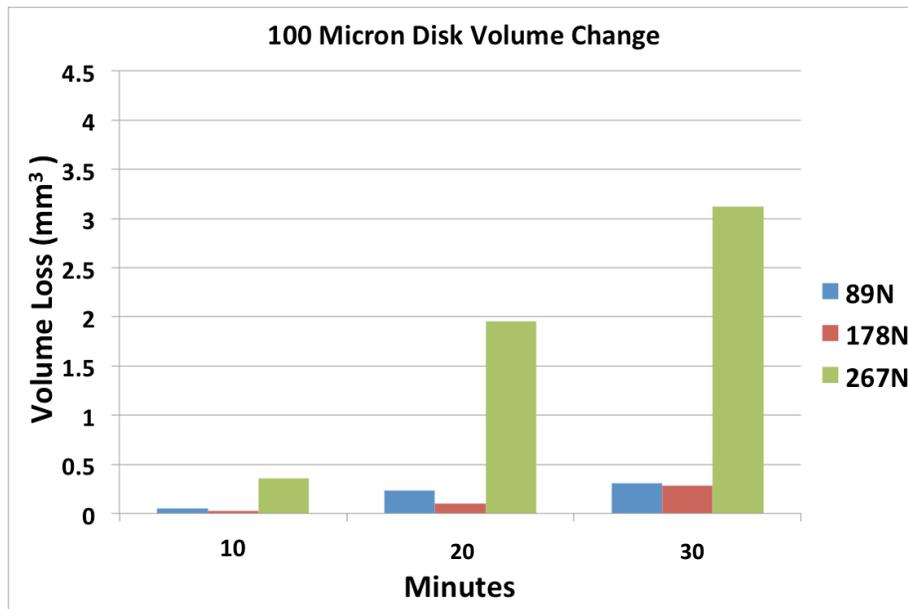
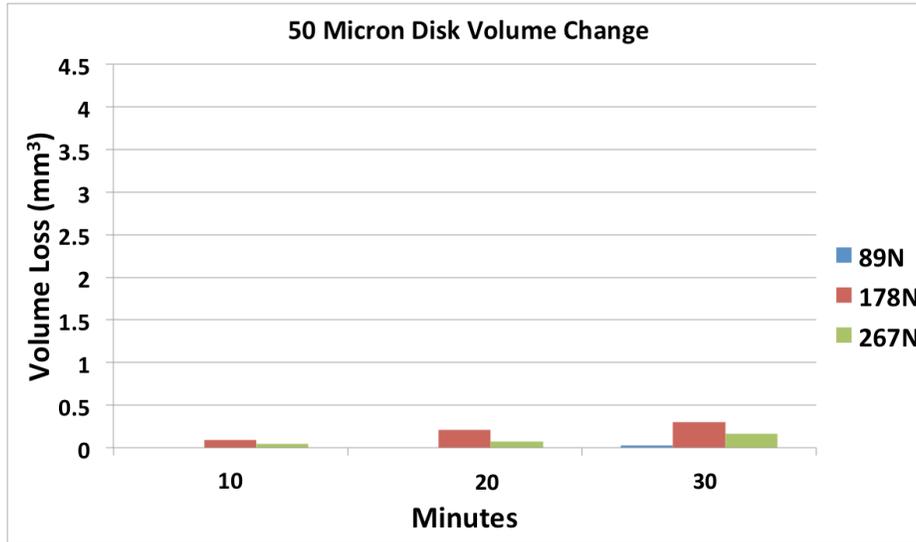


Figure 9: Micrographs of the sintered and infiltrated samples (layer thickness = 50 μm) showing the different phases, (left) 50x and (right) 200x.

Each pin and disk pair was tested for 30 minutes. The 30-minute intervals were divided into 3-10-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 using a Rockwell tester with a type "C" penetrator.

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. The results of the wear are shown in Figure 10.



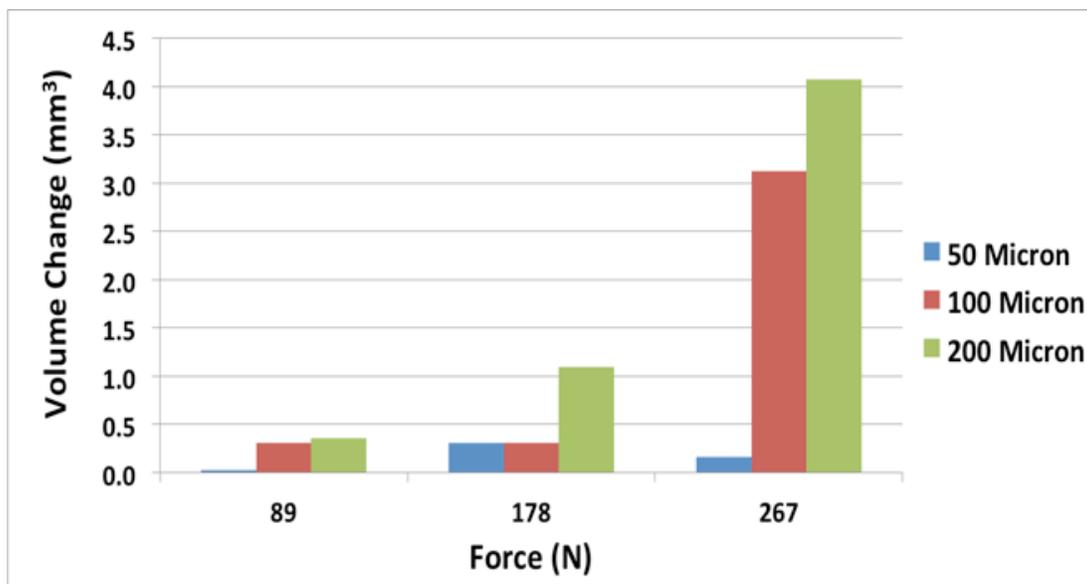
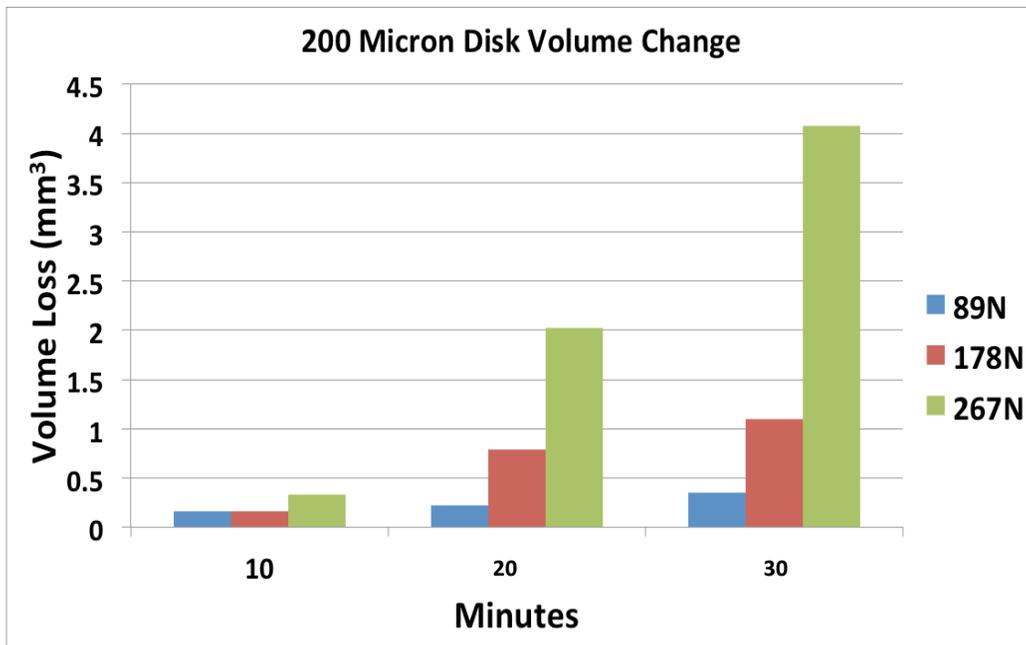


Figure 10: Results of the wear test

After the testing was done, the disks were examined under a SEM to evaluate the worn surfaces. The surfaces of the worn disks for the different layer thicknesses and applied forces are shown in Table 2. Another testing which was done was to evaluate the wear debris from the various tests. The wear debris would give an indication of the wear pattern and material. The results from the SEM study on the wear debris are shown in Table 3.

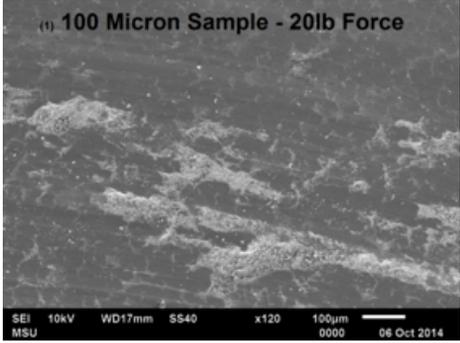
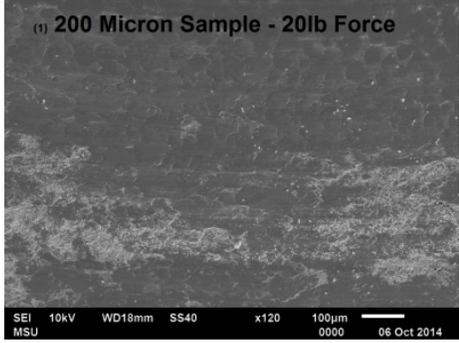
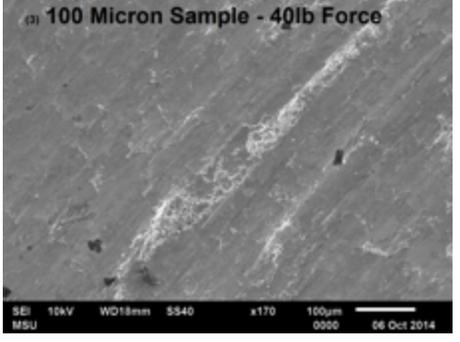
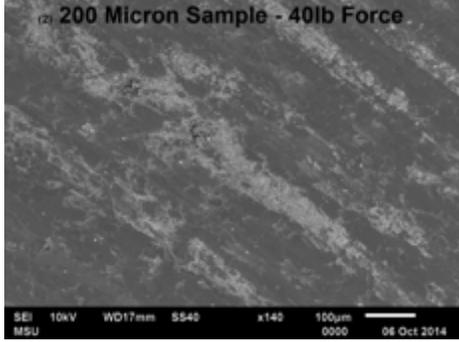
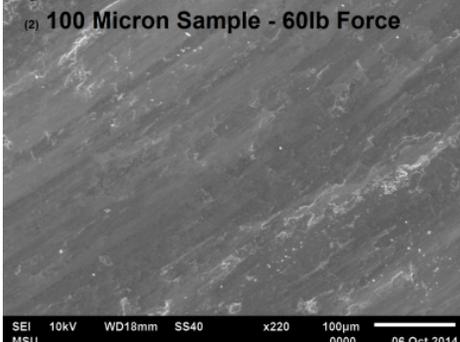
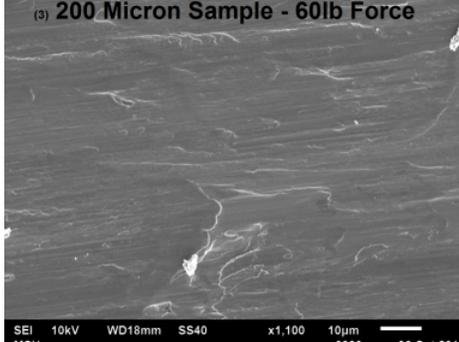
Layer Thickness / Force Applied	100 μm	200 μm
89 N	<p>(1) 100 Micron Sample - 20lb Force</p> 	<p>(1) 200 Micron Sample - 20lb Force</p> 
178 N	<p>(2) 100 Micron Sample - 40lb Force</p> 	<p>(2) 200 Micron Sample - 40lb Force</p> 
267 N	<p>(2) 100 Micron Sample - 60lb Force</p> 	<p>(3) 200 Micron Sample - 60lb Force</p> 

Table 2: SEM analysis of the wear surfaces of the disk after 30 minute testing

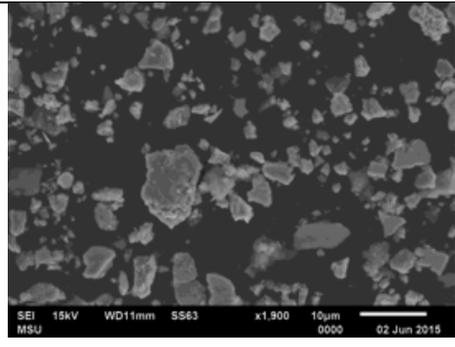
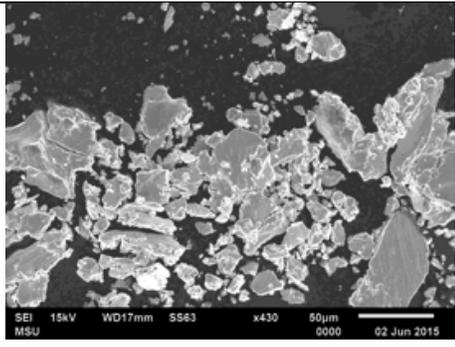
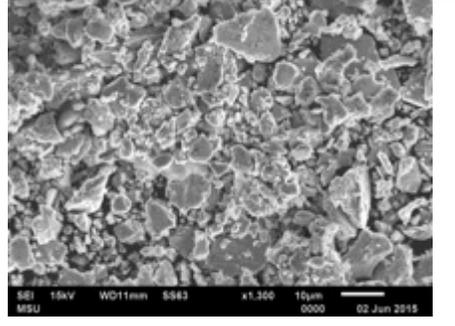
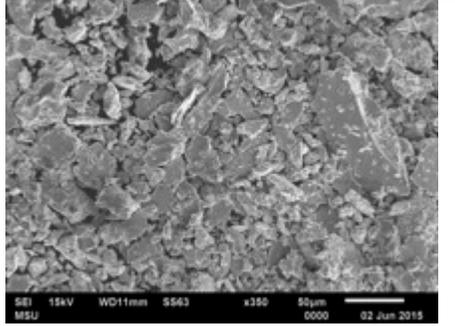
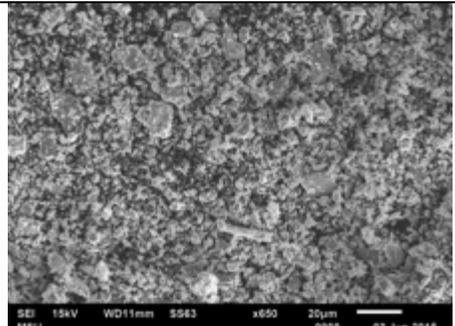
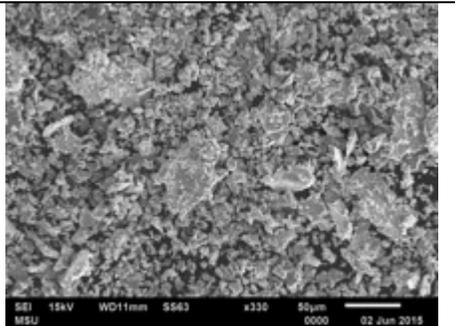
Layer Thickness/ Time	100 μm	200 μm
10 min		
20 min		
30 min		

Table 3: SEM analysis of the wear debris during and after testing for 89N applied force. The larger particles as mainly bronze while the smaller particles are debris of stainless steel.

Discussions

There are several interesting results that can be seen from this wear study.

- 1) There is a strong influence of Layer thickness of the binder jet additive manufacturing process on the wear of the part.
- 2) The applied force also plays an important role in the wear process. The influence of the applied force varies with the layer thickness of the sample.
- 3) For a given force, the wear increases as the layer thickness increases. (As shown in Figure 10).
- 4) The wear mechanism is adhesive wear at any applied force for the 50 μm layer thickness.

- 5) The wear mechanism for the 100 μm and 200 μm layer thickness is adhesive wear at lower forces of 89 and 178 N but changes to abrasive wear (micro-ploughing type) at forces of 267 N. This can be seen in the SEM images in Table 2 that show deposition of particles at lower forces while a more ploughed surface at higher forces.
- 6) For the 200 μm samples, the wear increases as the applied force increases. Initially the wear rate is the same for low forces, but the rate changes as the time increases. The wear debris in Table 3 shows that a force of 89 N, the wear of bronze particles occurs first. As more wear occurs, it changes to a mixed of bronze and stainless steel.
- 7) In 100 μm layer thickness, the wear rate decreases from 89N to 178N applied force and then increases. This is because at this layer thickness there is 50% Stainless steel and 50% bronze in the samples. At a lower force the pin can adhesively wear the bronze. But as the force increases, the stainless steel pin encounters the stainless steel particles in the matrix. This force is insufficient to wear these particles and the wear rate drops. When the force increases again, wear of both the stainless steel and bronze continues which increases the wear rate again.
- 8) A similar trend is found in the 50 μm layer thickness samples. These samples are 60% stainless steel and 40% bronze in composition. At very low forces there is not enough force to cause a substantial wear which is evidenced in Figure 10. As the force increases, the stainless steel in the pin is able to wear out the bronze in the matrix of the sample. When the force increase even further, the SS in the pin encounters the SS in the samples and is unable to wear that out. Hence the wear rate decreases at a force of 267N than at 178N. This is similar to the trend in 100 μm layer thickness but the only difference is that the “trigger” force at which this occurs changes due to the change in composition of the samples.

Conclusions

Additive Manufactured (AM) components can be used for form, fit or function. If these components have to replace the traditionally manufactured parts, they must be evaluated for their properties. One of the properties that are very important in many cases is the wear of material in service. The aim of this research was to study the wear behavior of additive manufactured components under dry sliding conditions.

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It is found that the layer thickness and the applied force both play a very important role in the wear of the AM samples. The modes of wear changes from adhesive to abrasive as the applied force is increased in certain samples. Also, the wear rate does not increase as the force

increases in all the cases. This is because of the composite nature of the samples and the percentage of individual constituent (SS or bronze) in the samples plays a very important role in determining the wear rate.

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