Tool life comparison between servo and pneumatic ultrasonic welders for cutting polylactic acid film

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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I'd like to thank my committee for not giving up on me, especially Dr. David Grewell. My uncle Matthew Miller who listened and helped try to make sense of my ramblings. My John Deere family who helped by taking on work, so I could finish.

ABSTRACT

Polylactic acid (PLA) is a biobased plastic that is the polymerization product of lactic acid which is produced by fermentation of starches derived from renewable feedstocks. PLA is used for many commercial applications such as medical implants, food packaging, and disposable tableware. In many applications, such as packaging, the PLA film needs to be cut to produce the final product.

The purpose of this research is to determine the effect of tool wear during ultrasonic cutting of PLA films. In more, this study compares tool wear between pneumatic and servo ultrasonic cutting systems. The study also investigated the effect of different amplitudes (using boosters with gains of; 1:1, 1:1.5, and 1:2) on tool life for servo and pneumatic systems.

There were significant differences in performance between the servo and pneumatic systems for the different amplitudes. The pneumatic system had consistently higher wear compared to the servo system for all the different amplitudes. It was believed that this was the result of cutting tool and horn contact was reduced for the servo driven system. In contrast, the pneumatic driven system, required cutting tool and horn contact to terminate the cutting cycle, that resulted in tool wear. In addition, it was found that high amplitudes, generally reduced tool wear. While this observation may initially be counter intuitive, it is believed that this was the result of faster cutting rates, that reduced the number of ultrasonic cycles (20 kHz) required to cut the films, reducing the tool wear.

CHAPTER 1. GENERAL INTRODUCTION

Ultrasonic Welding

Ultrasonic welding is a common process for joining components produced from plastics. This method can weld plastic relatively fast, with typical cycle times of less than 1 second and at relatively low cost. These attributes reflect the technique's speed, efficiency, lack of material contamination, and the fact that no consumables are required. The ultrasonic welding systems can also be adapted to a range of applications such as spot welding, stud welding, cutting applications, fabric and film sealing. It is important to note that there are limitations in term of part size and design [1]. The ultrasonic welding can be applied to packaging, electronic components, automotive and consumer products. This work focuses on the use of an ultrasonic cutting system and in particular tool wear.

Ultrasonic welding/cutting systems consist of several essential components: the stand, the power supply, the actuator, the fixture, and the controls. The stand constitutes the base, the frame and the column which supports the actuator, a unit comprised of the converter, booster and horn as show in Figure 1. The assembly of converter, booster, and horn, often referred to as the stack, produces the vibrational energy at frequencies above 20 kHz (ultrasonic). The actuator supports and translates the horn/stack assembly into contact with the parts to be welded and applies the force for welding (or cutting). After completing the welding/cutting operation, the actuator retracts the stack from the parts to the start/home position. The power supply produces the high-frequency electrical energy for the converter which transforms the electrical energy into mechanical vibrations (a motor). The booster can either increase or decrease the amplitude of the vibration supplied by the converter. The horn is the tool that transmits the vibrations to the part. Finally, the fixture rigidly holds the stationary component to be welded or a knife edge for cutting applications.

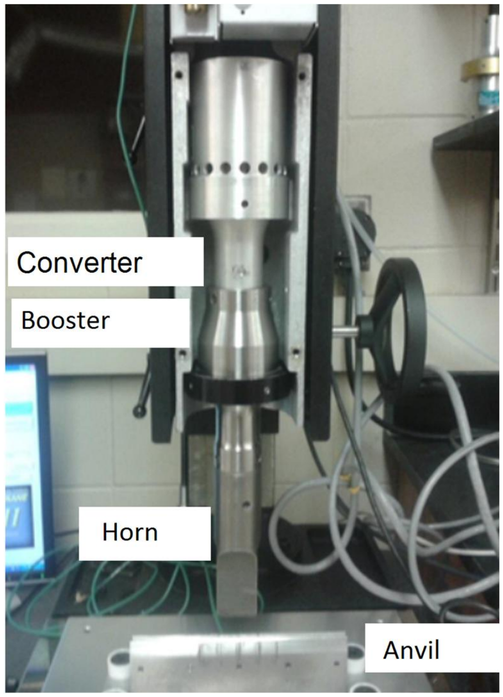


Figure 1 The open stack showing converter, booster, horn and the anvil.

Ultrasonic welding/cutting systems operate by applying relatively low amplitudes (10-200 μm_{p-p}) at relatively high-frequency mechanical vibrations to the part in the form of cyclical energy [2]. The converter consists of piezo-electric ceramics that expand and contract at the same frequency as the electrical excitation when alternating voltage is applied to the opposing sides of the ceramics. This sinusoidal mechanical vibration is then passed through the booster and horn into the part. The vibrations generate intermolecular friction at the joint interface which creates a melt and leads to molecular bonding, fusing the plastic parts together [3].

There are different frequencies with an array of sizes of horns for welding parts of different heights, thickness and shapes. The common frequencies for ultrasonic welding systems are 15, 20, 30, 35, and 40 kHz. Most ultrasonic horns are typically fabricated from aluminum or titanium because these materials have high strength to density ratios. A factor in designing a horn is the amplitude required for an application. Other factors include horn costs, wear, size of the horn and number of parts to be assembled. The ultrasonic horn is usually designed to fully engage the parts being welded. The booster is a tuned tool with a nodal mount point/plane that allows the actuator to secure the stack. The boosters are rated by the amount of gain by which they increase or decrease the amplitude. Gain (amplification factor) is the ratio of output amplitude to input amplitude of a horn or booster. The typical booster gains are 1:1, 1.5: 1:2 and 2.5:1.

Ultrasonic welding, while fast and efficient, does have limitations. Ultrasonic welding dates to the mid-1960s, and still struggles with problems of consistency because surface irregularities, material differences, and multi-cavity dimensional variations [1]. Thus, there is a need for better control to promote a more consistent ultrasonic welding processes as well as ultrasonic cutting. This is particularly true as part designs become more complex, new materials are commercialized, and requirements by industry become more stringent. There is also a need for strong, dimensionally consistent parts that show good cosmetic properties. The processes used to meet these increasing demands must be consistent and repeatable over time.

Ultrasonic Cutting

There are several methods to cut plastics films and/or synthetic fibers. They include mechanical systems, heated tools, plasma, laser, ultrasonics, and water jet cutting. Some of these technologies are expensive and require complex equipment or degrade the cut edge by introducing stresses or micro cracks. However, ultrasonic cutting can circumvent some of these disadvantages. In more detail, ultrasonic cutting systems can be used with materials that are difficult to cut with standard mechanical systems; it is relatively fast and can often produce a relatively smooth edge as the tooling melts the edge being cut [4].

Ultrasonic cutting can have the horn or the anvil being serve as the cutting edge. When the horn is the cutting edge, it vibrates, heating the substrate during cutting (Figure 2). When the anvil has the shape of a blade, the horn has a flat surface applying a cyclic stress on the part placed between the horn and anvil and cuts the plastic (Figure 3). The oscillation of the horn applies a cyclic cutting force at the cutting tip/plastic interface that causes heating, which significantly reduces the overall cutting force required to cut through the material [4] [5], as well as promotes a smooth cut edge.

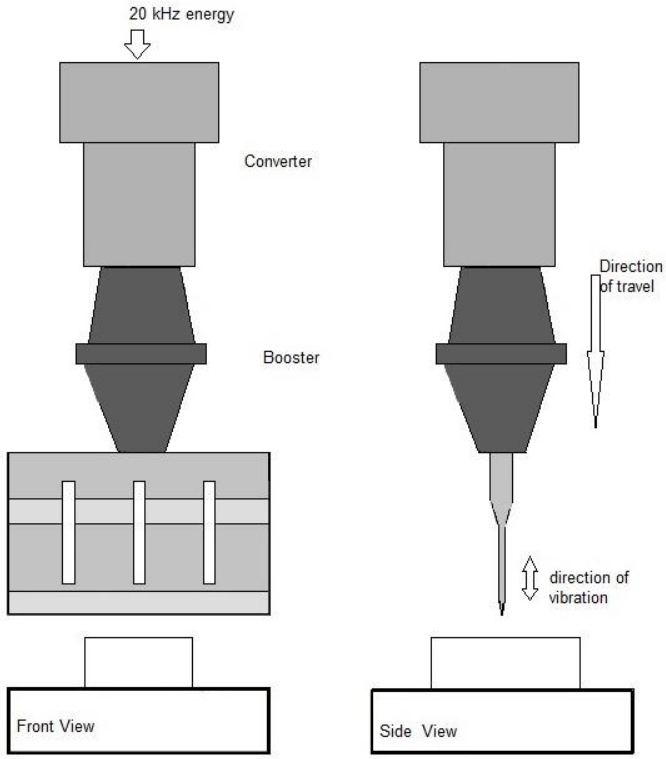


Figure 2 Example of horn being used as the cutting edge

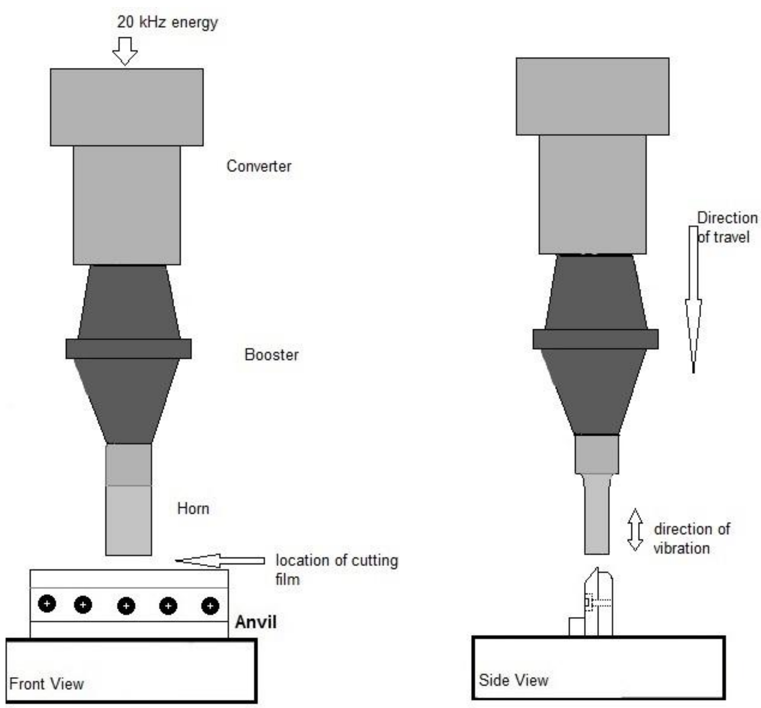


Figure 3 Example of anvil being used as the cutting edge

For mechanical cutting systems, brittle materials present a problem because it produces micro-cracks that weaken the material at the cut edge. Another advantage of ultrasonic cutting is the application of ultrasonic vibration decreases the force required for plastic deformation to occur and the heating of brittle material promotes “healing” of the cut edge.

Comparison of Servo and Pneumatic Actuators

There are two designs of ultrasonic welding actuators (also used for cutting), pneumatic and servo driven. Pneumatics have long been the staple of ultrasonics, where the distance is controlled indirectly by controlling the pressure to the air cylinder once the desired distance is achieved. Because there are limitations to the level to which compressed air can be controlled, as well as other factors, the press typically travels beyond the desired collapse distance by varying amounts. In this study, a pneumatic system was used with a ground detect mode on (Figure 4).

The ground detect feature is a function in which the anvil is electrically isolated by fastening a plastic insulator between the fixture and the base plate. A ground detect wire is connected to the generator (5VDC signal). The end of cutting cycle is determined when the horn and anvil are electrically engaged, and the circuit is closed. In short, the horn is grounded and acts as a switch closure when it with the fixture.

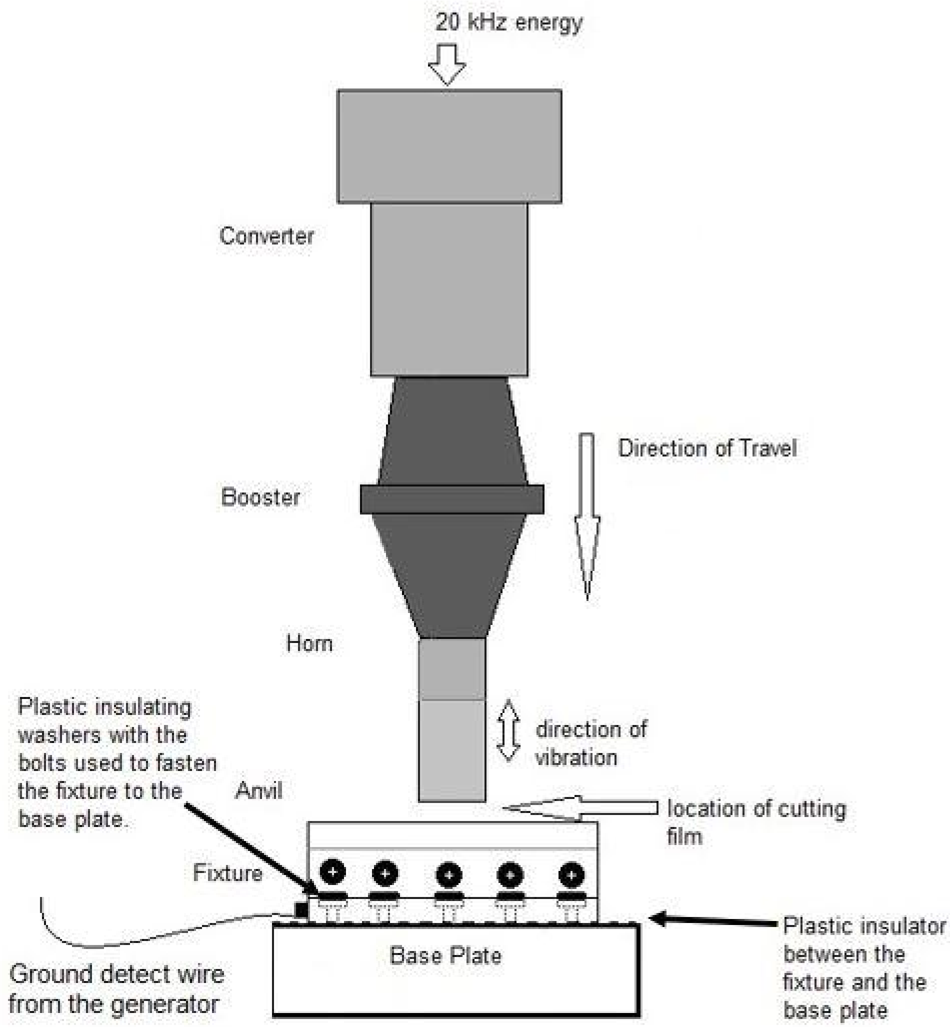


Figure 4 Diagram of ground detect

Servo-driven actuator welding systems offer a more precise control of the force and travel distances. The servo system controls the distance directly through a closed-loop servo position control (Figure 5). The servo press system can have an acceleration as high as 0.50 in/s^2 (1 in/s over 0.020 s), [6] during a typical welding/cutting cycle. Servo-driven ultrasonic welding systems offer greater process control compared to pneumatic based systems, which allows welding and cutting of materials with more precision.

In more detail, it is believed that relying on the servo-based system to terminate the cutting motion/force at an accurate predetermined position without allowing the horn and anvil from making contact will result in less tool wear. In contrast, with a pneumatic system, because of the required contact between the horn and anvil during the ground detect mode, there is likely excessive tool wear. The hypothesis is that a servo welding/cutting system provides more constant velocity, applied force, and more precision distance control compared to a pneumatic welding system [7] and this will result in more consistent cuts as well as extended tool life.

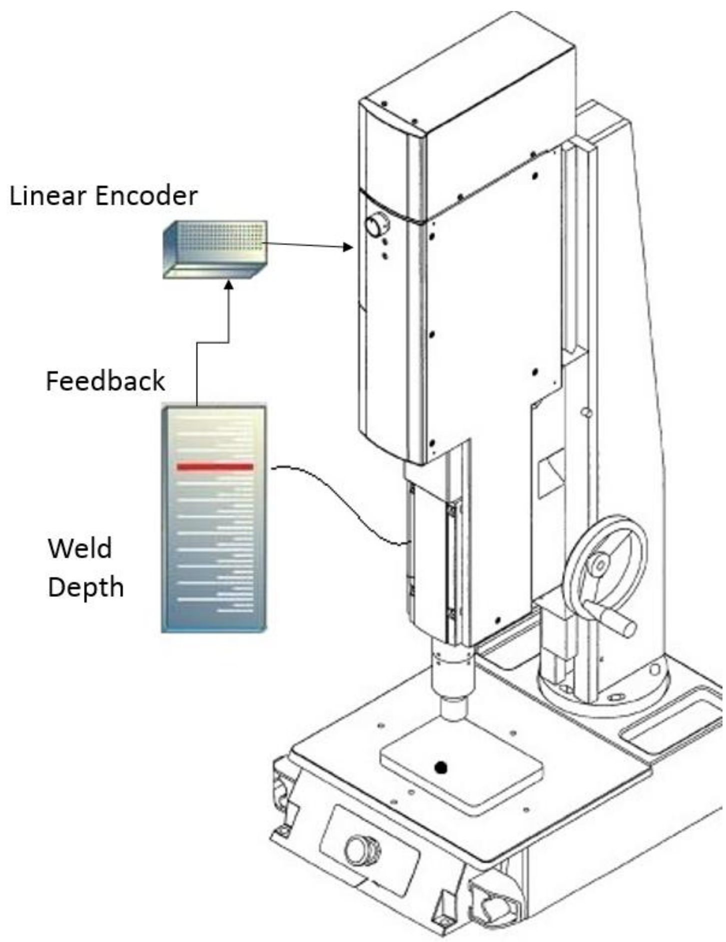


Figure 5 Distance control for a typical Servo system

CHAPTER 2. TOOL WEAR

In the late 1880s, F.W. Taylor published well-known studies of machining and this work is still widely used to model tool life and machining parameters. Tool life is defined as the length of cutting time that a tool can be used while producing quality parts [8]. As technology has progressed, these models are still used despite their early beginnings. Modern Computer Numerical Control (CNC) machines can predict tool failure based on power consumption or acoustic emission using Taylor's model. Taylor showed that there is a typical tool wear relationship between tool life and machining parameters as shown in Figure 6, depicting flank wear, which is tool wear at the interface between the tool and part. While any tool wear is undesirable, flank wear is the most common and is easily repeatable [9]. Figure 7 shows an example of different types and locations of tool wear on a lathe cutter. Based on the relationship seen in Figure 6, Taylor developed the well-known Taylor Tool Life equation (Eq. 1).

$$VT^n = C_t$$

Equation 1 Taylor Tool Life equation [9]

Where

T = Time

V = cutting speed

C_t = tool life constant

n = constant found by experimentation

In this equation, these parameters are typically imperially determined for a given setup but can be used to predict tool wear for a range of machining parameters (V, and T). While Taylor's tool life relationship is typically used for metal machining tools, it is proposed that the method can be applied to cutting of plastic with ultrasonics. While studies have related tool wear to speed and feed rate [10], other have compared tool wear in tools or fixtures excited by ultrasonic energy [11].

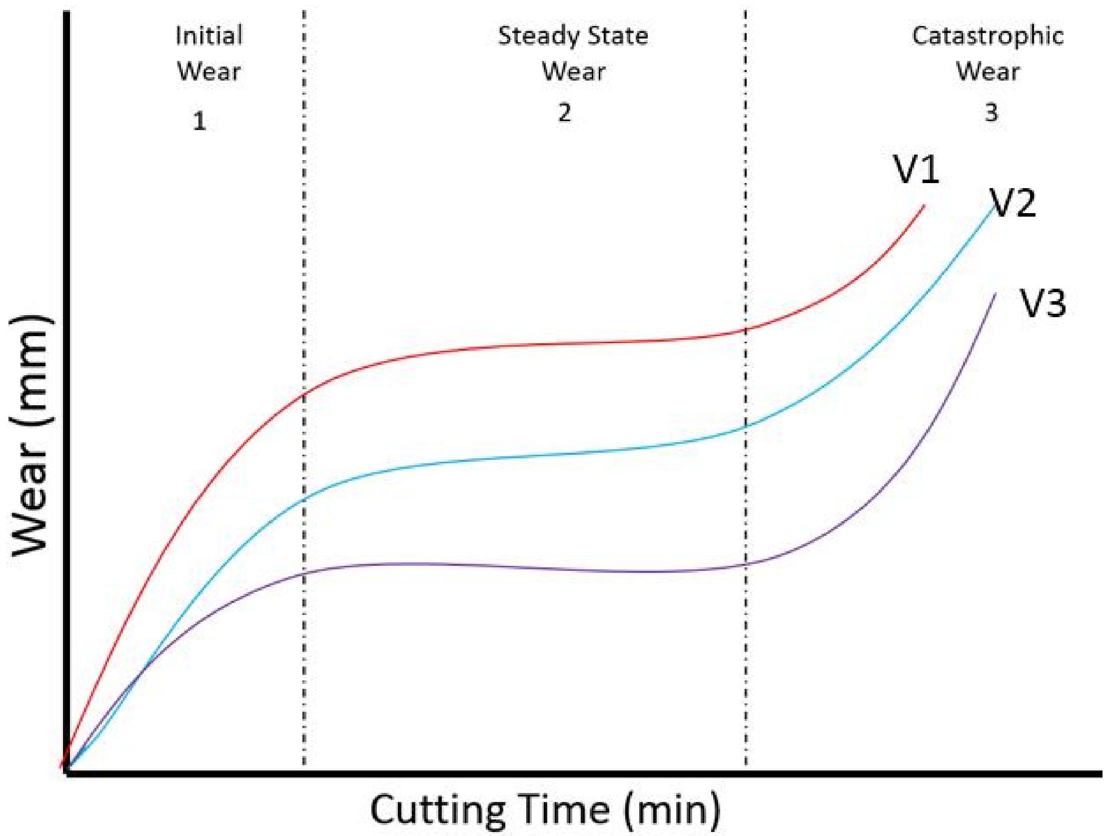


Figure 6 Typical tool wear curve (Lau *et al*., 1980)

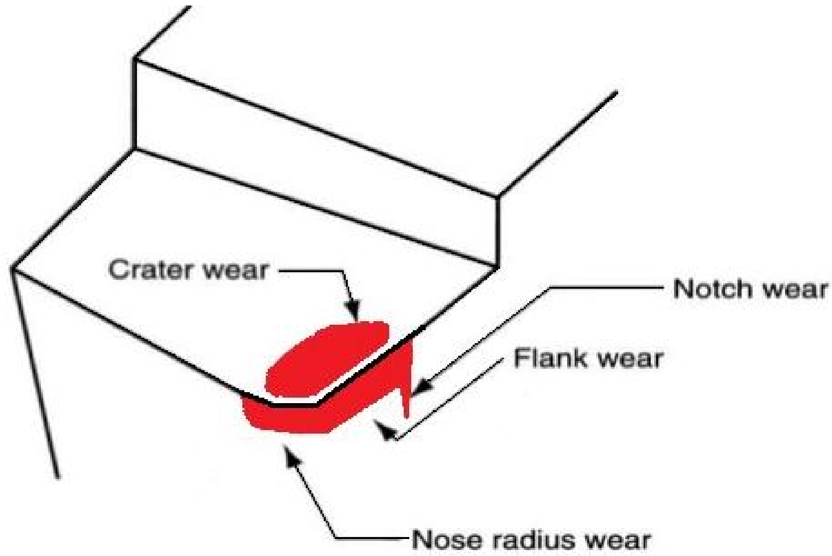


Figure 7 Example of different types of tool wear on a lathe cutter

Tool wear is a gradual process created by relative motion between two interfaces (tool/part). This occurs naturally when parts are manufactured repetitively. Speed, feed and temperature can impact the rate of wear and it is often difficult to control for all of them. Because a ground detect method requires tool to fixture contact while cutting to a distance, this wear could be avoided by use of a distance controlled method, it is hypothesized that there will be significant difference in tool wear between the two types of actuators, namely pneumatic and servo driven actuators.

Tool wear as a function of the number of cuts varies depending on the different machine settings, including ultrasonic amplitude and cycle control method (distance control (servo): ground detect (pneumatic)). Wear is typically non-linear as a function of the number of cutting cycles and can have different phase/stages over the range of cutting cycles. Typically, the rate of tool wear is initially relatively high, then the wear rate reaches a steady state condition. Near the end of the tool life, there is often an inflection point in which the rate of tool wear increases dramatically prior to tool failure [12]. Tool failure is usually associated with either catastrophic tool failure, the tool failing to work as intended, or the quality of the production parts not meeting product specifications.

In more detail, Figure 6 shows typical progression of tool wear. There is an initial break-in period (1) followed by a constant rate of wear (constant slope) (2) that eventially leads to an inflection point with an accelerated rate followed by failure (3). The three different wear (lines) in Figure 6 represent an example of different processing conditions, such as cutting speeds (V) which will follow similar trends but at slightly different amount of wear. For example with increased cutting speeds, the tool wear is accelerated but follows a similar relationship.

The focus of this study is to compare tool life for two different ultrasonic cutting systems using a cutting anvil, comparing a standard pneumatic system to a servo controlled system.

CHAPTER 3. EXPERIMENTAL PROCEDURES

Material Selection

The film used was aluminum coated PLA (polylatic acid) consisting of six layers, 20 µm thick film which was 90% PLA by weight [13]. The film was cut in long strips that were wider than the horn so that each ultrasonic cut produced a "button-hole" like cut profile. Figure 8 shows the setup during cutting. The strip of film was moved approximately 0.5 in (1 cm) after each cut which produced a series cut patterns as seen in the figure.

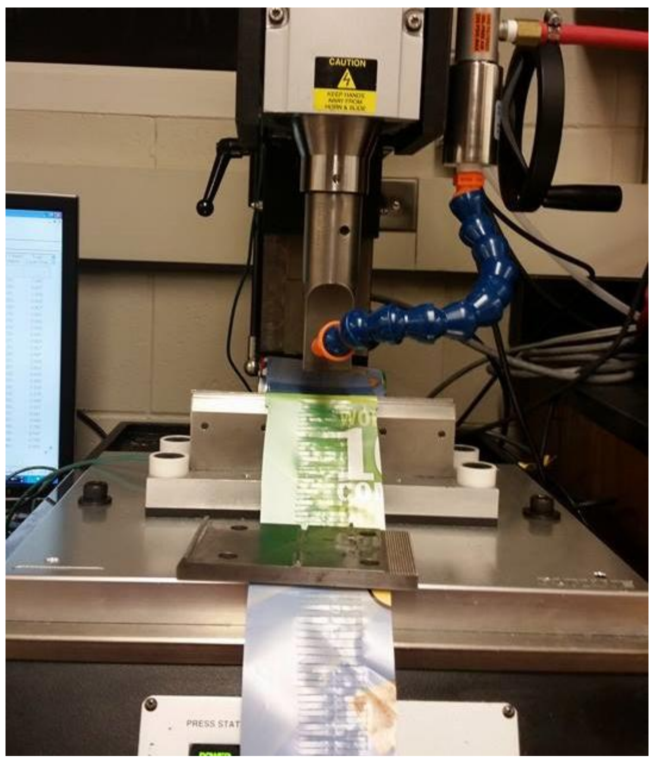


Figure 8 Setup of cutting PLA film on pneumatic-based system

Figure 9 and shows the two ultrasonic welding/cutting systems that were used: a pneumatic-based system and a servo-based system, respectively. Both systems were manufactured by Dukane Ultrasonics, (iQ series), had 100% digital controls, multi-core processing, with 20 kHz ultrasonic tooling systems [6]. The pneumatic system was configured with a ground detect control system. Ground detect is used to control the final dimensions of the cut part by continuing the ultrasonic vibrations until the horn and fixture make physical/electrical contact. The fixture was electrically insulated from the base of the machine to allow it to be electrically non-grounded (floating).

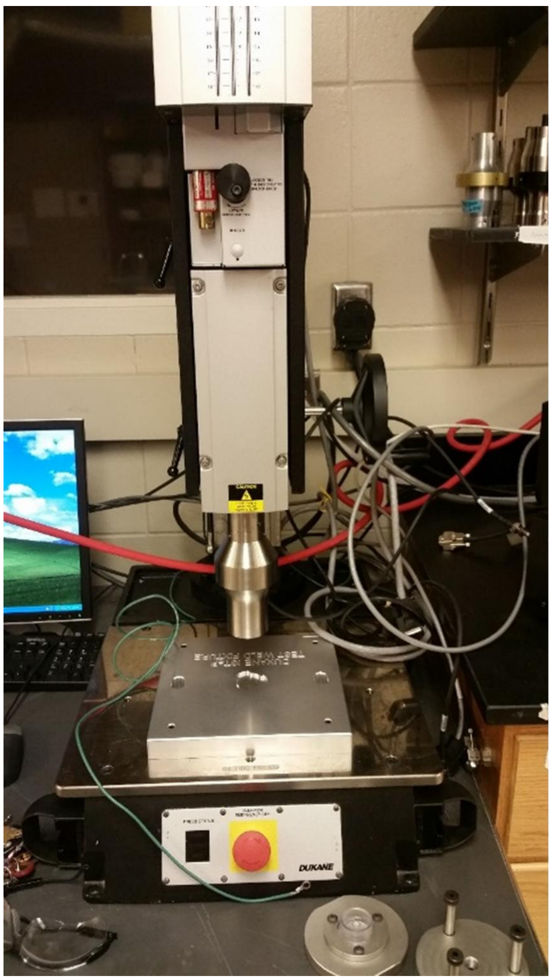


Figure 9 Dukane pneumatic ultrasonic welding system

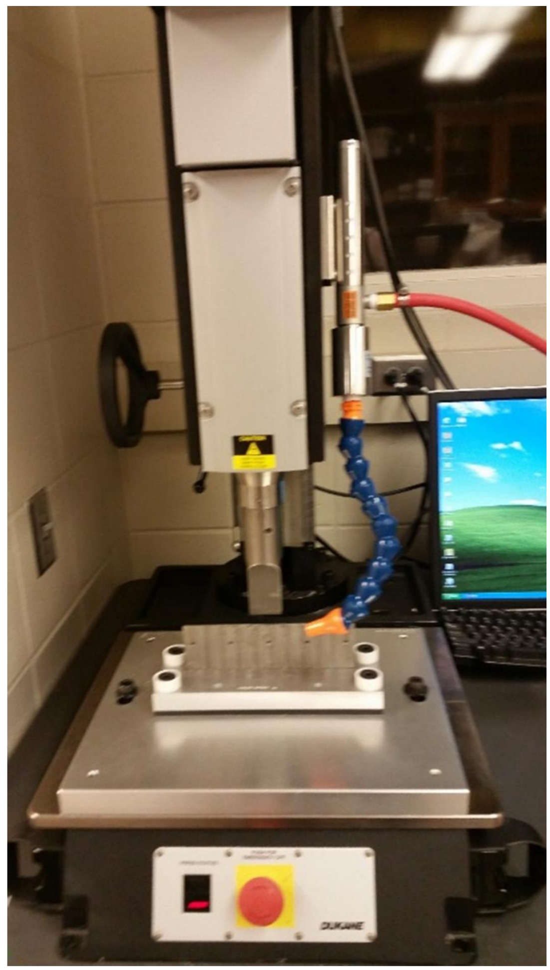


Figure 10 Dukane servo ultrasonic welding system

The servo system was programmed in a distance control mode. In more detail, the horn/stack assembly was set to travel to a preset distance to cut through the films without contacting the fixture. This allowed a direct comparison between the two modes, ground detect and distance mode (pneumatic and servo based actuator). The trigger force (from the horn) was set to 10 lbs. with a maximum trigger time of 1 second on both systems. The weld/cut method was set for ground detect on the pneumatic with a maximum time of 3 seconds.

The anvil was provided by Dukane and was produced from hardened steel in a blade type configuration (Figure 11). In initial trial runs, no wear developed with the hardened steel anvil using a titanium carbide tipped horn even after several thousand cycles. The hardened steel anvil was replaced with an aluminum anvil (Figure 12) to accelerate the wear process. The aluminum anvil was made in the same design and shape as the hardened steel anvil and was created and manufactured by the researcher. The same aluminum anvil was used for each run because it showed wear relatively quickly and it was easily sharpened between experimental runs.

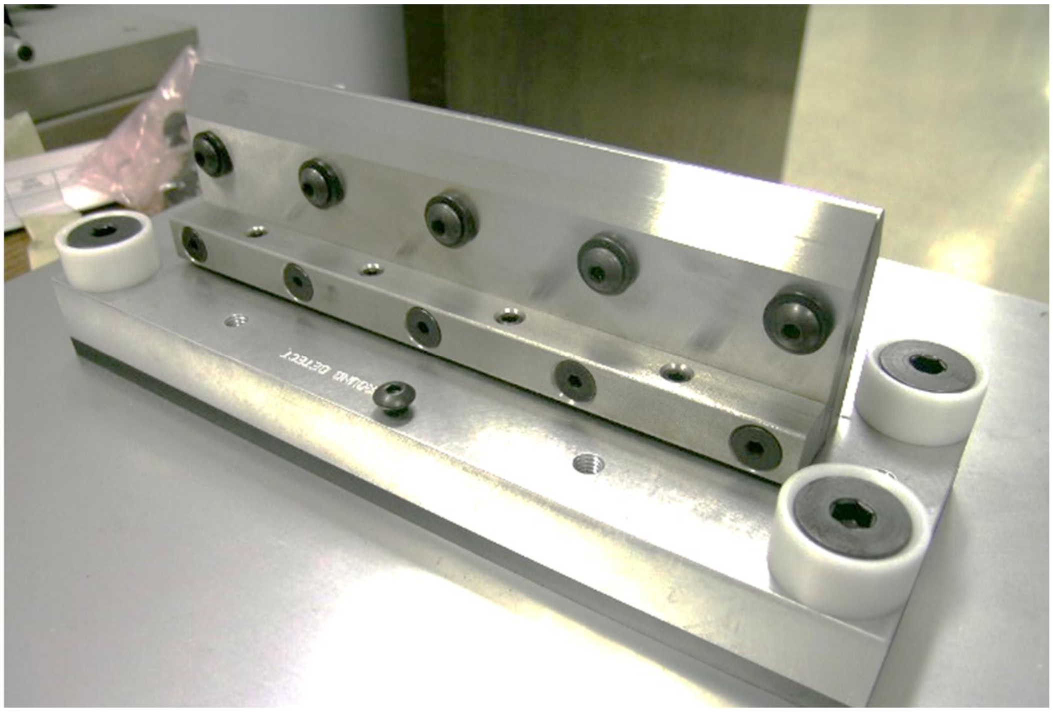


Figure 11 Hardened steel anvil

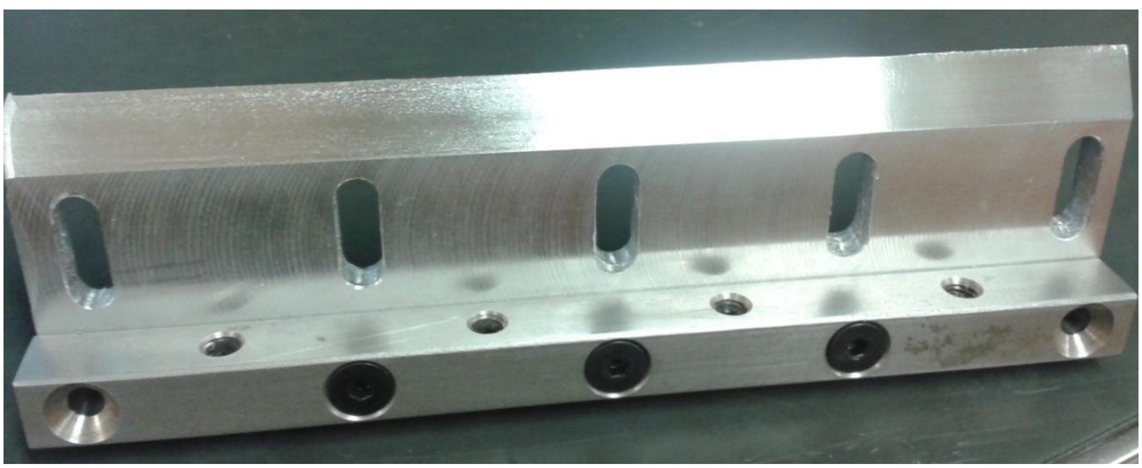


Figure 12 Aluminum anvil

Figure 13 details the setup for sharpening of the Aluminum anvil on a manual mill machine. During the machining/sharpening of the anvil, the head of the mill was set to 30 degrees and several passes were completed until the anvil was level and smooth.

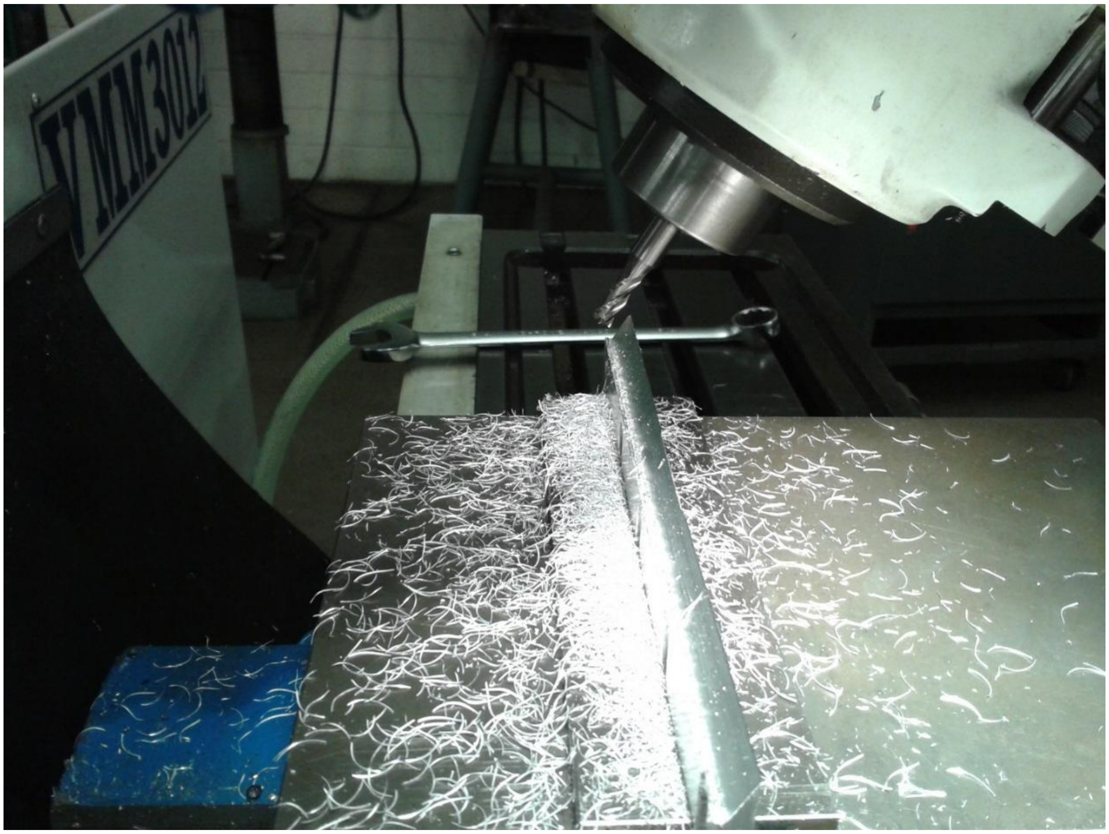


Figure 13 Mill machine with angled end mill head at 30 degrees sharpening aluminum anvil

To reduce experimental error, as many of the independent parameters as possible were held constant. For example, the same stack was used in both machines to eliminate the differences potentially caused by transducer, booster, or horn variance (Figure 14). The same computer running the software and the generator, shown in Figure 15 and Figure 16, was used to control both system. Thus, the only independent variable was machine type: pneumatic or servo actuator and the corresponding control modes, ground detect and distance mode.

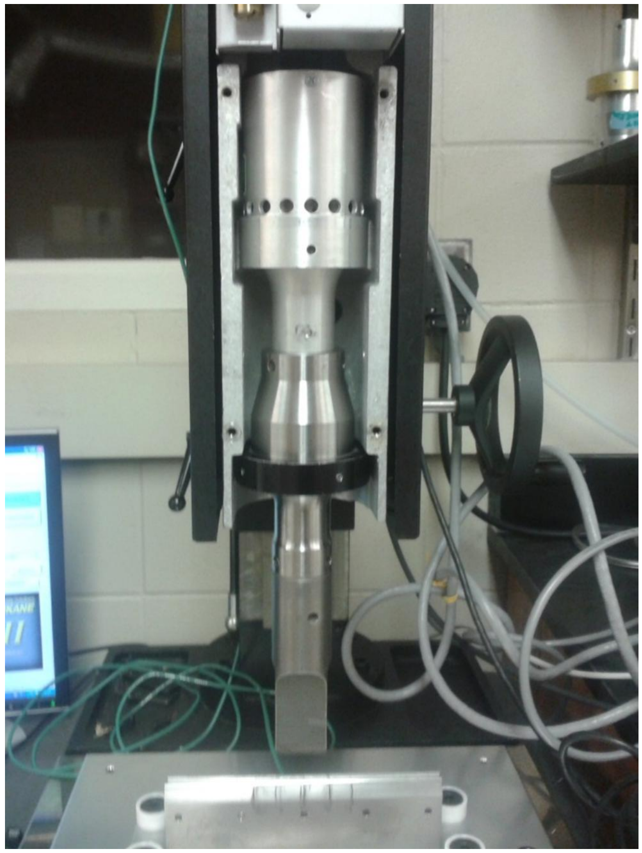


Figure 14 Open stack showing transducer, booster, and horn above the anvil

Figure 15 Generator

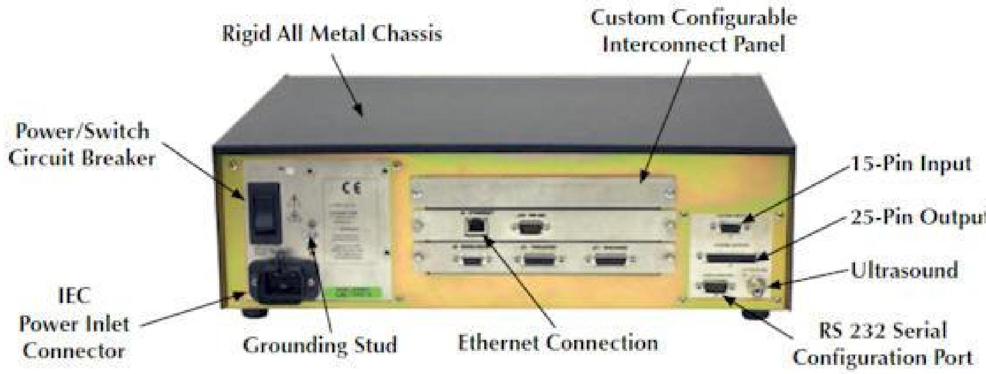


Figure 16 iQ Generator/power supply features

Gauge Repeat and Reproducibility

A Gauge Repeat and Reproducibility (Gauge R&R) was performed to provide an assessment of measurement precision to determine which measuring tool would be most accurate in measuring wear. In more details, a gauge R&R is a statistical tool to quantify the variation in a measurement system from the measurement device or the operator [14]. The technique relies on using two to three operators, several parts, and repeating the measurement three times. Each operator measures an item (sample dimension) multiple times (repeatability) and their measurements of the item are compared to the average of the measurement tools (reproducibility). Because there is the potential that various operators will use/interpret the measurement equipment in different ways, this approach allows characterization of the variability of the operator. In this study, the results of the assessment were used to characterize the various methods to determine which were most accurate and resulted in smallest experimental error. Three sets of data were taken for each measurement which are the three points of measurement for the anvil, each point being repeated three times by both operators:

1) The researcher
2) Laboratory assistant,

each using each three different measurement devices. Figure 17 details the locations of the three points on the anvil that the measurements were taken before the anvil was used to cut samples.

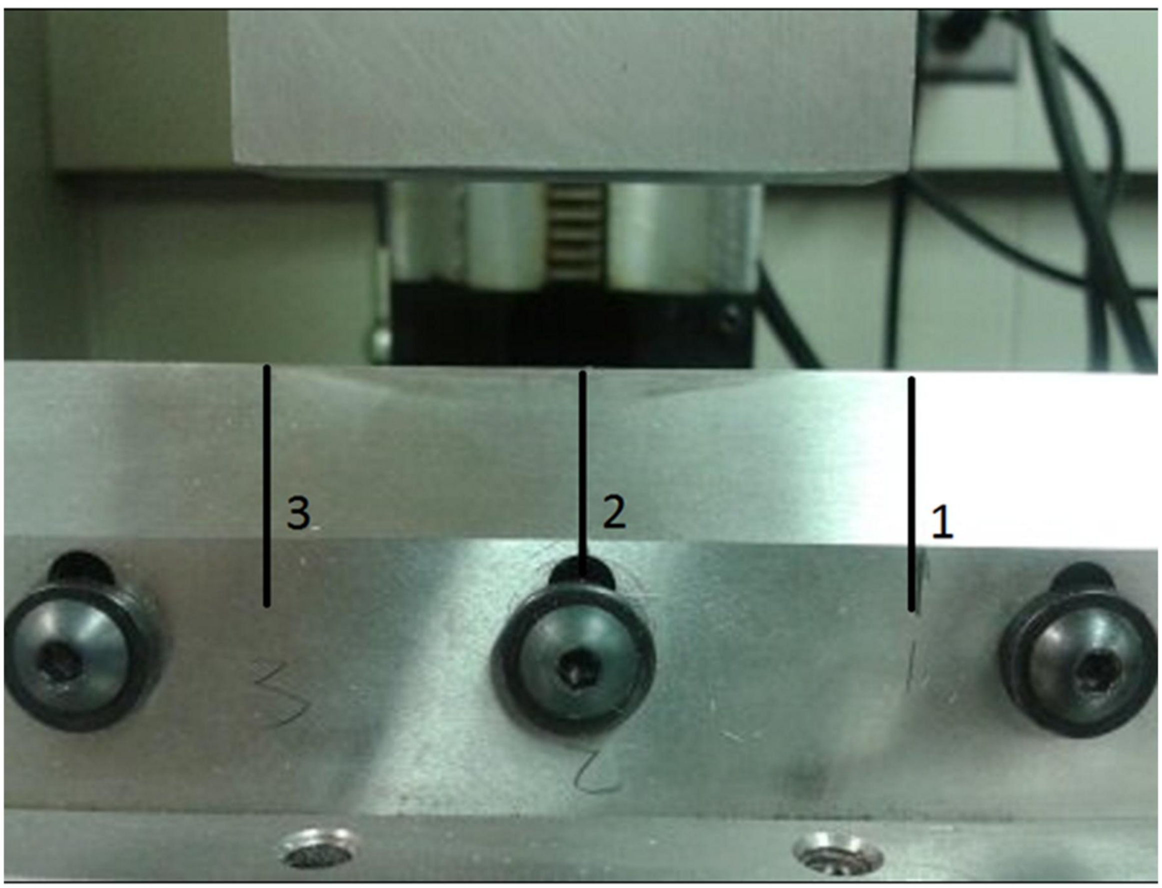
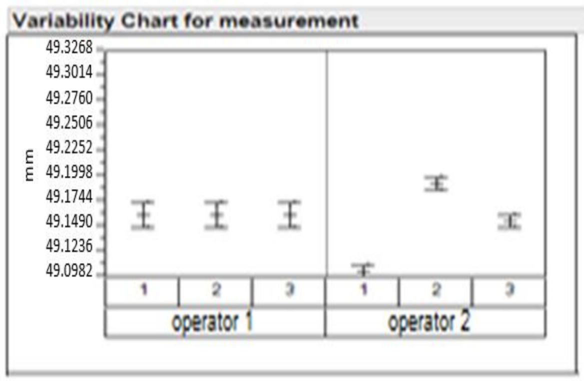


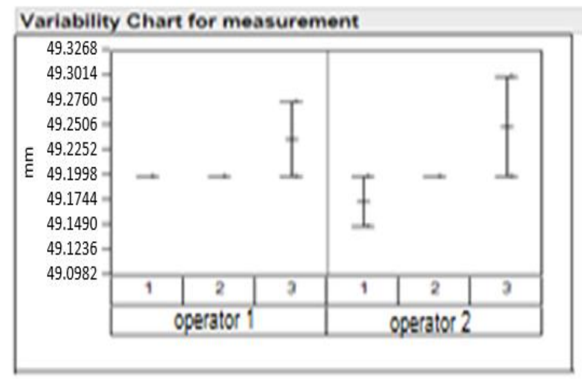
Figure 17 The three points measured on the anvil; the left of the horn contact (3), center (2), and right side of the horn contact (1)

The first set of data was taken with a digital caliper because of its simplicity of use. However, it is important to note that in order to measure the anvil with calipers, the anvil had to be removed from the fixture which may introduce experimental error as anvil placement/alignment can fluctuate between measurements. The second device was a Vernier caliper which is the simplest construction featuring two sliding scales that need aligned to give precision measurements, thus minimizing experimental error. However, the Vernier also required the anvil to be removed and replaced during the measurement. The third device was a height gauge. The height gauge had a dial indicator allowing it to be aligned in the direction of wear and a support beam connected to the base of the fixture. With the height gauge method, anvil removal was not required to be removed to measure the wear because the gauge was placed next to the anvil and mounted on the base of the system.

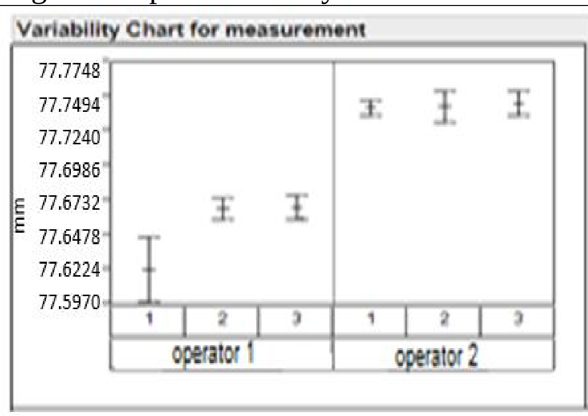
Figure 18 shows that, in general, the measurements made with the digital calipers exhibited the smallest variations. In more detail, each data point is the average of the repeat measurements, and the error bars correspond to one standard deviation. In addition, it is seen that measurements by operator #2 had relatively small variations compared to operator #1. Measurements taken by the digital caliper and the height gauge exhibited lower overall variance compared to those taken by the Vernier caliper.



Digital Caliper Variability Chart



Vernier Caliper Variability Chart



Height Gauge Variability Chart

Figure 18 Gage R&R variability charts from JMP Pro 10 for each measuring device measuring the anvil before cutting

Figure 19 shows the variance component results of the Gauge R&R from JMP Pro 10 which is the relative error by device, operator, or the part. Part to part component had low variance because the only difference was the locations measured on the same part. The height gauge had the smallest variance for repeatability. The largest variance for the height gauge was produced by the operators (reproducibility) thus one operator was used for the experiment. The height gauge had the added advantage of ease of use and not requiring removal of the anvil. Thus, based on the results of the gauge R&R evaluation, the height gauge was selected as the method of measurement.

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	7.883e-7	72.39	
Repeatability	2.32853e-7	21.38	
Reproducibility	5.55447e-7	51.01	
Part-to-Part	3.00639e-7	27.61	

Digital Caliper

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	1.74214e-6	75.94	
Repeatability	1.2915e-6	56.30	
Reproducibility	4.50643e-7	19.64	
Part-to-Part	5.51833e-7	24.06	

Vernier Caliper

Variance Components for Gauge R&R

Component	Var Component	% of Total	20 40 60 80
Gauge R&R	6.80083e-6	99.12	
Repeatability	4.93333e-7	7.19	
Reproducibility	6.3075e-6	91.93	
Part-to-Part	6.04167e-8	0.88	

Height Gauge

Figure 19 Gauge R&R results from JMP Pro 10 for digital caliper, Vernier caliper, and height gauge.

Methods

In the initial cutting trials using the pneumatic system with the 1:1 gain booster it was found that after 12,000 cutting cycles, the samples were not fully cut by the aluminum anvil because of excessive wear of the tool by the pneumatic system (ground detect) and the experiments were discontinued. Thus, 12,000 cutting cycles was defined as the maximum number of cutting cycles used for each run thereafter.

Initially the anvil was measured every hundred cuts however because of limited wear it was decided to measure the wear at every 500 cuts. The anvil was measured using the height gauge as described in the previous section. As seen in Figure 17, three locations of wear where measured (1, 2, and 3). Point 2 was directly in the center of the horn hits the anvil. Points 1 and 3 were on the edge where the horn hits the anvil (3 is left side and 1 is right side).

An initial measurement was taken before any cuts were made as a reference point. Tool wear was calculated by the initial measurement minus the measurement made at the last cut. Both machines were set to make a cut through the entire thickness of the film. During set up, three to five cuts were taken to make sure that the cuts were complete. The initial measurements were taken after setup to assure that wear during setup was not considered. The servo was set to stop moving 0.050 mm. above the anvil. Figure 20 shows the anvil with the different reference marks of the initial measurement (top line) and the measurement taken after the cutting cycles (bottom line) where the gap between the lines corresponds to the amount of wear.

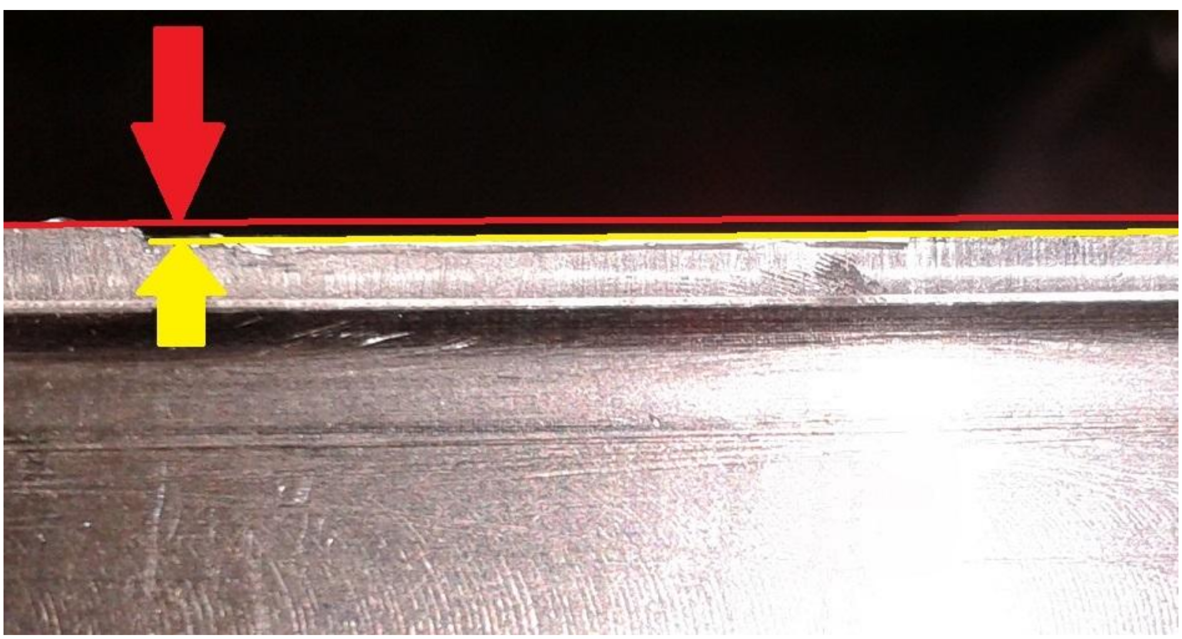


Figure 20 Anvil showing the difference in wear

The anvil was sharpened between each experiment (amplitude and equipment) using a standard end mill as previously describe. The sequence of testing includes:

1) Servo system was tested with the 1:1 booster
2) Pneumatic system was tested with the 1:1 booster (removed from #1)
3) Servo system was tested with the 1:5 booster (new stake assembly)
4) Pneumatic system was tested with the 1:5 booster (removed from #2)
5) Servo system was tested with the 1:2 booster (new stake assembly)
6) Pneumatic system was tested with the 1:2 booster (removed from #5)

CHAPTER 4. RESULTS

Tool wear as a function of cutting cycles for the various cutting amplitudes follows a typical trend of wear for machining tools, as seen in Figure 21 and Figure 22. It is important to note that rapid tool wear near the end of tool life were not always seen because the tools were not all taken to failure because of time limitations. However, with the pneumatic actuator system and the 1:1 booster (Figure 23), this inflection point is seen near tool failure between 11,000 and 12,000 cuts.

It is also seen that in general, tool wear was inversely proportional to the amplitude (amplitude gain). While this may be counterintuitive, it is believed that because higher amplitudes produce higher heating rates, resulting in shorter cutting time (number of ultrasonic oscillations) and there was a reduction in total ultrasonic cycles (at 20,000/s) for each cutting cycle. In Figure 21 and Figure 22, it is seen that the wear is lower for the higher amplitudes (booster gains).

Figure 21 shows wear as a function of cutting cycles for all the amplitudes for the pneumatic system. For all three amplitudes, the curves of the tool wear follow a similar trend however at different wear rates with the higher amplitude (1:2 booster) having the lowest amount of total wear.

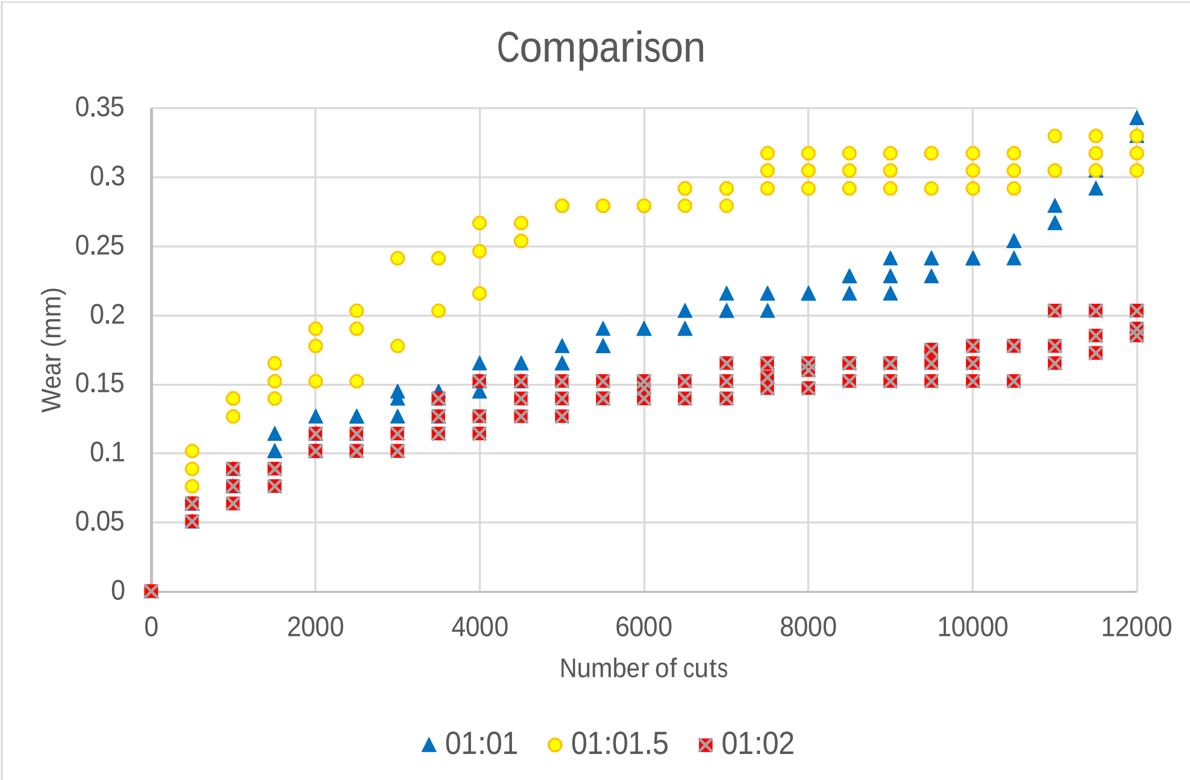


Figure 21 Pneumatic comparison of all the amplitudes

Figure 22 shows wear as a function of cutting cycles for the servo comparison for all the amplitudes studied. Again, as reported with the pneumatic system, the tests with the 1:2 booster had the lowest amount of wear for the servo systems. Again, this is believed to be the result of higher heating rates and reduced cutting times and corresponding cyclic wear on the tool.

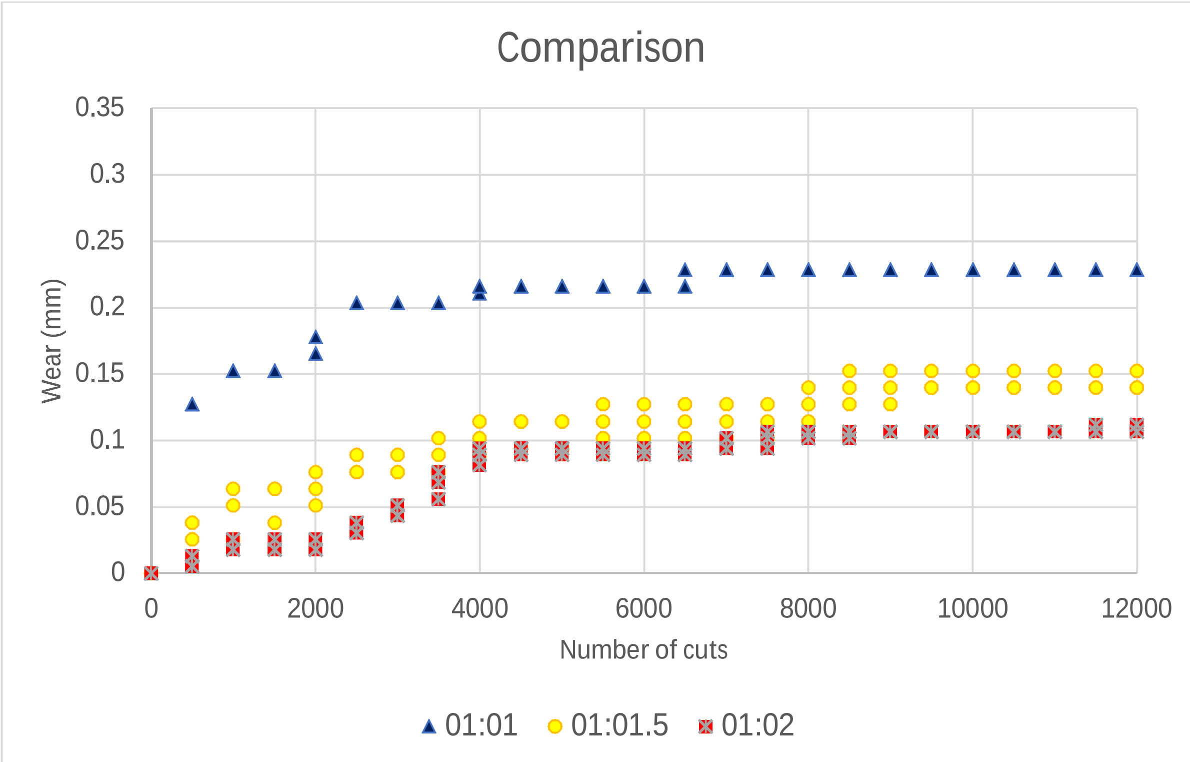


Figure 22 Servo comparison of all the amplitudes

The trendlines for all the runs, as seen in Table 1, are in the format of y=mx +b, where *m* is the slope and *b* is the y intercept. The slopes (rate of wear) of the regression lines for the measurements were similar for the various amplitudes however differed between the servo and the pneumatic actuator systems by a full magnitude.

Table 1 Trendlines of pneumatic and servo actuators

Amplitude	**Pneumatic**	**Servo**
1:1	y= 2E-05x+0.0658	y=8E-06x+0.1581

Table 1 (continued)

Amplitude	**Pneumatic**	**Servo**
1:1.5	y=2E-05x+0.1444	y=9E-06x+0.0488
1:2	y=1E-05x+0.0766	y=9E-06x+0.0247

Also seen in Figure 23 and Figure 24, the trends of the lines for the pneumatic tool (1:1 and 1:1.5) were very similar, as seen in similar regression lines slopes (coefficient). In Figure 23, the 1:1 pneumatic system rapidly reached failure while the servo system had a wear rate that was relatively low. Figure 24, for the 1:1.5 booster, shows greater difference between the servo and pneumatic wear rates. Figure 25 shows less wear overall with the use of the 1:2 booster compared to the other two boosters. Again, it is believed that the higher amplitude resulted in short cutting cycle times. However, it is seen that overall the pneumatic system produced the highest wear and wear rate compared to the servo system.

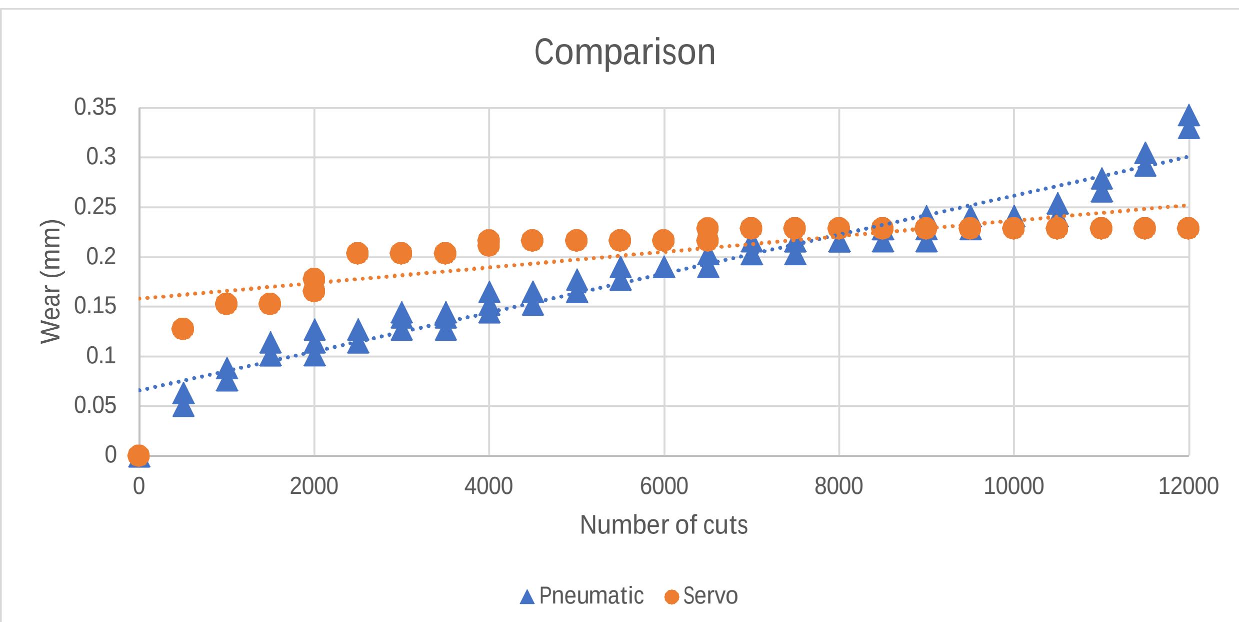


Figure 23 Pneumatic and servo tool wear with 1:1 booster

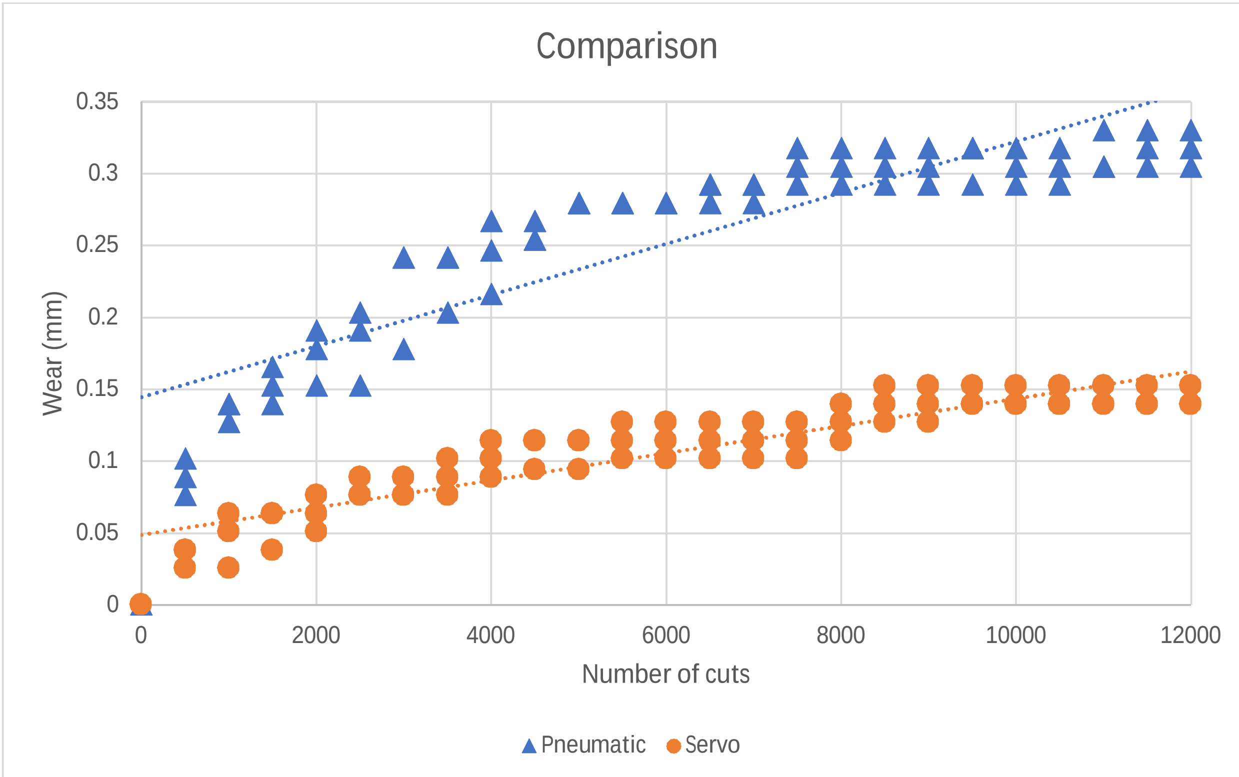


Figure 24 Pneumatic and servo tool wear with 1:1.5 booster

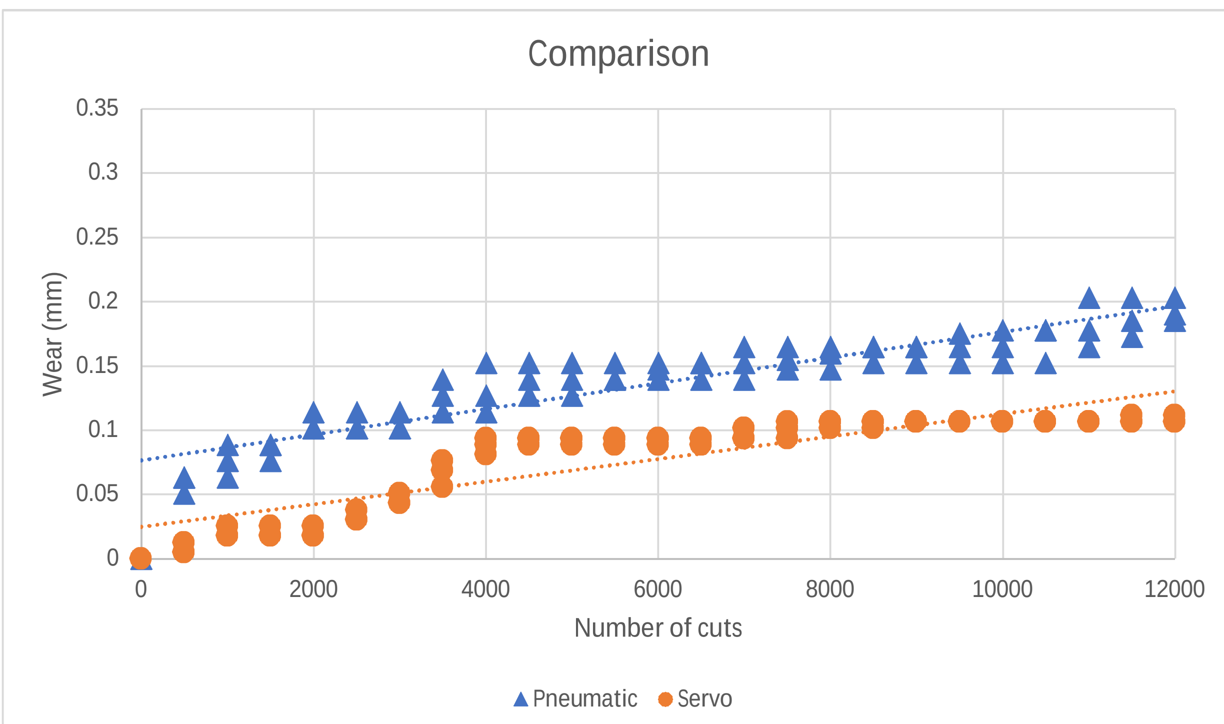


Figure 25 Pneumatic and servo tool wear with 1:2.0 booster

When the data is analyzed within the different wear regions, additional similarities are seen. As shown in **Error! Reference source not found.**, **Error! Reference source not found.**, and Figure 28, the slopes of the trendlines of all the runs for the first 2,000 cuts is higher compared to the balance of the cuts. This first region is called initial wear or break-in region. This can also be seen in Table 2 and Table 3 which has all the trendlines split out into the different wear regions.

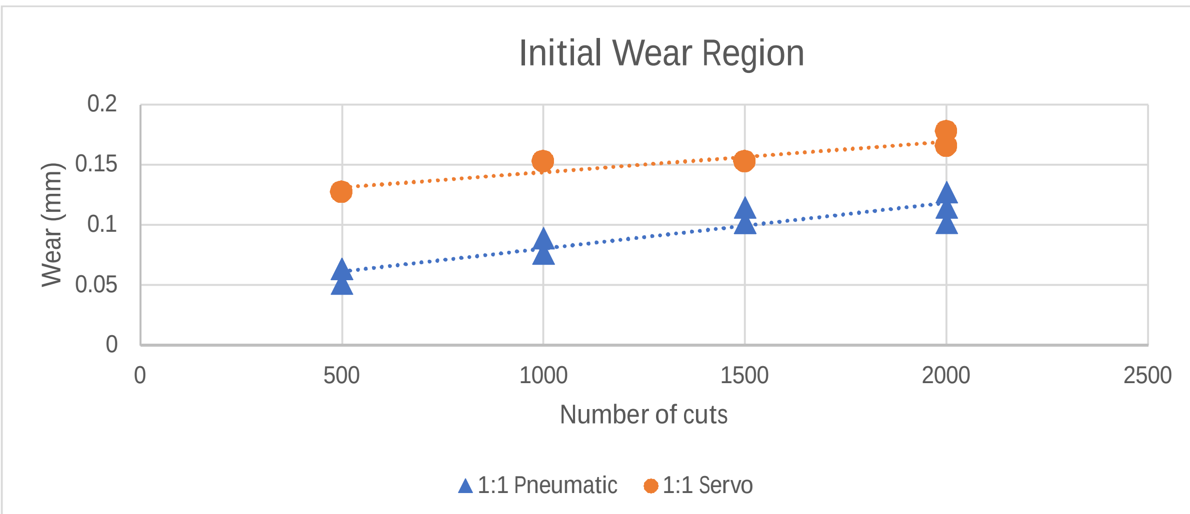


Figure 26 Initial Wear Region with 1:1 Booster

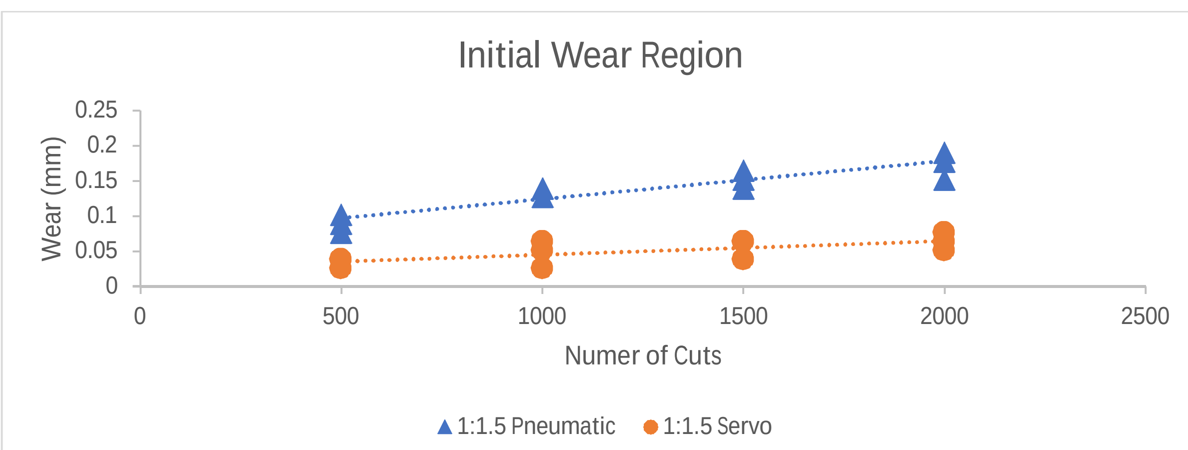


Figure 27 Initial Wear Region with 1:1.5 Booster

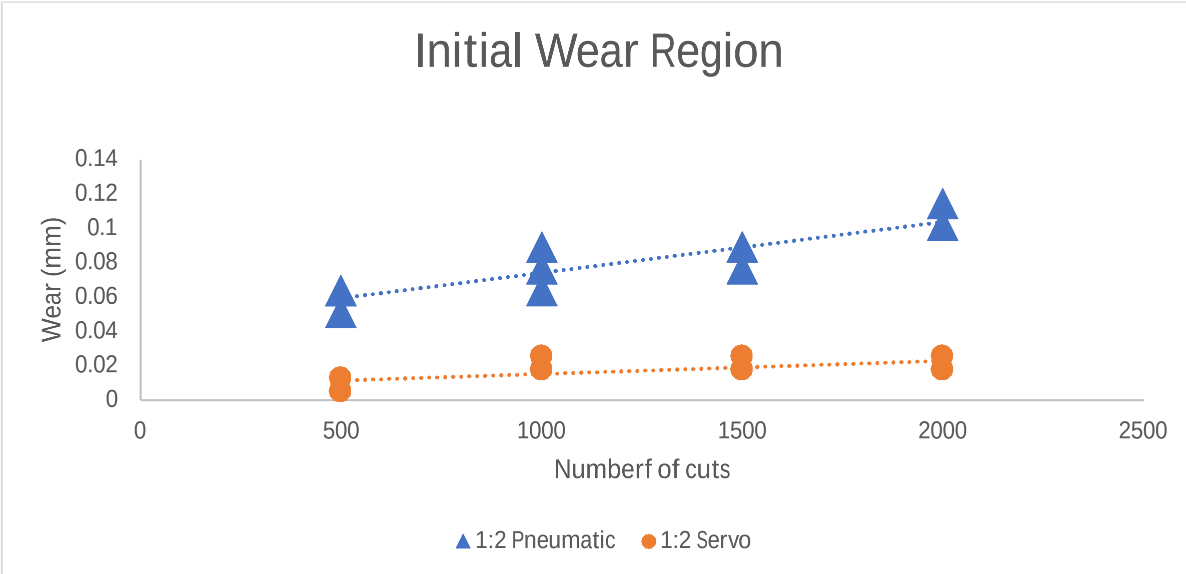


Figure 28 Initial Wear Region with 1:2 Booster

Table 2 Trendlines of servo system split into the different wear regions

Servo			
Amplitude	**Initial**	**steady**	**final**
01:01	y = 3E-05x + 0.1185	y = 4E-06x + 0.1951	y = -4E-18x + 0.2286
01:01.5	y = 2E-05x + 0.0254	y = 8E-06x + 0.0621	y = 1E-18x + 0.1439
01:02	y = 3E-05x + 0.0444	y = 8E-06x + 0.0405	y = 1E-06x + 0.0923

Table 3 Trendlines of servo system split into the different wear regions

Pneumatic			
Amplitude	**Initial**	**steady**	**final**
01:01	y = 4E-05x + 0.0423	y = 2E-05x + 0.0893	y = 6E-05x - 0.4043
01:01.5	y = 5E-05x + 0.0698	y = 1E-05x + 0.184	y = 8E-06x + 0.218
01:02	y = 8E-06x + 0.0076	y = 7E-06x + 0.0977	y = 2E-05x + 0.0114

The center region is called the steady state region (generally 2,000 to 10,000 cuts) and shows a reduced tool wear rate compared to the initial break-in. As seen in Figure 29, the tool wear data with the servo actuator and the 1:1 booster is nearly independent of the number of cuts and the wear rate (slope of the line) is approximately zero.

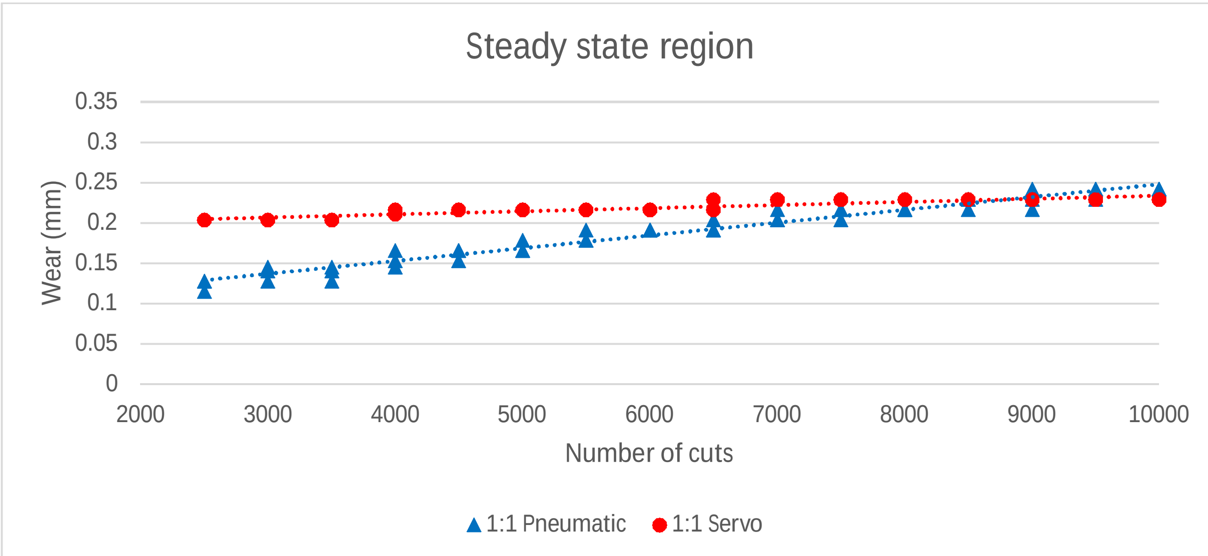


Figure 29 Steady state regions with 1:1 booster

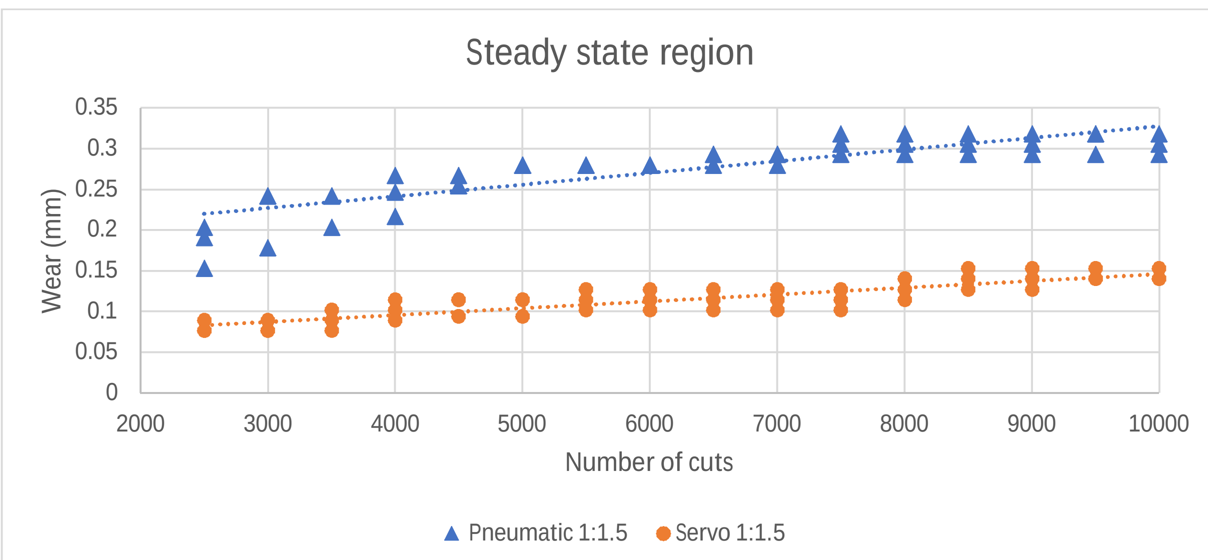


Figure 30 Steady state regions with 1:1.5 booster

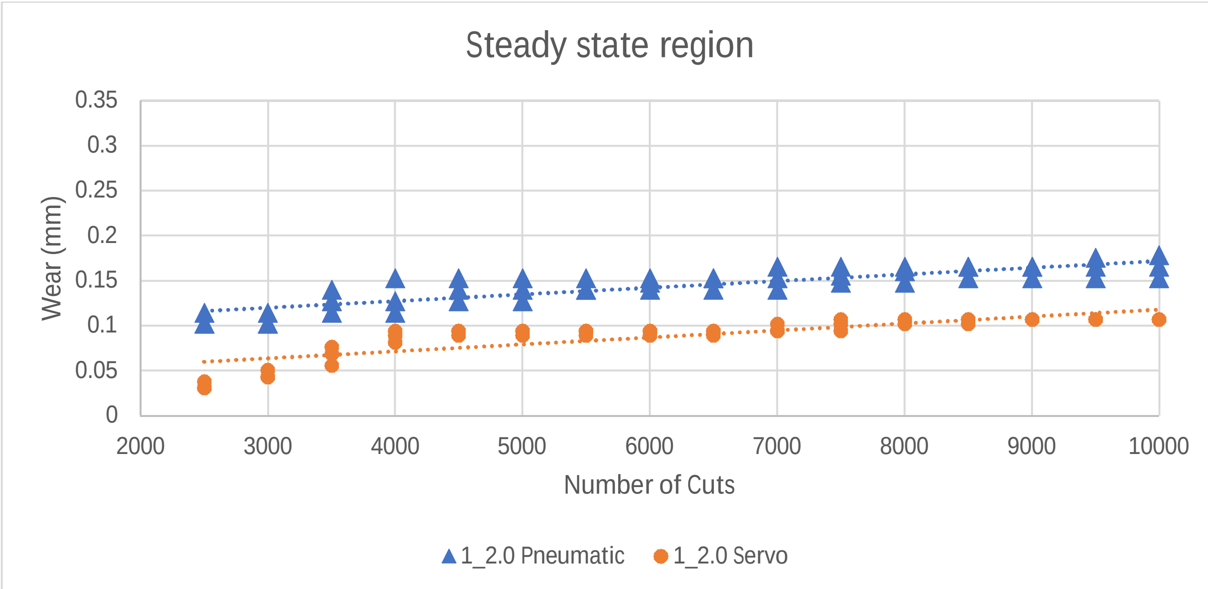


Figure 31 Steady state regions with 1:2.0 booster

In reference to the servo tool, during the end of the cuts (10,000 to 12,000), the system has a tool wear rate (slope of line) near zero, and thus it appears to remains in a state of no wear, independent of the amplitudes tested as seen in Figure 32, Figure 33 and Figure 34. This suggests that the servo system maintains a near zero rate of tool wear.

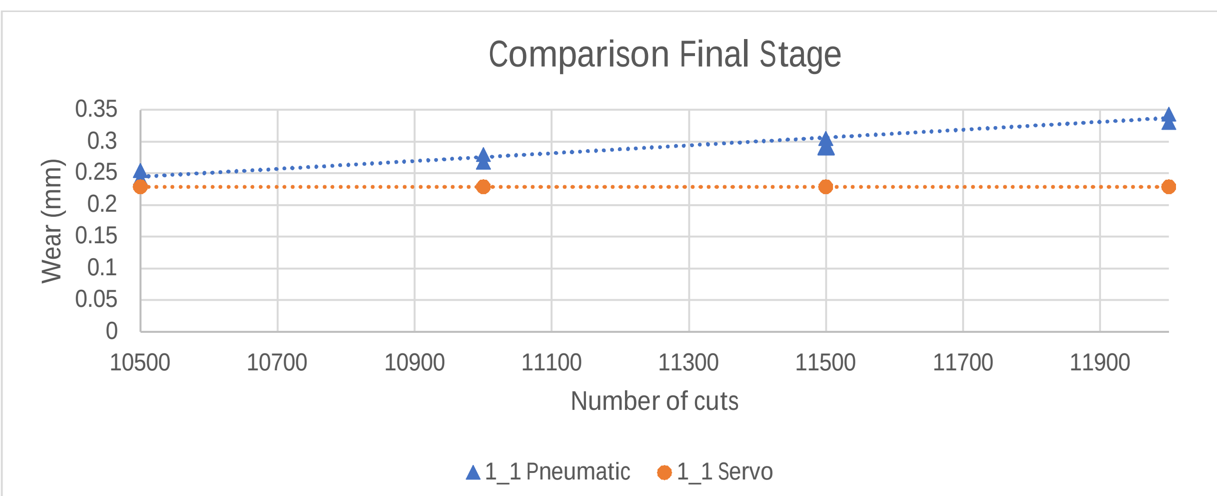


Figure 32 Final stage comparison 10,000 – 12,000 cuts with 1:1 booster

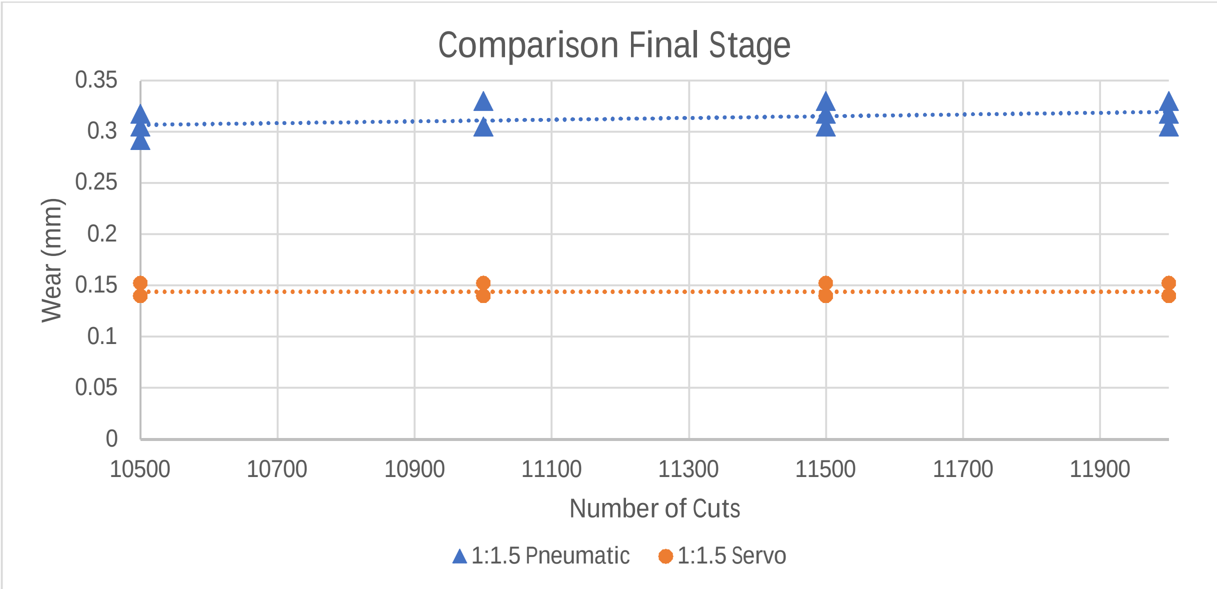


Figure 33 Final stage comparison 10,000 – 12,000 cuts with 1:1.5 booster

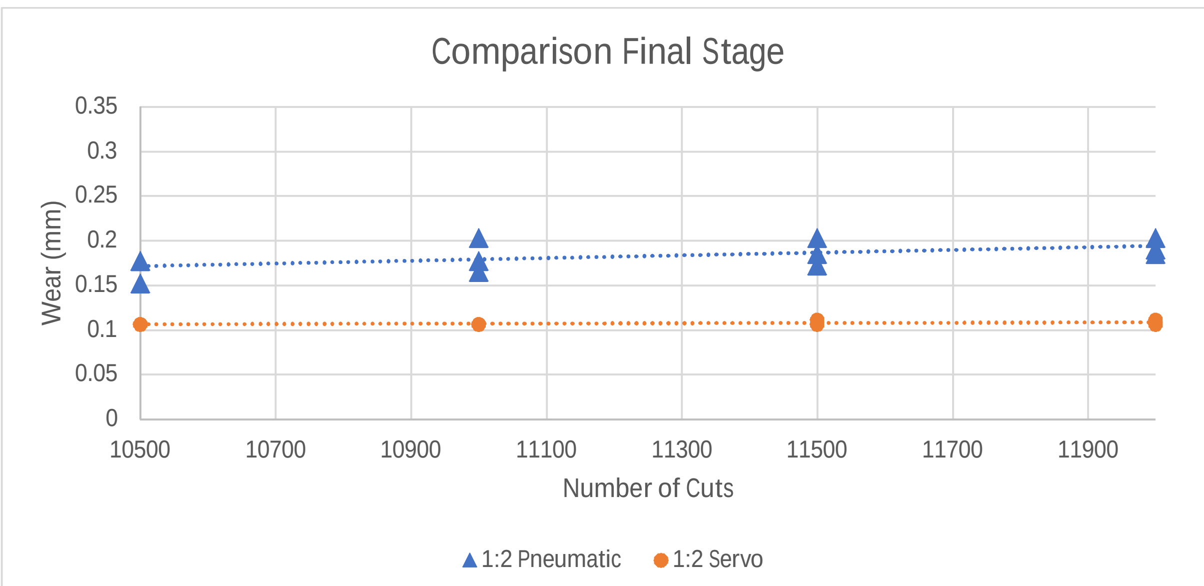


Figure 34 Final stage comparison 10,000 – 12,000 cuts with 1:2.0 booster

Figure 35 to Figure 40 show Scanning Electron Microscope (SEM) photographs of the anvil (used with pneumatic and servo actuators, respectively) after 12,000 cuts. It is seen that in all three locations the anvil with the servo system appears to be smoother compared to the anvil with the pneumatic system. In addition, it is seen that the tool wear "land" is larger for the anvil with the pneumatic system (Figure 37 and Figure 38). It is also seen that portion of the anvil with the pneumatic system appears to be eroded away, suggesting excessive wear.

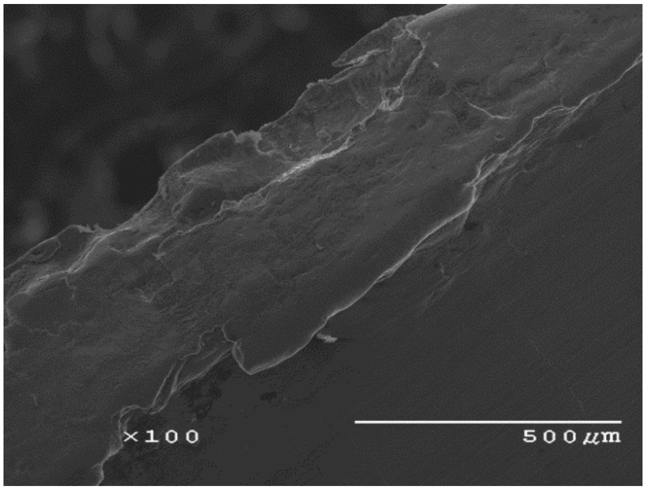


Figure 35 Pneumatic actuator, center of anvil 100x magnification

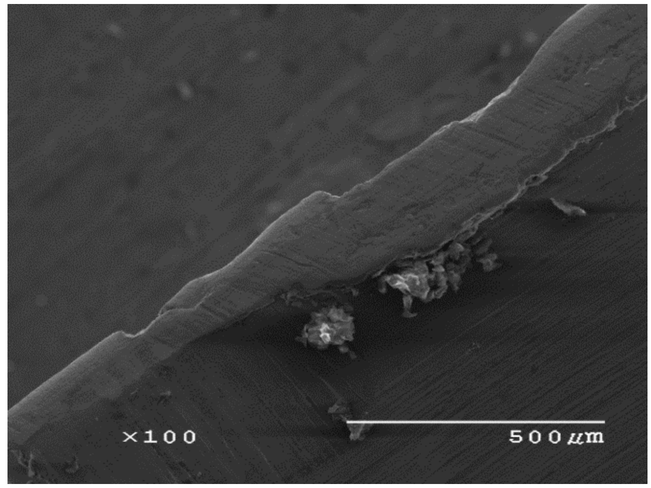


Figure 36 Servo actuator, center of anvil, 100x magnification

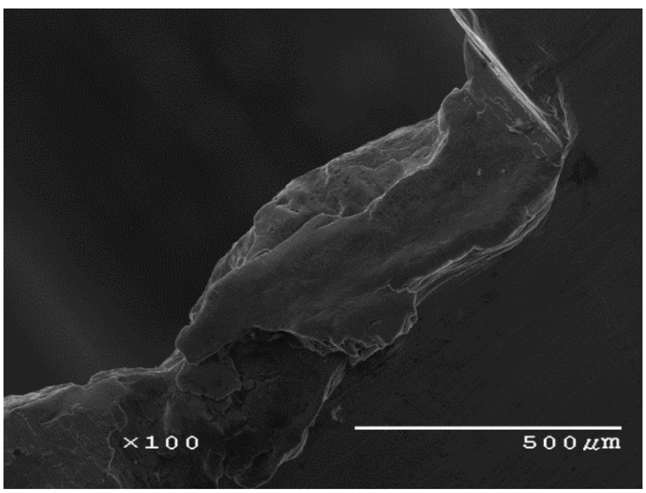


Figure 37 Pneumatic actuator, right edge of anvil, 100x magnification

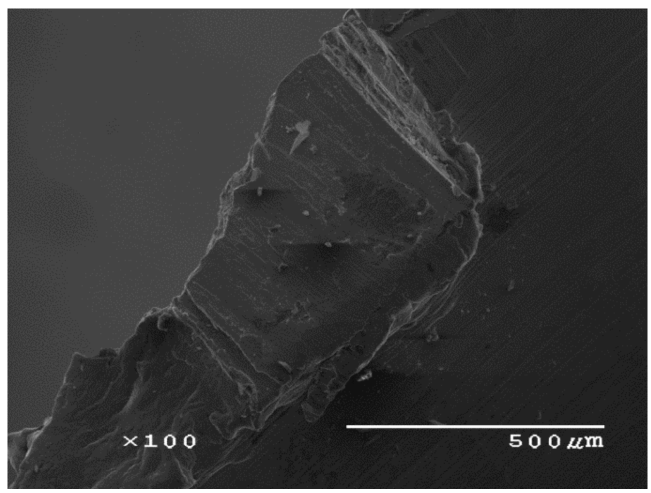


Figure 38 Servo actuator, right edge of anvil, 100x magnification

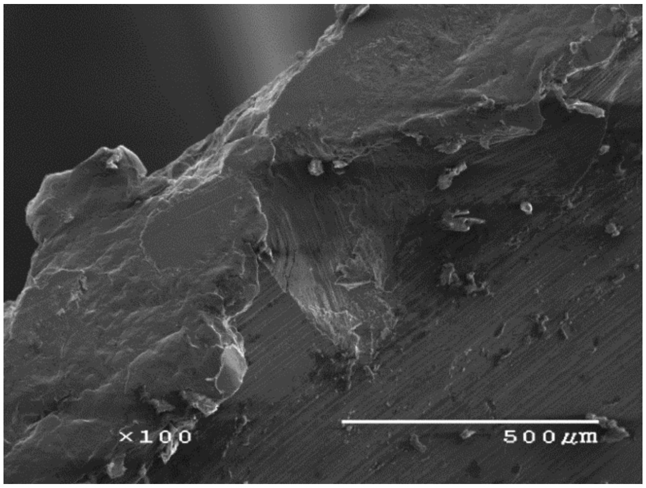


Figure 39 Pneumatic actuator, left edge of anvil, 100x magnification

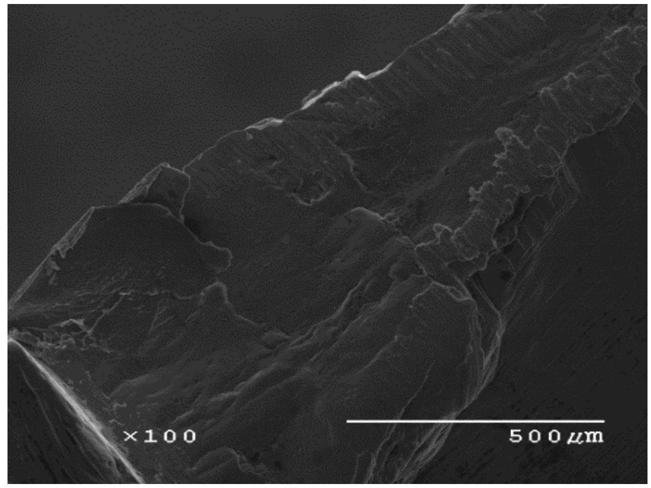


Figure 40 Servo actuator, left edge of anvil, 100x magnification

Figure 42 to Figure 46 show SEM photographs of a sample of the film (cut with pneumatic and servo actuators, respectively) after 12,000 cuts. Figure 41 details the orientation of the film during the SEM imaging, with the edge of the cut facing towards the camera. It is seen that the film cut with the servo system appears to be smoother and there is less frayed compared to the film cut with the pneumatic system. PLA is a brittle material which forms cracks along most standard cut edges. While cutting with ultrasonic vibrations, the edge is heated, and any cracks formed by the process are also healed. It is important to note that the servo system appears to “heal” the edge of the material more uniformly because of the reduced tool wear, making for the appearance of a smoother edge after 12,000 cuts.

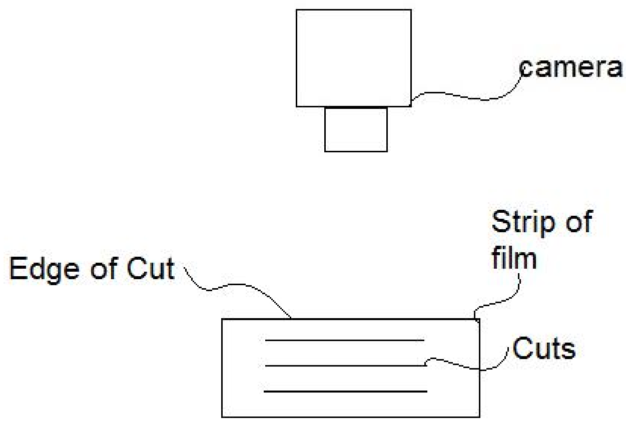


Figure 41 Set up of how SEM photograph were taken of film

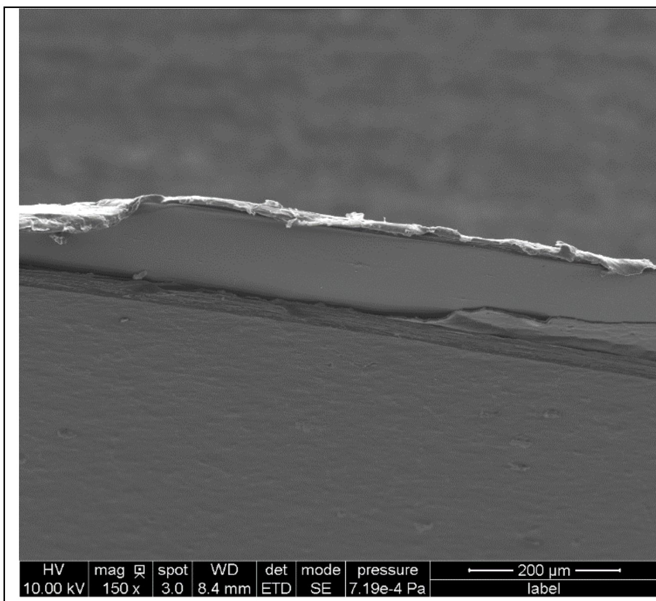


Figure 42 SEM of film after pneumatic actuator cutting 1:1, 150x magnification

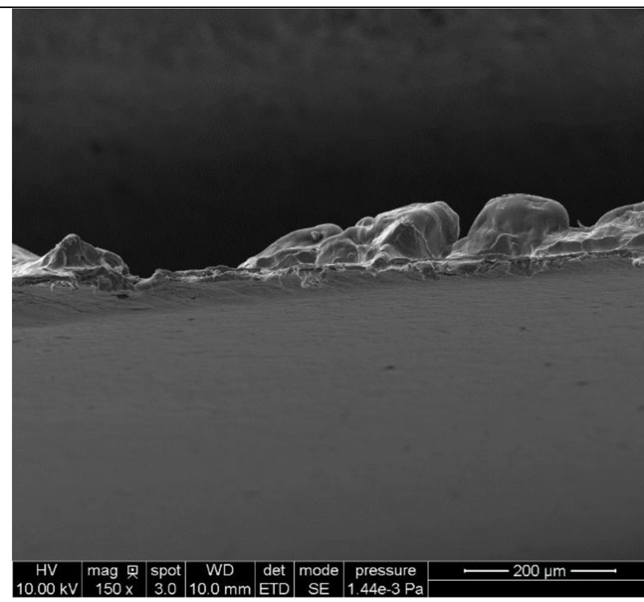


Figure 43 SEM of film after servo actuator cutting 1:1, 150x magnification

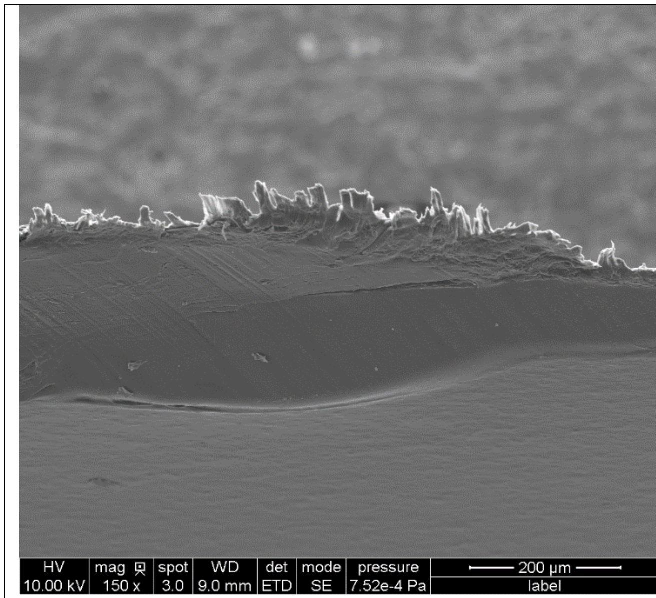


Figure 44 SEM of film after pneumatic actuator cutting 1:1.5, 150x magnification

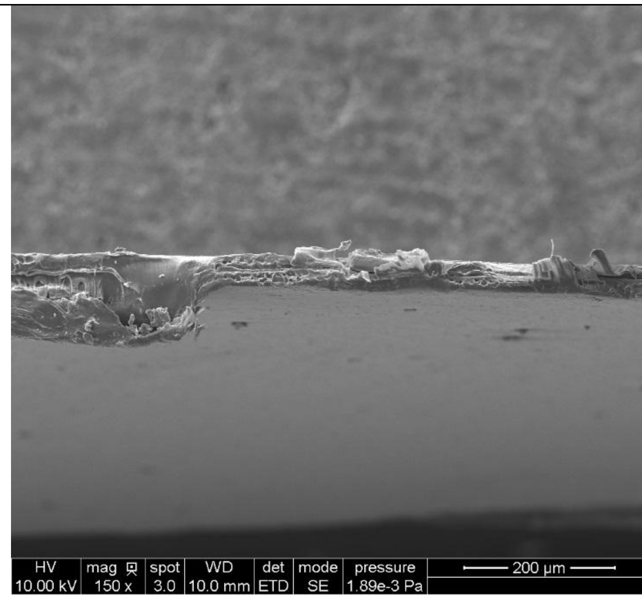


Figure 45 SEM of film after servo actuator cutting 1:1.5, 150x magnification

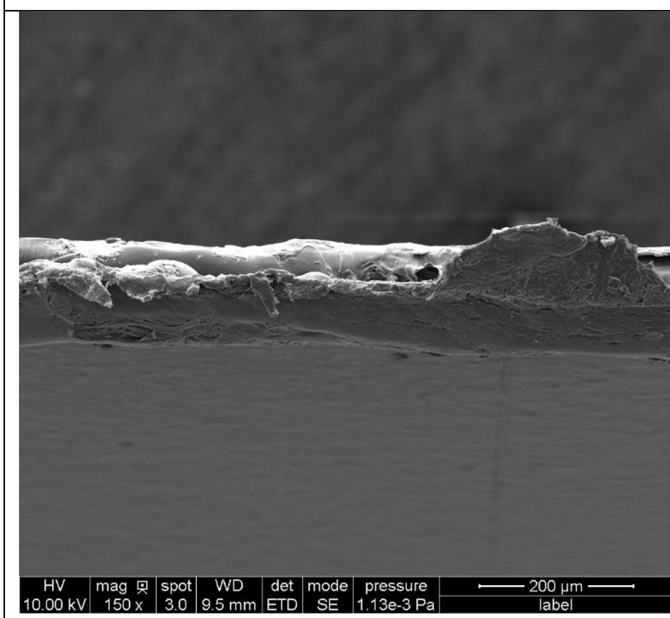


Figure 46 SEM of film after pneumatic actuator cutting 1:2, 150x magnification

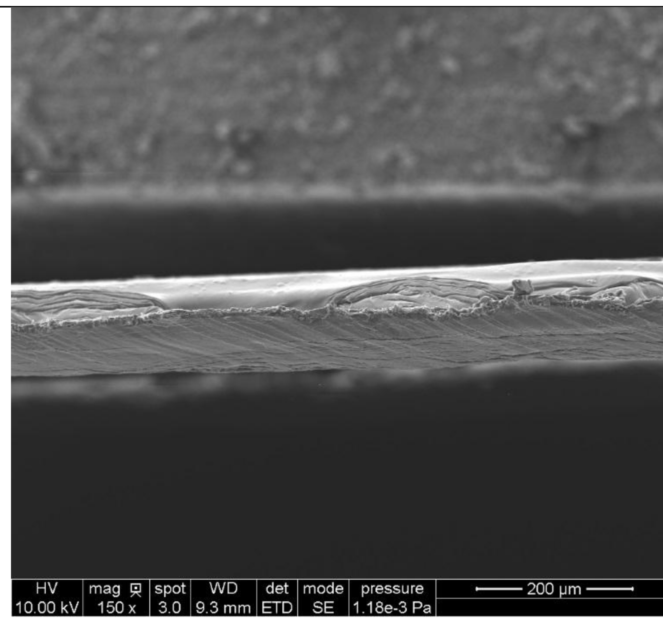


Figure 47 SEM of film after servo actuator cutting 1:2, 150x magnification

CHAPTER 5. GENERAL CONCLUSIONS

In general, tool wear for ultrasonic cutting of plastic films follows a typical wear rate trend of typical aluminum machining tools. In more detail, there are three phases of wear, namely, 1) an initial high rate of tool wear, followed by a 2) slower rate of tool wear (steady state of wear rate) and 3) the final phase of a high rate of tool wear leading to tool failure. The results suggest that there is a difference in the tool wear between servo and pneumatic systems when cutting film. The tool wear was higher with a pneumatic system to cut the PLA film. The servo system produced cut edges that were relatively smooth as seen with SEM photography, showing 'healing' of the edges.

It was also seen that in general, tool wear is inversely proportional to the amplitude (amplitude gain). While this may be counterintuitive, it is believed that higher amplitudes produce higher heating rates, resulting in shorter cutting times (number of ultrasonic oscillations) for the higher amplitudes and thus shorter total ultrasonic cycles (at 20,000/s).

When analyzing the data for the three different wear phases, the initial phase, steady state phase, and end phase, similarities were seen which followed the trend of machining tool wear rate. The rate of tool wear (slopes) for the initial wear region (2,000 cuts) were higher compared to the balance of the cutting cycles. The steady state region (2,000 to 10,000 cuts) exhibited reduced wear rates compared to the other phases. At the end phase of tool lives, the tool wear rate (slopes) typically demonstrated an inflection point and the tool wear rate accelerated. It is important to note that tool wear with the servo-actuated system (10,000 to

12,000 cuts) maintained a constant near zero tool wear (slope). Thus, the servo systems maintain no wear for a longer period compared to pneumatic systems.

Despite these findings, it is difficult to draw a complete comparison of the tool wear equation for both systems because not all runs were taken to failure. In future research, all experiments should be taken to failure, to allow the imperial determination of the tool life constant (C_t) in Equation 1 for both the pneumatic and the servo systems. Overall, the results of this study showed higher tool wear using a pneumatic system compared to a servo system.

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