Senior Design Fall 2007-Spring 2008

GT Technologies™

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Spring Semester Final Report

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1.0 Abstract

This project examines the hydraulic lash adjuster assembled by GenTek Technologies of Tallahassee, Florida. The subject of interest is the valve seat surface and the polishing process performed by GT Technologies to improve the performance of the hydraulic lash adjuster. The purpose was to develop a quality control system capable of developing quantitative data on the quality of the valve and valve seat surface and relating this quantity to oil leakage through the valve.

The desired end state was to possess a system capable of determining the predicted leak rate of the hydraulic lash adjuster and to have determined whether the polishing process needs to be applied after the supply of plungers had changed. In addition, the sponsor of the project, GenTek Technologies, desired to improve the polishing process such that the finished surface has a better quality than the products currently produced.

Research began with a close inspection of the current polishing process and an identification of what variables could be changed with the present setup without requiring the purchase of new machinery. Different grades of polishing stones and different materials were identified as test subjects. The visual inspection and air leak quality control systems currently used were determined to be insufficient to give quantitative data on the valve seat. Therefore, a suitable replacement was identified.

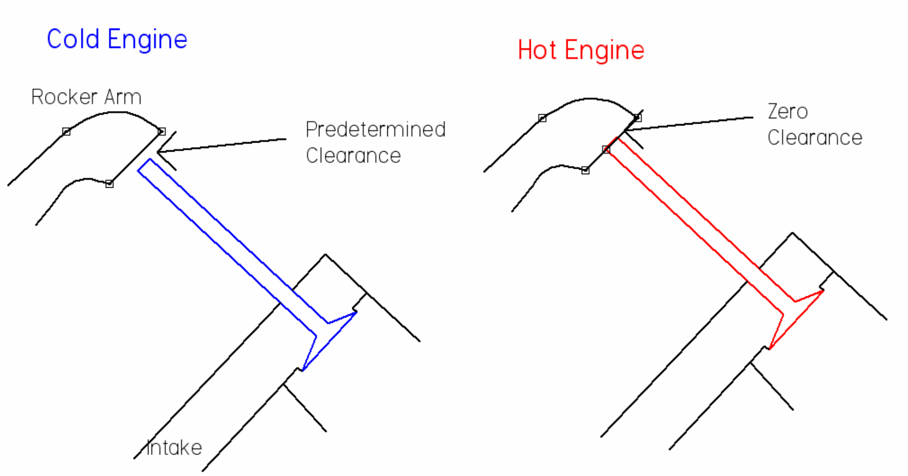
A large number of polishing processes were found which, for different reasons, were not suitable for this application and it was concluded that mechanical polishing could produce a better result than other commonly used methods.

2.0 Introduction

2.1 *What the hydraulic lash adjuster is and how does it work and effect of HLA on automobile performance*

Our design project revolves around improving the plunger seat polish of GT Technologies' hydraulic valve lash adjuster. To understand the importance of a good plunger seat polish, we must first understand what a lash adjuster's function is. Hydraulic valve lash adjusters are used in most present day internal combustion engines. There are few different designs out on the market, but they all serve the same purpose; and that is to keep the rocker arm in contact with the valve stem. Zero clearance is desirable to the everyday driver because it prevents the annoying valve train rattling noise that may occur upon engine startup. Additionally, zero clearance is also crucial to the life of the valves themselves because without it, they will burn rapidly from the high temperature gasses exiting from the combustion chamber, especially the exhaust valve. That will lead to expensive maintenance that could have been avoided by use of lash adjusters.

Lash adjusters have the ability to keep the valve at zero clearance before and after thermal expansion of the valves takes place. In most cases, the valve stem is manufactured to a certain length during engine assembly. This valve is designed to be shorter than necessary when cold. Thermal expansion allows the valves to fit the engine perfectly and run with minimal clearance at normal engine operating temperatures. However, the deliberate shortness of the valve stem means that there is a gap, about 0.010" – 0.025", between the rocker arm and valve stem when the engine is cold.



Hydraulic lash adjusters compensate for valve stem shortness before thermal expansion occurs. Once the engine heats up, the lash adjuster will yield to the force of the expanded valve stem pushing on the rocker arm. The amount of force created by a lash adjuster is only enough to keep the rocker arm in contact with the valve stem; only the cam can overcome the valve spring force and push the valves open. A functioning lash adjuster will not be able to push a valve open. Only under extremely rare circumstances will an adjuster “pump up” and prevent the valve from closing.

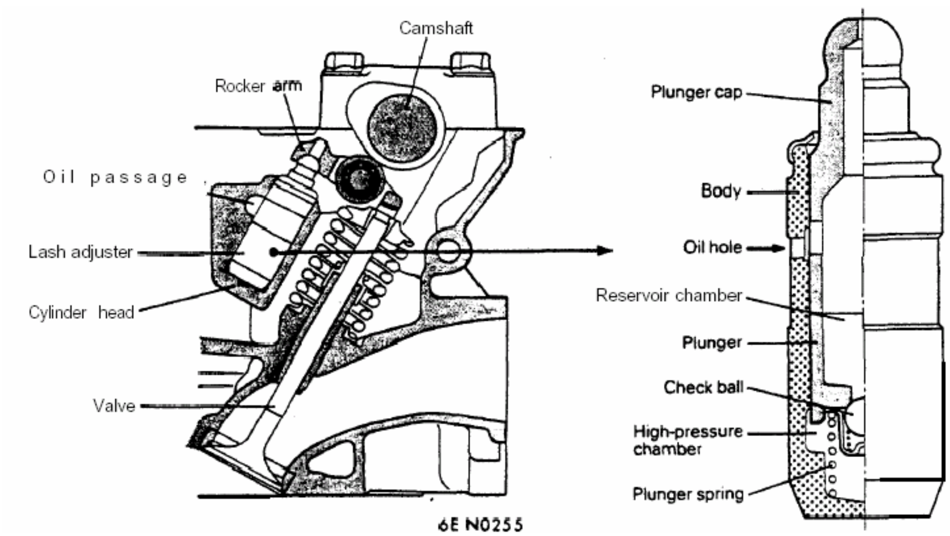
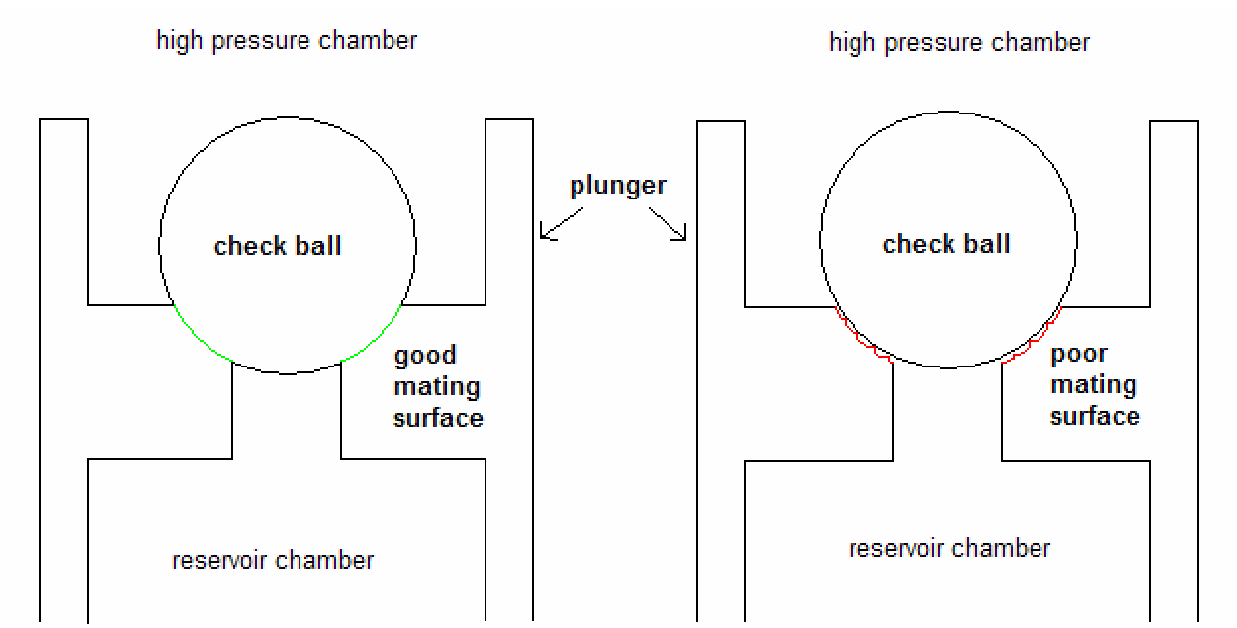


Figure 01

Referring to **Figure 01**, here is a walkthrough on how lash adjusters function. First, pressurized oil is brought to the adjuster via the oil passage. It then enters the lash adjuster through oil holes in the body and the plunger. Once inside the plunger’s reservoir chamber (RC), the oil is forced down past the check ball (which works as a one way valve) and is trapped in the high pressure chamber (HPC). When this trapped oil builds up enough pressure, it pushes up on the entire plunger, which then pushes on the rocker arm, which in turn forces the rocker arm to a zero clearance position with the valve stem. Notice that once a certain amount of oil is in the HPC, no more can enter due to the plunger oil hole and the body oil hole being out of alignment. This leaves virtually no possibility of the lash adjuster expanding so much as to force the valve open. Once the engine is turned off and the car sits parked for a while, the oil in the HPC slowly leaks out through an extremely small clearance between the plunger and the body (roughly 35 millionths of an inch). The lash adjuster is no longer in effect, which is why there may be a noticeable rattling noise at engine startup. However, the noise should end within a couple of minutes, usually a few seconds with good lash adjusters.

2.2 *Effect of the seat polish on valve performance*

The focus of our project is on the plunger seat where the check ball contacts the plunger. This area is quite crucial to the overall quality of the assembled hydraulic lash adjuster. As stated in the previous explanation, the check ball is purposed to work as a one way valve between the RC and the HPC. Ideally, oil inside the RC will be forced into the HPC and trapped there by the check ball. If the geometry of the plunger seat prevents the check ball surface from mating perfectly, there will undoubtedly be some amount of backflow. **Figure 02** illustrates a good and a bad plunger seat mating surface.



(Not drawn to scale)
Figure 02

If the mass flow rate of oil leaking back into the RC is too large, the pressure in the HPC will not build up enough for the lash adjuster to function as it should. The importance of attaining a good mating surface is such a high priority that GT has designed a test specifically for the plunger seat / check ball seal. **Figure 03** demonstrates this test. They place a check ball on top of the plunger seat; then they clamp an air jet on top of the plunger, symbolizing the high pressure chamber. Most of the air flow is blocked, but a small portion makes it through to the reservoir chamber. The testing device is able to get a measure of the flow being blocked. The results are displayed on an LED scale. Good plungers with a low amount of leakage produce a reading in the “green” region on the scale. Failing plungers with too much leakage produce a reading in the “red” region.

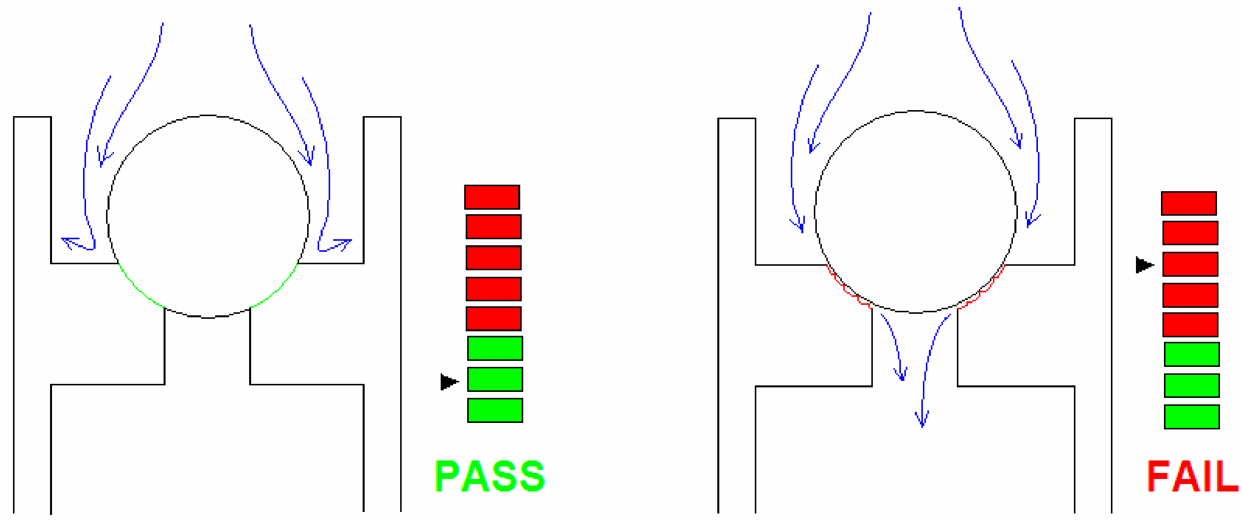
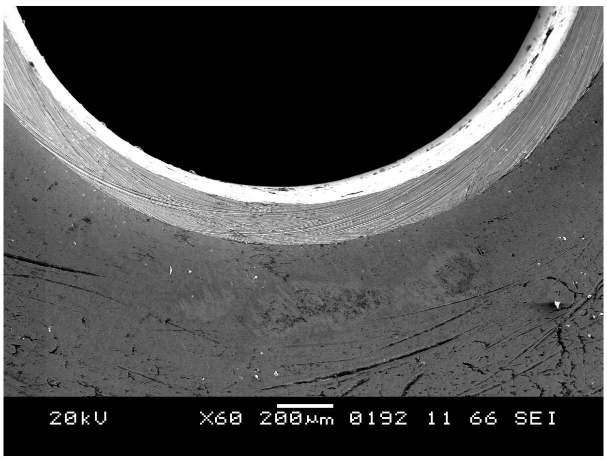


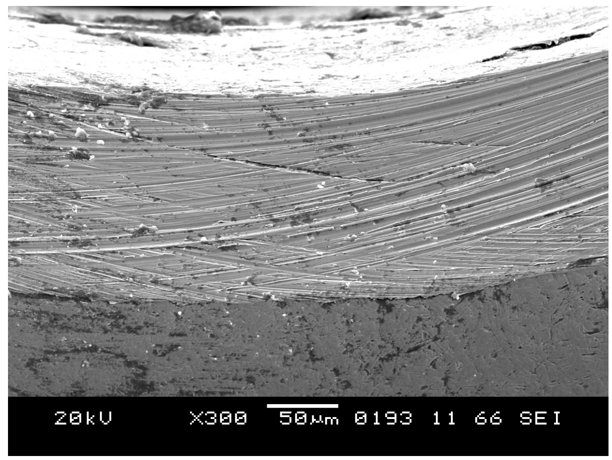
Figure 03

If a failing plunger is found, production stops immediately and the bad plungers are weeded out. It would be a devastating blow to the company if a large quantity of poor quality products hit the market. They would have to do a recall on the parts, they would lose credibility as a reliable manufacturer, and they might even face a lawsuit. Looking at money the company could potentially lose due to producing malfunctioning lash adjusters, it is very much worth discarding a batch of faulty plungers at one dollar a piece.

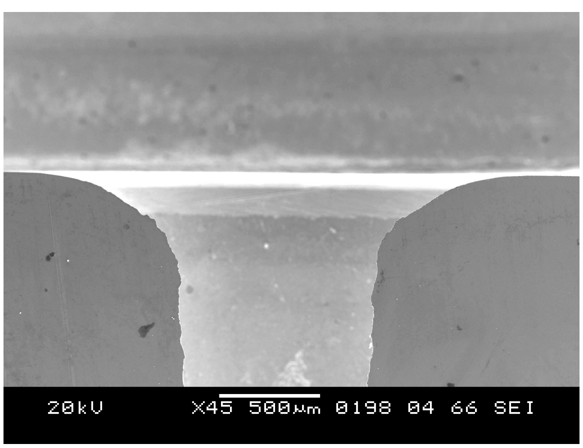
<u>2.3</u> *Polishing Process*

The polishing process used by GT technologies has been standardized over the past 12 years of operation. The plungers used in the hydraulic lash adjuster were tempered at 400 °F to help increase its strength, the side effect being the scales produces at the plunger seat. The process was original introduced to rid the seat of the plunger of scale and other imperfections.





A side effect of polishing the plunger seat is that the radius of the check ball is imposed onto the seat, which provides more surface area for the check ball to sit. Once, the manufacturer heat treated the plungers. This was a necessary step to remove carbide scale that would adversely affect product performance.

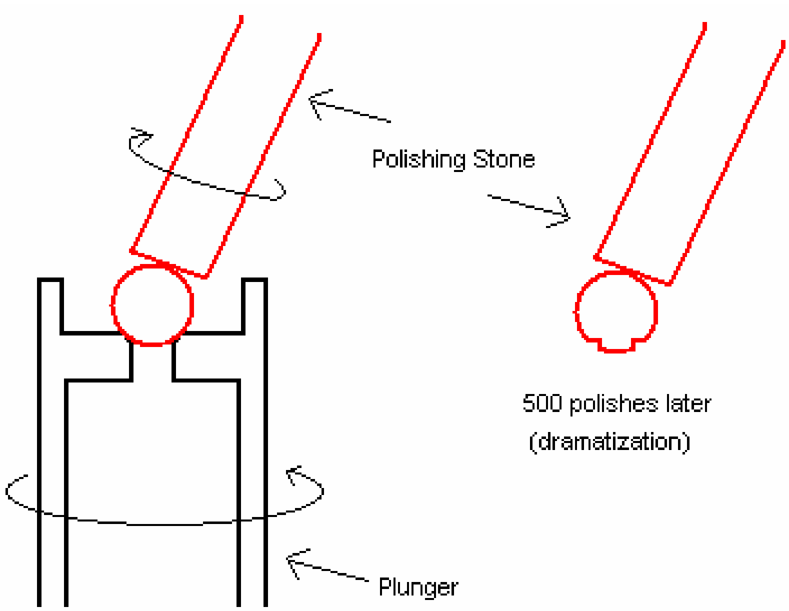


See Appendix E for more microscopy pictures

GT Technologies wishes to utilize the advancement in technology to stay competitive. The manufacturer supplying the plungers has changed the way produces the parts. The plungers have moved changed from being heat treated the plungers to cold formed. The plungers retain their strength without the side effects of scale deposits on the plunger seat. However, GT Technologies has not updated the processing of the plungers. The polishing process continues, but now instead of removing the heat scale the machines are actually grinding grooves into the seat. The grooves actually degrade surface finish. This could allow oil to leak faster than intended causing engine noise that is not destructive but affects customer perception. The goal is to reduce this side effect and determine if the process is even necessary.

The polishing process is autonomous. Three machines perform the polishing:

1. A hopper that stockpiles raw parts, orients in plungers with the valve in the proper direction, and feeds them to the spindle
2. A spindle that holds the plunger during polishing and ejects them when finished
3. A drill arm, offset at a previously optimized angled, adapted to hold a polishing stone and geared to polish for a set time



The polishing process repeats a five step cycle:

1. A plunger is fed to the spindle which rotates the plunger counter clockwise
2. The drill arm translates forward coming into contact with the plunger valve seat
3. The drill continues to translate forward a preset distance, depressing a spring in the drill head and applying a fixed amount of force from the polishing stone to the seat
4. The drill head finishes its cycle and retracts, removing contact of the polishing stone with the valve seat
5. The spindle finishes its timed cycle and ejects the plunger

In order to protect GenTek Technologies proprietary process, the specific details have been deliberately omitted.

Mechanical polishing has many variables that affect the surface finish. Eight of these variables were identified and are listed below:

1. Polishing stone material
2. Drill/polishing arm pressure
3. Drill head rotational speed
4. Plunger holding rotational speed
5. Lubricant
6. Time duration of polishing
7. Angle of drill head offset from plunger
8. Longevity of polishing stone use

This process repeats for another 499 parts. Once the 500 part capacity of the stone has been reached the machine stops and the operator must change the stone and restart the machine. This 500 part cycle takes about 30 minutes.

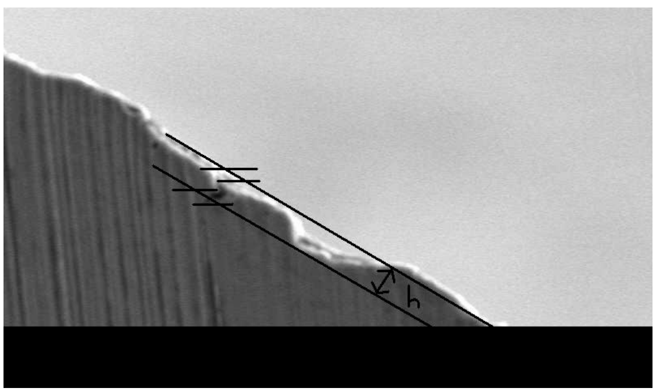
The stone currently used is course grit ¼" x 4" round ruby stone. This single stone is cut into four polishing stones with the 1/8" diameter of the check ball cut into the head. The stone used is manufactured by a company called *Gesswein*. They produce multiple grits of this same material as well as other finishing stones of the same dimensions and different materials.

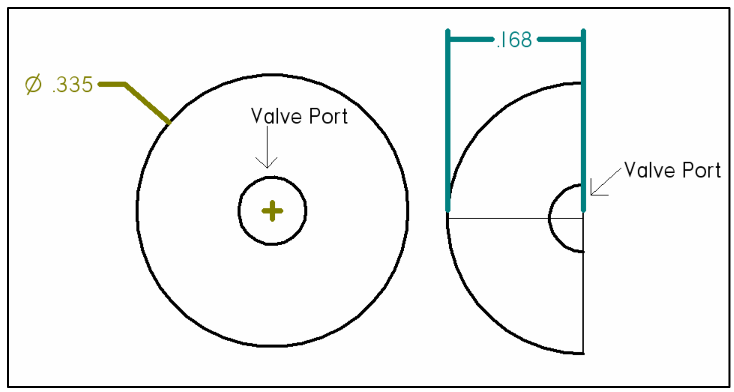
See Appendix F for Screenshots of www.gesswein.com

3.0 Technical Investigation

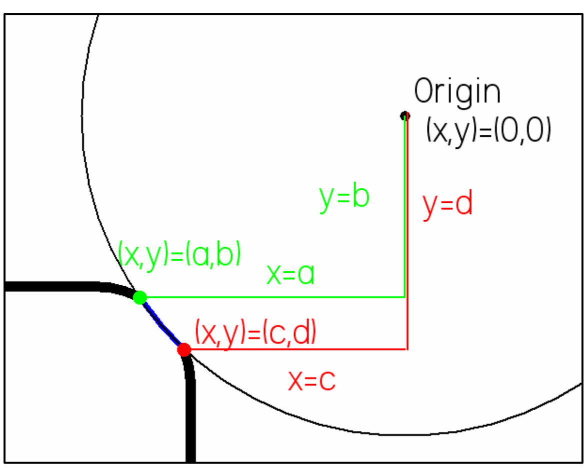
3.1 *Calculation of Valve Contact Surface*

Calculation of the surface finish is reasonably simple. Once a high resolution side view picture is obtained that contains the full check ball, the peaks and valleys of the grooves can be measured normal to the surface. The picture shown below and left is a 400x magnification of a plunger that has been cut along its long axis. For future testing, the accuracy of the surface calculations requires that the plungers be cut exactly in half. This will be done by measuring the sectioned plunger with precision calipers to verify that the piece is exactly half the diameter of a standard plunger.





Measuring the contact surface is also relatively simple. The ends of the contact band can be plotted on a coordinate system with the center of the check ball as the origin. Then a multi-variable calculus formula can be applied that finds the area of a surface of revolution. The contact surface can be viewed as a two dimensional surface revolved around a central axis that passes through the center of the valve hole and the check ball. Once coordinates are established, the "height" of the band is found by simple algebra.



$$y_2 - y_1 = h$$

Surface area = S

See Appendix G for proof

3.2 *Theory of cause of leaks*

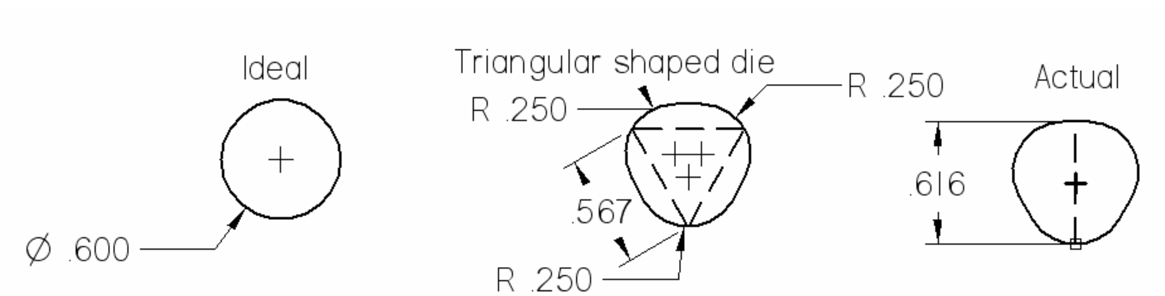
The main characteristics of the hole can be divided into two categories: geometry of the valve hole and surface finish of the seat. Valve geometry is determined solely during the manufacturing of the plunger, which takes place at the suppliers manufacturing plant and is beyond the scope of this experiment. Surface finish is determined by many factors, some of which can be easily changed and some require retooling and new machinery.

The specifications for the valve are as follows:

- Valve port is 0.086” ±0.006” diameter
- Ideal port is countersunk at 86° angle
- Tapered valve contact surface is a minimum of 0.006” wide after polishing
- Check ball used is a 0.125” ±0.00012” diameter grade 24 ball bearing

See Appendix H for Pro Engineer model and live picture of plunger

According to Ken Bunne, an engineer employed by GT Technologies, the manufacturer uses a triangular shaped tool to tap the hole in the plunger. The resulting hole therefore slightly takes on the shape of the tool. Even after rounding out the hole in a milling machine, the valve will retain some triangular characteristics.



These dimensions are not accurate to the design specifications and are exaggerated to demonstrate the concept.

This leads to deviation of the hole from the defined roundness tolerance. Clearly, a sphere will not share as much contact surface with a non circular hole as with a circular hole. Less contact surface results in more leakage. The engineer stated that the roundness of the hole has a larger impact on the amount of backflow fluid leakage than any other factor including surface finish. Consequently, the new quality check method would need to measure the roundness as well as surface finish.

Technicians began to notice horizontal grooves in the valve seats after changing the supply of plungers from heat treated to cold formed parts. Different manufacturing process will give the stainless steel plungers different properties, particularly surface hardness. Though little is known about what cooling method the manufacturer used when forming the plungers, it is accurate to state that the heat treated plungers for which the polishing process was designed have different material properties than the cold formed plungers now in use. The original purpose was to remove carbide scale from the steel. Carbides materials are alloys of metals and nonmetals and carbon. Materials such as aluminum carbide, silicon carbide, and boron carbide are known for their hardness and strength. Boron carbide is among the hardest known materials. Therefore, heat treated plungers likely had a harder surface than the current cold formed plungers. Softer metals should respond better to a softer grit polishing stone and lighter pressure from the polishing arm.

In conclusion, the two primary causes of leaks are roundness of the hole and change in surface hardness of the valve seat. Roundness has a larger effect on leakage but is determined by the manufacturer of the plungers. Surface finish will affect the clearance between the check ball and the valve seat but the polishing process in its current form may be degrading the surface quality rather than helping it.

3.3 *Cost analysis*

The money spent on the polishing process is a significant cost to GT Technologies. The polishing machines are run during the first and second operating shift. Each shift is 8 hours long and the polishing machines run continuously for those 16 hours. GT Technologies operates 24 hours a day 7 days a week 365 days a year. The operating cost for each machine is approximately $9.12/hr. That amounts to operating cost of $53,260.80 per year for one machine. Multiply that by three and the total cost is (not including operator’s cost) $159,782.40 per year. One worker is in charge of operating all three polishing machines used by GT Technologies. Depending on the labor grade of the operator determines the amount of money they are paid for operating the machines. In other words if they make $9.00/hr divided by three machines that means $3.00 more dollars is added to the operating cost of each machine. GT Technologies even includes a 41% fringe benefit plan for its workers, which would increase the hourly pay of the worker to $12.69/hr. The labor grade of the operator is usually a 5 whom gets paid 12.38/hr plus fringe benefits. In total, the operator makes $17.46/hr. Their hourly rate is divided by the 3 machines and is added to its operating cost, which now totals $14.94/hr. This now bring the total cost of running all three machines for the year to $261,724.27 per year. Now this is for a perfect scenario with no needed machine repairs. Since these are manmade machines with multiple moving parts, break downs are inevitable. Clearly, running these machines greatly cuts into GT Technologies profits.

See Appendix H for Tabulated Cost Data

3.4 Viton® fluoroelastomer

The analysis of the seal and the notion that GT wanted to completely eliminate the polishing process led to an idea of changing the material used in the seal. A material considered for the application is Viton, a fluoroelastomer commonly used in engines for O-ring, seals, and gaskets.

Fluoroelastomers are fluorinated polymers or copolymers that incorporate monomers such as vinylidene fluoride, hexafluoropropylene, and chlorotrifluoroethylene with tetrafluoroethylene. The addition of these monomers produces properties that make the material resistant to oxygen, ozone, heat, swelling by oils, and fuels. This works well for engine applications where the working fluid is engine oil. Viton has a service temperature of up to 250 degrees Celsius or 450 degrees Fahrenheit. However, Viton does become glassy at temperatures close to and below room temperature.

This material would work well for this application because it could aid in fixing the roundness parameter. Viton is a polymer that has a lesser hardness than the steel check balls currently used. Because the initial punch used in the forming of the plunger body is triangular, the roundness is not uniform. The steel check balls used have a significantly smaller manufacturing tolerance to the roundness; therefore the surfaces do not match in the pre-polishing phase. With the use of a softer material, the Viton ball might be able to deform under pressure sealing the check valve. The polishing process could potentially be eliminated.

The hardness of the polymer is close to that of a hard skateboard wheel, Shore A durometer of 95. This could be much softer than a solid steel ball. This did produce concerns from engineers at GT Tech that it would not be able withstand the forces from the engine. However, research continued to find if the possibility of using the polymer was financially feasible.

Price quotes for Viton balls of 3/8" size were found at $0.49 per ball from Small Parts Inc and over $0.80 per ball from Rubber Mill. With an estimate of under $0.10 per ball for steel ball bearing balls, and the cost of the machinery and labor to only be $0.01 per part, the use of Viton would increase the cost of this process by over $1,000,000 per year.

3.5 Alternative Polishing Materials

As part of the effort to improve polish quality and decrease machine down time by increasing stone longevity, alternative materials were researched. Two materials, cubic boron nitride (CBN) and synthetic diamond were chosen for their increased hardness over the synthetic ruby currently used. The Engis corporation was contacted after Gesswein sales representatives stated that Engis could custom make polishing mandrills. Engis uses two methods to coat polishing shanks with super abrasive materials; full impregnation and electroplating. Custom made polishing shanks could potentially save time by eliminating the need for a machinist to reshape used ruby stones.

However, due to the custom manufacturing, price quotes for the super abrasive diamond and CBN polishing shanks ran quite high.

See Appendix J for price quote charts

Additionally, an engineer at Engis stated that repeated grinding of the relatively soft stainless steel of the plunger might clog the super abrasive much like the ruby stones. Even use of a lubricating mineral oil might not be enough to mitigate such an effect. The data has been included here to inform GT Technologies of the possibility of the use of super abrasive materials to improve the polishing process.

4.0 Quality Control System Development

4.1 *Leak down rate*

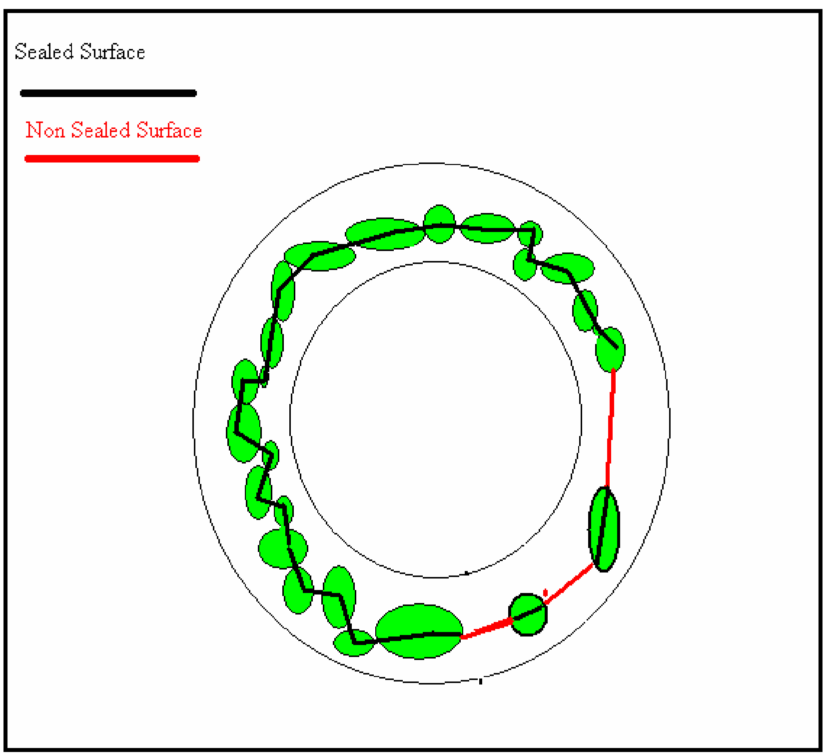
The leak down rate is the automotive industry's method for specifying the required performance of the hydraulic lash adjuster. Under certain pressure, temperature, and oil viscosity conditions the hydraulic lash adjuster needs to evacuate the volume of fluid in the high pressure chamber in a specified amount of time.

See Appendix K for leak down calculation supplied by GT Tech Engineering

4.2 *Setting Manufacturing Tolerances*

One of the challenges of this project was to establish specifications and tolerances for surface roughness, roundness profile, and polishing bandwidth. Such tolerances would allow technicians to accurately predict the amount of leakage through the check ball valve that would occur under operating conditions and therefore determine if the leak down rate of the hydraulic lash adjuster fell within customer specifications.

The below image describes how an acceptable seat surface might be described.



The area enclosed by the two concentric circles represents the polished band on the seat. The green ellipses represent finite areas that match the inverse profile of a 1/8” diameter sphere, such that they will contact the check ball. If a continuous line can be drawn from one imaginary area to the next with no space in between contact patches then this can be considered to be a perfectly sealed surface. If there are areas of discontinuity between contact patches than this is a non sealed surface. The total amount of non sealed surface could be calculated and leakage estimated based height, width, and length.

Lubrication theory fluid dynamics was used to create models representative of the lash adjuster. *Theory and Practice of Lubrication for Engineers* by *Dudley Fuller* provided two such models.

See Appendix L for images from

Theory and Practice of Lubrication for Engineers

These were the capillary seal and step bearing models. Using the theoretical formulas provided in the reference book, MathCAD functions were created that can give the ideal maximum check ball clearance given the physical and geometrical characteristics of the lash adjuster.

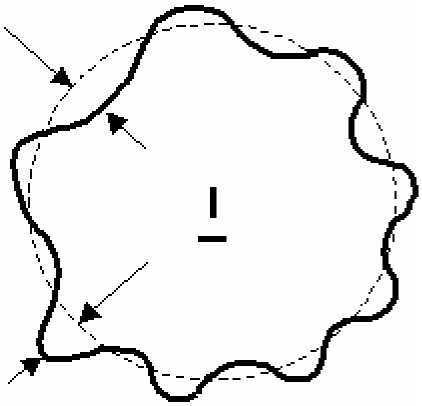
See Appendix M for MathCAD functions

It was found that the fraction of the fluid leakage through the check valve is function only of the geometry of the plunger and plunger body. Since the same oil pressure and viscosity act on both the plunger body capillary, these variables cancel out on either side of the equation. Therefore it can be concluded that in order to reduce the amount of leakage through the check valve one can either reduce the effective clearance between the check ball and valve or increase the clearance between the plunger and plunger body. The latter, however, would decrease the leak down rate; possibly to the extent of exceeding the specification.

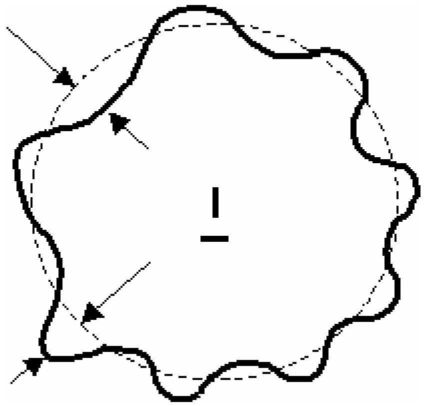
The greatest challenge in setting manufacturing tolerance and that ultimately caused this part of the project to be unsuccessful was how to determine the effective clearance between the check ball and seat given surface roughness and roundness.

These images below, taken from *Taylor Hobson LTD*’s website, show a few of the different techniques for measuring the roundness profile of a circle. However, the surface that the check ball will contact the seat is in fact spherical and not circular.

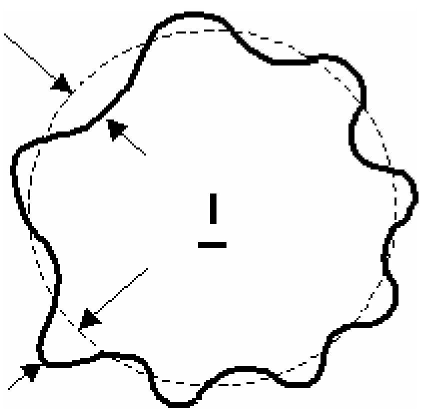
Therefore, a technique for measuring *sphericity* of the seat is needed. This is because any two dimensional surface from which a roundness measurement is taken is not necessarily representative of the entire contact band that the check ball will sit. This is especially true after a plunger seat has undergone any type of polishing process that will reshape the seat.



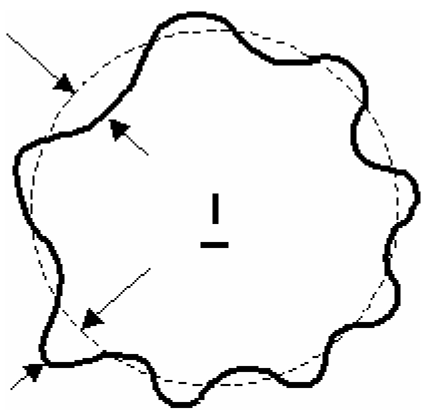
Least Squares Reference Circle



Minimum Zone Circle



Maximum Circumscribed Circle



Maximum Inscribed Circle

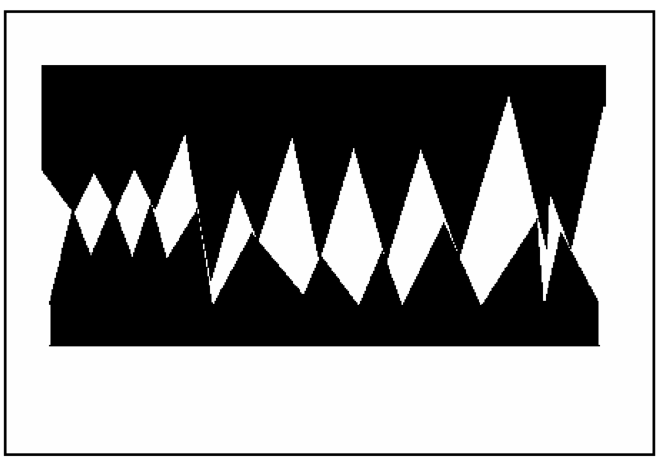
The roughness characteristic of a surface cannot be fully described by any single parameter. A list of types of roughness parameters is listed below.

R_a , R_{aa}	Arithmetic average of absolute values
R_q , R_{RMS}	Root mean square
R_v	Maximum valley depth
R_p	Maximum peak height
R_t	Maximum height of profile

R_{sk}	skewness
R_{ku}	kurtosis
R_{zDIN} , R_{tm}	Average distance between the highest peak and the lowest valley in each sampling length
R_{zJIS}	Average of the five highest peaks and lowest valleys over the entire sampling length

A solid understanding of the different roughness characteristics is required in order to calculate the effective clearance between the surface of the check ball and valve seat.

The most difficult challenge was to comprehend how the combination of out-of-roundness profile and surface roughness combine to create gaps or clearance in between the check ball and valve seat. Being able to envision how the two surfaces contact microscopically proved difficult. In theory, on a powerfully enough magnification any two surfaces will contact along a series of points.



Conceptual image of microscopic surfaces

The following questions need to be answered before tolerances can be set:

1. At what point or surface finish can surfaces be considered to be contacting along a finite surface?
2. How much surface area do two objects need to be in contact to prevent fluid to flow in between them?

A more in-depth study of microscopy and micro-surfaces is required to fully grasp the nature of this problem. Once this is done, specifications for roughness and roundness/sphericity can be set with greater confidence.

4.3 Optical Profiler

A suggestion that will be made to GT Technologies is the implementation of an automated surface profiler. The current quality control system involves an air check gauge that measures the leakage between the check ball and plunger. The accuracy of this method can be a problem mainly because the parameters of the gauge are not standardized. Thus, an automated optical surface profiler was proposed. With a surface profiler, the company can set several tolerances ranging from several measures of roughness to roundness. Every incoming plunger will be measured against a master copy designed within the company.

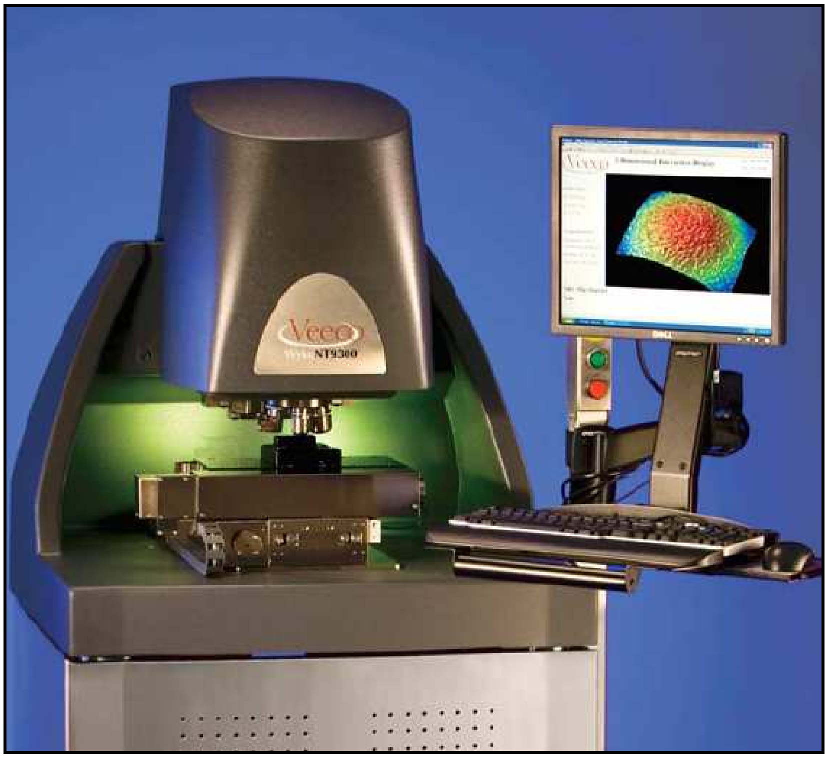
Since the machine is automated, each part will be tested under the same conditions. Instead of testing one piece per every five hundred pieces, a larger batch of samples can be taken so that there would be less of likelihood for a faulty plunger to stop production further down the assembly line. This process also serves as an integral part in quality control research. Unlike the current air check process, engineers can constantly monitor the output data in order to maximize the effectiveness of the polishing process by customizing the process for each order of plungers that comes from suppliers.

A surface profiler can be a very effective tool in qualitative analysis. Their main purpose is to measure surface profile, roughness, and other finish parameter. There are two types of surface profiler technologies: contact and non-contact. Stylus profilometers fall within the contact category. They measure surface texture by dragging a sharp, pointer stylus across the surface. Height differences in the tip are recorded and then used to make an image profile of the surface. From the measured profile, roughness and other parameters can be calculated. Non-contact profilometers scan the surface optically with a light or laser. The optical profiler can thus create a 2-dimensional or 3-dimensional image.

Surface profilometers differ in terms of measurement capabilities and common specific parameters. Choices for measurement capabilities include: roughness, spacing, waviness, and hybrid parameters; automatic defect classification (ADC); flatness, thickness, and step height; lay or pattern; and warp or bow. There are many common specific parameters for surface profilometers. Examples include: roughness average, mean peak-to-valley height, base roughness depth, maximum peak height, average peak profile height, maximum valley depth, total roughness height, profile depth, maximum roughness depth, and ten-point height. Other choices for common specific parameters include: skewness, kurtosis, waviness average, waviness height, peak count, peak spacing average, core roughness depth, bearing ratio, and slope. There are two different slope measurements: Slope Ra and Slope Rq. Slope Ra or Delta a is a measure of the slope of the average profile within the sample length. Slope Rq or Delta Rq is a measure of the root mean square (RMS) slope of the profile within the sample length.

Selecting surface profilometers requires an analysis of performance specifications such as vertical range, vertical resolution, lateral range, lateral resolution, scan or traverse length, scan rate, and part diameter or width. Vertical range is the range of surface textures or peak-to-valley distances or heights that surface profilometers can measure. Vertical resolution is the minimum profile-height resolution that a surface profilometer can attain. Lateral range is the spatial or linear range the instrument can measure across the sample or surface. For surface profilometers that measure surface roughness, this is parallel to the surface of the part. Lateral resolution is the minimum attainable profile peak, valley or spacing resolution. Scan or traverse length is the full distance, optically scanned or over which the stylus is drawn, for a data collection operation. Scan rate is the speed required to optically scan or drag a stylus over the transverse length during the collection of profile data.

A non-contact surface profiler is a lot faster, it can test many samples at one, and it is less susceptible to vibrations in the factory floor. Another advantage is that they are easily programmable and can be automated for a specific task. There are also many disadvantages as well. These include surface vibrations and most importantly the cleanliness of the lens. In the factory floor, there are many impurities that can get into the lenses of the machine and this will disrupt the quality of the profiler readings. A proposed solution is to place the incoming plungers into an ultrasonic bath that will remove any oil molecules or dirt that might be present in the part. Another solution that is already implemented in other processes at GT is the use of a Plexiglas cover that will fit around the machine in order to keep foreign particles out of the objectives and other sensitive components.



Through extensive research, the Wyco NT-9300 (see appendix ___for technical specifications) was determined to be the most suited machine for the job required at GT Technologies. This model is produced by Veeco, one of the world leaders in 3D metrology. Their expertise includes nano-scale imaging, LCD technology, and automated profiler systems. The reasoning behind this choice was simply the advantages that optical profilers have in an assembly line.

Technical Specifications

Measurement Capability	Non-contact, three-dimensional, surface, film thickness, tribology
Objectives	1.5X, 2.5X, 5X, 10X, 20X, 50X for magnifications from 0.75X to 100X; Long working distance objectives available; Optional motorized turret; Optional through transmissive media objective
Field of View Multipliers	0.55X, 0.75X, 1X, 1.5X, 2X; Auto-sensing motorized selector, discreet zoom
Measurement Array	Maximum array 640 x 480, high-speed, non-interlaced; Optional 1392 x 1040 camera
Light Source	Long-lifetime green and white LEDs
Stages	Automated 100 mm Z axis std.; 200 mm XY auto stage std.; Optional 300 mm XY stage; Optional 200 mm R-theta stage
Optical Assembly	Integrated computer-controlled illuminator; Closed-loop precision vertical scanning assembly
Computer System	Latest Dell with 24/7 support line; Dual 17 in. flat panel monitor std.; Optional "small footprint" config. with 17 in. flat panel monitor on Ergotron® adjustable arm
Software	Vision running under Microsoft® Windows XP® Professional; Production mode, built-in data basing with pass/fail for any parameter; Optional Stitching, MATLAB/TCPIP, Film Analysis, Optical Analysis and SureVison
Vertical Measurement Range	0.1 nm to 10 mm std.
Vertical Resolution[1]	<0.1 nm
RMS Repeatability[2]	0.05 nm std. (0.01 nm with PZT option)
Vertical Scan Speed	User-selectable up to 25 μm/sec
Lateral Spatial Sampling	0.1 to 13.2 μm (≤160 nm with high-resolution camera)
Optical Resolution	0.55 μm min. (based on Sparrow Criteria at 600 nm)
Field of View	8.45 mm to 0.05 mm (10.8 mm x 8.1 mm max. with high-resolution camera); Optional stitching
Reflectivity	<1 to 100%
Step Height	0.8% accuracy; <0.1% at 1σ repeatability
Footprint	1245 mm W x 775 mm D x 1549 mm H

[1]As demonstrated by a PSI measurement with nulled fringes on a SiC reference mirror.

[2]As demonstrated by taking the one sigma Rq value of 30 PSI repeatability measurements on a SiC reference mirror.

Note: Specifications are subject to change without notice.

<u>5.0</u> Improvements to Polishing

<u>5.1</u> Experimental Ruby Stone Test Report

Procedure:
Collect Base Line Data

- Measure radius on virgin cut stones (production and experimental) and record
- 500 pc sample runoff with production stone– collecting samples (first and last ten pieces out of 500 and 5 pieces at every 100 piece intervals)
- 500 pc sample runoff with experimental stone- collecting samples (first and last ten parts out of 500 and 5 parts at every 100 part interval)
- Post measurement of stone radii (production and experimental)– record
- Visual inspect stone for build-up – note visual observations and take pictures
- Record bandwidth on 2 samples from each sample set (first 10, 5 from 100, 5 from 200…last 10) for production and experimental stones
- Send 1 sample from each sample set to VEECO Instruments to be measured for the following:
  - Average Bandwidth
  - Roughness characteristics Ra, Rt, Rq
  - Roundness profile

Current Polishing Stone:

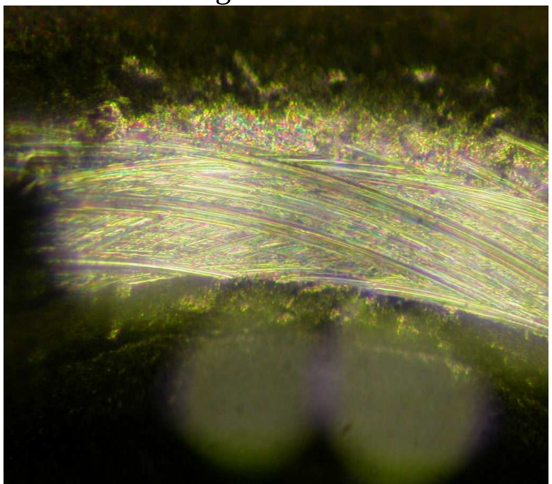


Figure 1

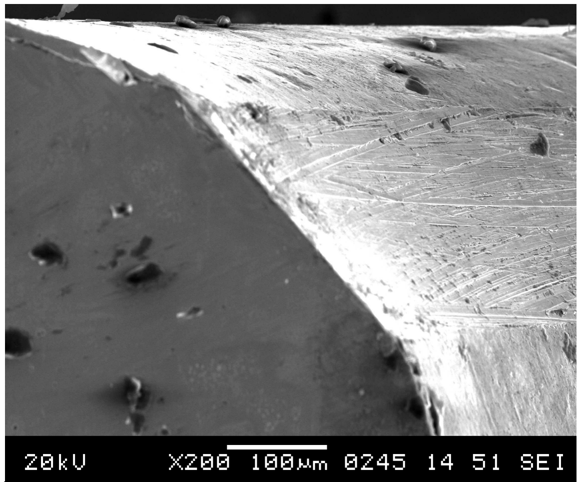


Figure 2

Figure 1, taken in the GT Technology, is an accurate representation of what occurs during the current production polishing operations of the plunger seat with a medium coarse stone. Cross hatch grooves are cut into the seat of the plunger with some heavier gouge marks believed to be from material displacement. These grooves reduce the quality of the check ball seat and may allow increased oil leakage. Oil leakage back through the check valve would decrease leak down performance rates. The sectioned plunger, Figure 2, taken at the National High Magnetic Field Lab, further illustrates the surface elevation changes along the plunger seat.

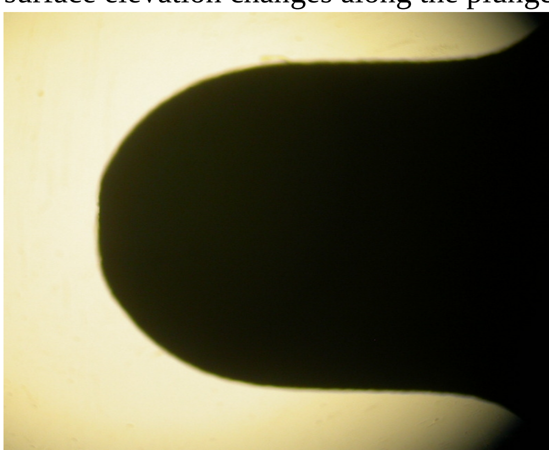


Figure 3

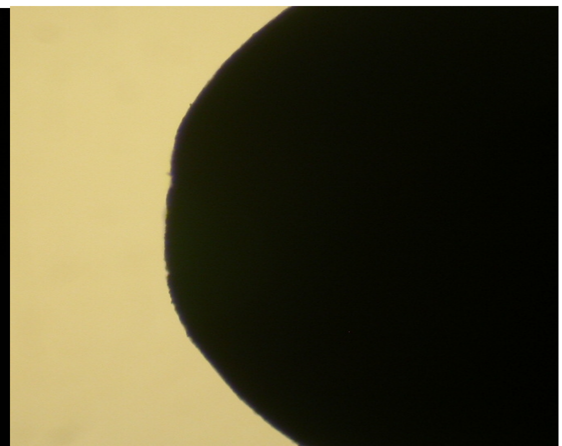


Figure 4

The polishing stone was pre and post measured during this experiment. Before the production stone was placed into the polisher, its diameter measured 0.06355in. We then ran the stone for a full polishing cycle, 500 parts, and then reanalyzed the stone. We found that the diameter increased by 0.002in to a final diameter of 0.0655in. The tip of the polishing stone was also deformed as is indicated by the increase in measured diameter.

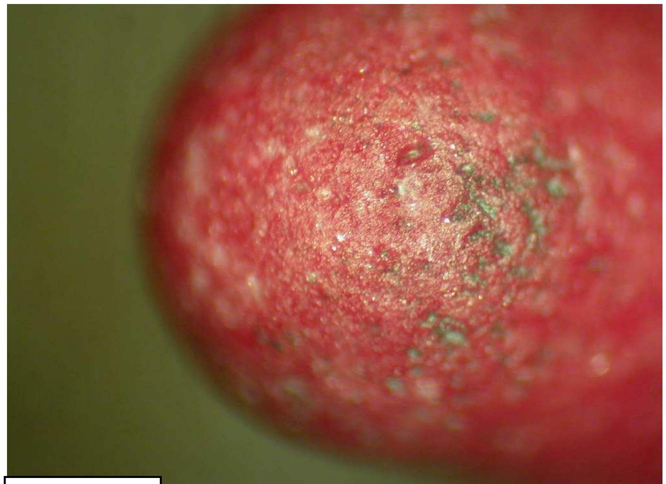


Figure 5

Another post cycle observation is the amount of foreign material from the seat that is imbedded into the tip of the polishing stone. The production stone appears more pitted after a 500 piece runoff than the experimental stone. These pits are results from material being pulled off the plunger seat, which helps, explain varying depths of cross hatch groove patterns in the seat area.

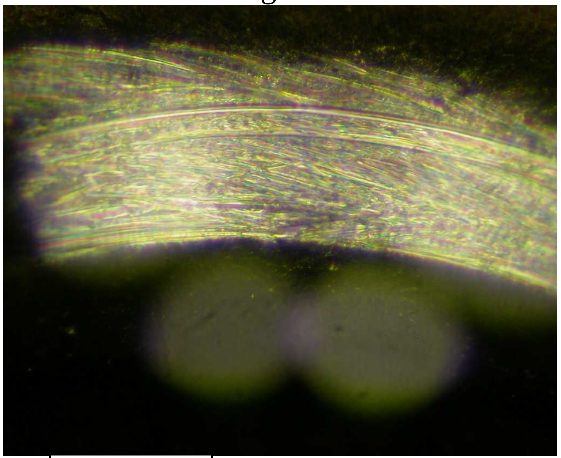
VEECO Data:

Additional samples were sent to VEECO, an optical profiler company, for additional analysis. VEECO measured the average surface roughness, Ra, maximum roughness, Rt, and the root mean square roughness, Rq, of the plunger seat. Below is the data received from VEECO and shows a quantitative representation of the seat roughness. The highlighted data was way out of range and not included in our overall average.

Table 1

Sample #	Stone	Sample Set	Ra (nm)	Rq (nm)	Rt (um)	Avg Ra (nm)	Avg Rq (nm)	Avg Rt(um)
8	Course	1-10	517.78	674.55	8.54	304.87	395.14	4.56
9	Course	100-105	487.22	632.81	7.77			
10	Course	200-205	2820	3450	44.62			
11	Course	300-305	12.06	17.82	0.18052			
12	Course	400-405	243.99	313.42	3.29			
13	Course	490-500	263.29	337.12	3			

Test Polishing Stone:



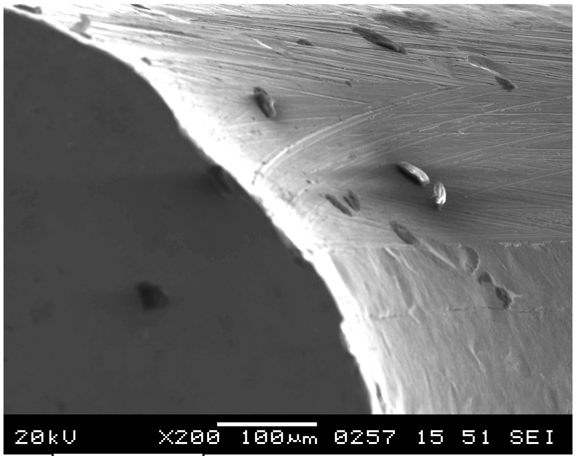
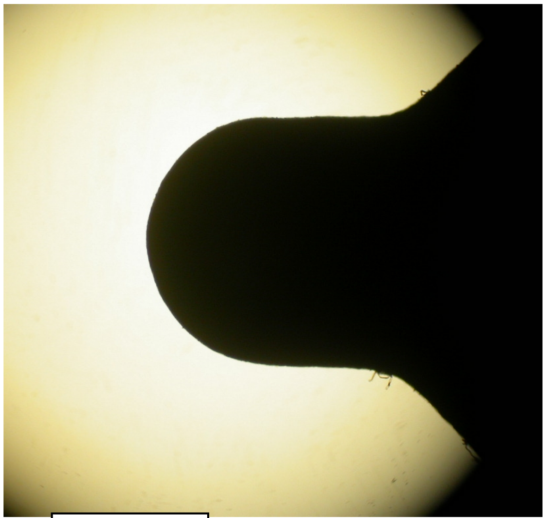


Figure 6

Figure 7

In comparison, Figure 6, under the same test condition, the fine polishing stone appears to make a smoother surface polish than the coarse stone. The seat looks cleaner and smoother with less drastic elevation changes. Once again, Figure 7 confirms that the fine stone provides a cleaner surface polish, though not 100% smooth, but way better than the coarse stone.



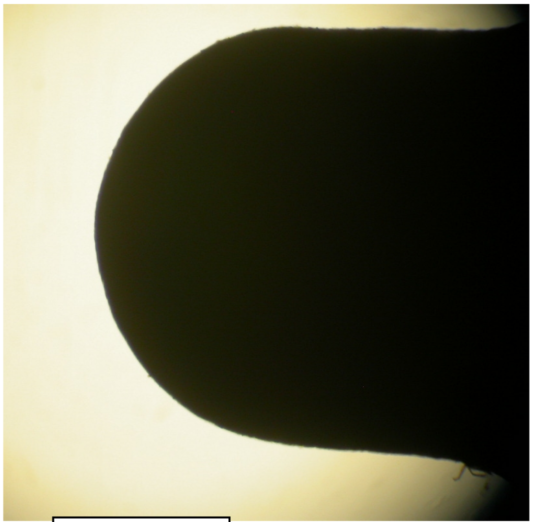


Figure 8

Figure 9

We repeated the same pre and post measurement of the fine grit stone. Before the polishing run, the initial diameter of the stone measured 0.0630in. We examined the stone after its run and can clearly see that the stone held its shape. Also the diameter of the stone decreased to a final diameter of 0.0625in. Since the stone was actually polishing the surface rather than grinding the wear is less evident on the stone. This is a good sign since the longevity of the stone will allow an increase in the number if plungers polished before stone replacement. The increased cycle time will also save in time lost by reducing the down time of replacing the stone.

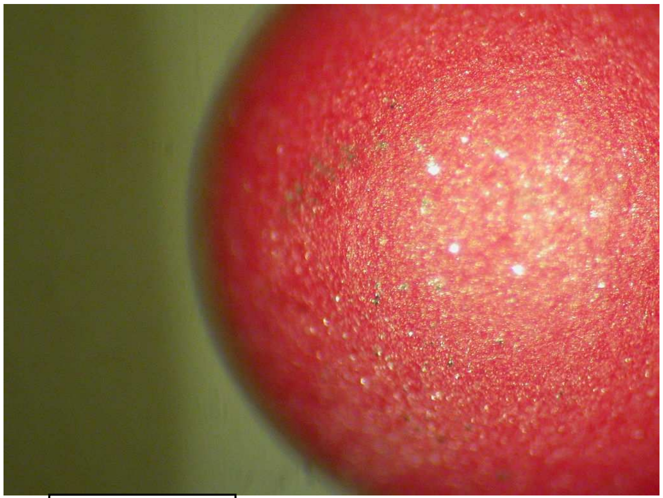


Figure 10

Analyzing the close up view of the fine stone you immediately notice that there is less material present on the surface of the stone. Also the surface is far less pitted than that of the coarse stone. The smoother surface allows the stone to polish rather than gouge into the surface of the seat. Reducing the amount of cross hatch grooves cut into the seat increases the quality of the seal thereby reducing the oil leakage

VEECO Data:

Compared to the coarse stone the seat roughness for the plungers polished with the fine stone is significantly less.

Table 2

Sample #	Stone	Sample Set	Ra (nm)	Rq (nm)	Rt (um)	Avg Ra (nm)	Avg Rq (nm)	Avg Rt(um)
1	Unpolished		549.72	708.31	9.93			
2	Fine	1-10	28.95	44.48	0.56744	149.21	195.26	2.04
3	Fine	100-105	93.83	140.04	1.34			
4	Fine	200-205	7.67	9.86	0.06269			
5	Fine	300-305	248.71	323.49	3.33			
6	Fine	400-405	294.66	374.34	4.2			
7	Fine	490-500	221.45	279.33	2.73			

Bandwidth:

. At different intervals during the polishing samples were collected to document the polish quality over time. The band width was compared for each of the polishing stones. The quality of the polish and bandwidth remained consistent between each of the two stones with an average difference of about 0.0015”. However, it was apparent from the photographs that bandwidth varies across the surface of any given plunger. Therefore, an average bandwidth across an entire seat needs to be taken in order to assure objective comparisons.

Table 3

Stone type	Sample #	Band With (1)	Band Width (2)	Band Width (3)	AVG
Course	1 to 10	0.01255"	0.01325"	0.01390"	0.011386
	100	0.01425"	0.0136		
	200	0.0094"	0.01325"		
	300	0.00845"	0.01155"		
	400	0.01205"	0.01145"		
	490 to 500	0.00775"	0.0082"	0.00975"	

Table 4

Stone type	Sample #	Band With (1)	Band Width (2)	Band Width (3)	AVG
Fine	1 to 10	0.01030"	0.00790"	0.00805"	0.009589
	100	0.01025"	0.0086"		
	200	0.0137"	0.0111"		
	300	0.00935"	0.00845"		
	400	0.0141"	0.0086"		
	490 to 500	0.00825"	.0079"	.00775"	

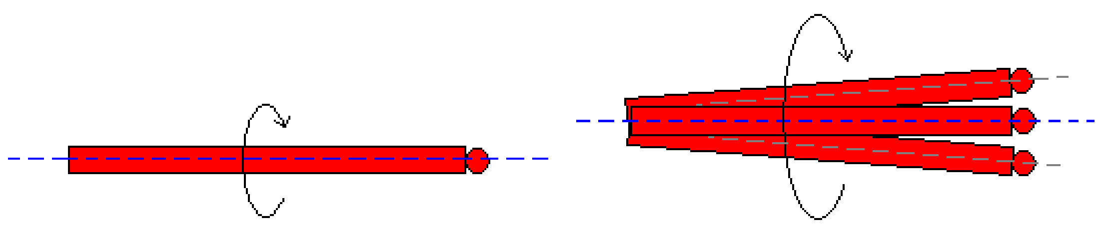
Conclusion:

Based on the data from the VEECO optical profiler, the experimental fine grit ruby stone appears to give a better seat finish. The photographs of the used ruby stones suggest that the fine grit stone may have a longer lifespan. However, because the number of samples measured was so small and because oil residue on the VEECO samples may have affected the analysis further testing should be performed in order to confirm the results.

The one remaining variable that was unable to be removed from the testing was the affect of the ruby stone holder on the polish. The rubber grommet on the experimental stone holder was a much tighter fit than the production stone.

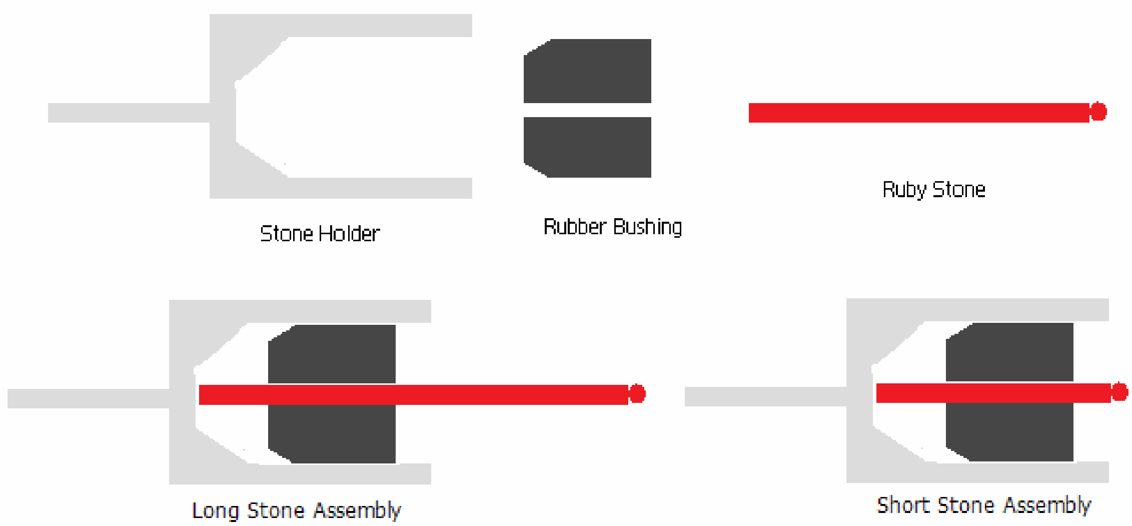
5.2 Improved Ruby Stone Holder Designs

Another issue brought to us late in the semester by GT Technologies was polishing stone wobbling. This problem is definitely affecting the plunger seat polish in a negative way. What happens is the ruby stone deviates from its intended spinning axis, and the polish is not being fully applied to the correct area; where the check ball sits. The following diagram illustrates this.



Ruby stone spinning on its correct axis. Ruby stone deviating from its correct axis.

The wobbling problem stems from lack of support necessary support in the ruby stone holder. If the stone's deviation is drastic enough, it can ultimately damage the plunger's oil-tight seal; rendering the plunger un-usable. And of course, the more parts that fail quality control testing, the more money GT is wasting.



Current stone holder design and assembly.

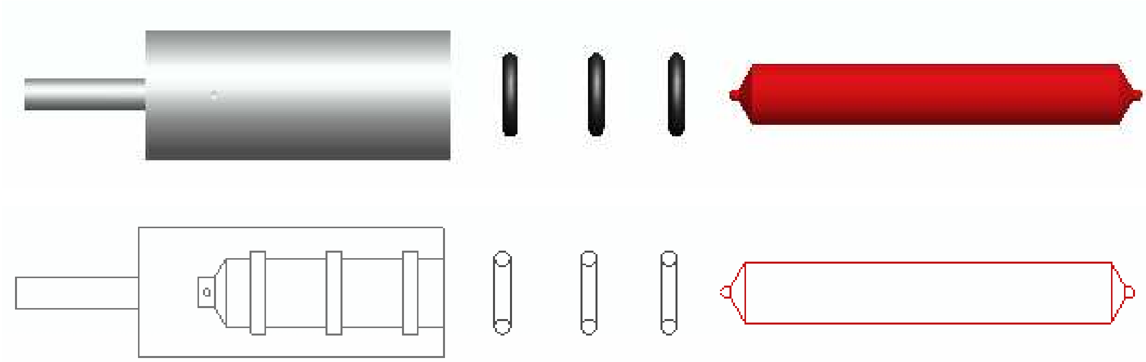
Further examination of the problem revealed that wobbling occurs mostly with the “long” variety of polishing stones (ranging from 1.150 – 1.975 inches in length). No surprise here. As you can see from the diagram above, the current stone holder design does not provide the best support for the full length of these stones. For the shorter ruby stones (ranging from 0.850 – 1.149 inches in length), an entirely different problem arises. Since the stone contacts the plunger seat at about a 15 degree angle, there is a chance that the stone holder itself may collide with the spindle that rotates plunger. With both parts rotating at high speeds, the friction would definitely cause substantial damage to both the spindle and the stone holder. It has become apparent that one standard stone holder is inadequate for all of the different lengths of stones being used. So we have come up with a couple of new stone holder designs to help remedy the situation.

Our first idea was to create a holder which was universally adjustable. The design is similar to the original holder, but with a threaded metal sleeve attachment on the end. This sleeve could be screwed up or down along the stone to apply better distributed support along the entire length; which is desperately needed, but missing in the original model. This extra support would surly eliminate the wobbling issue.

Threaded sleeve stone holder design.

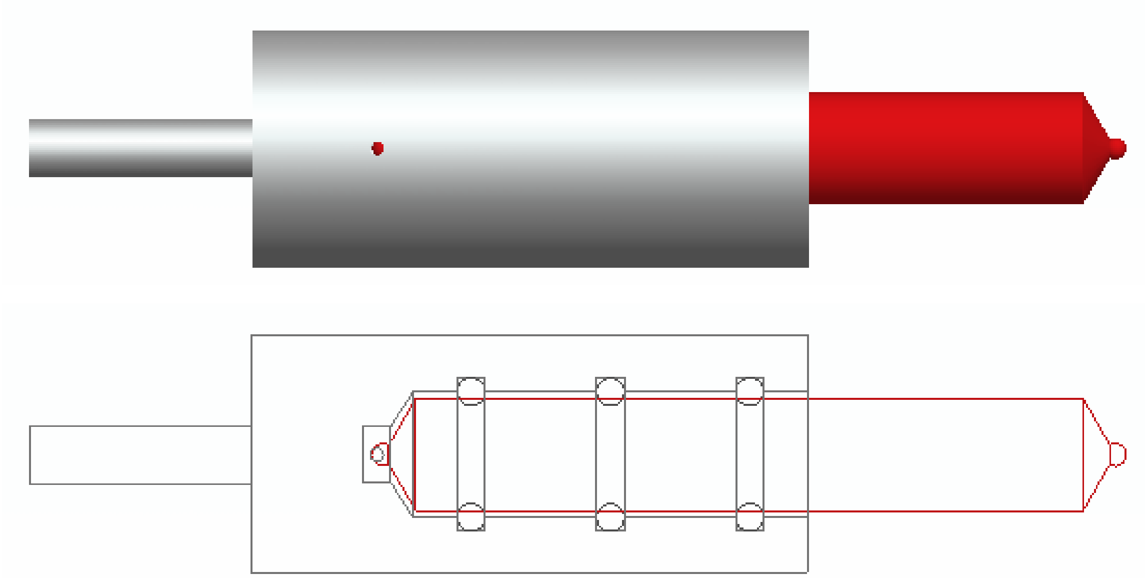
The major con to this design is the amount of time it would take the operators to remove, replace, and re-adjust the polishing stones in the holders. In industry, time is money. There would simply be too much idle time between every polish cycle.

What GT wanted was more of a “slip fit” design to the holder. Slide the used stone out, slide the new stone in, done. Dan Faulkner, one of our company contacts, pitched us a design idea which he felt was most suitable, and we further developed it on our own.



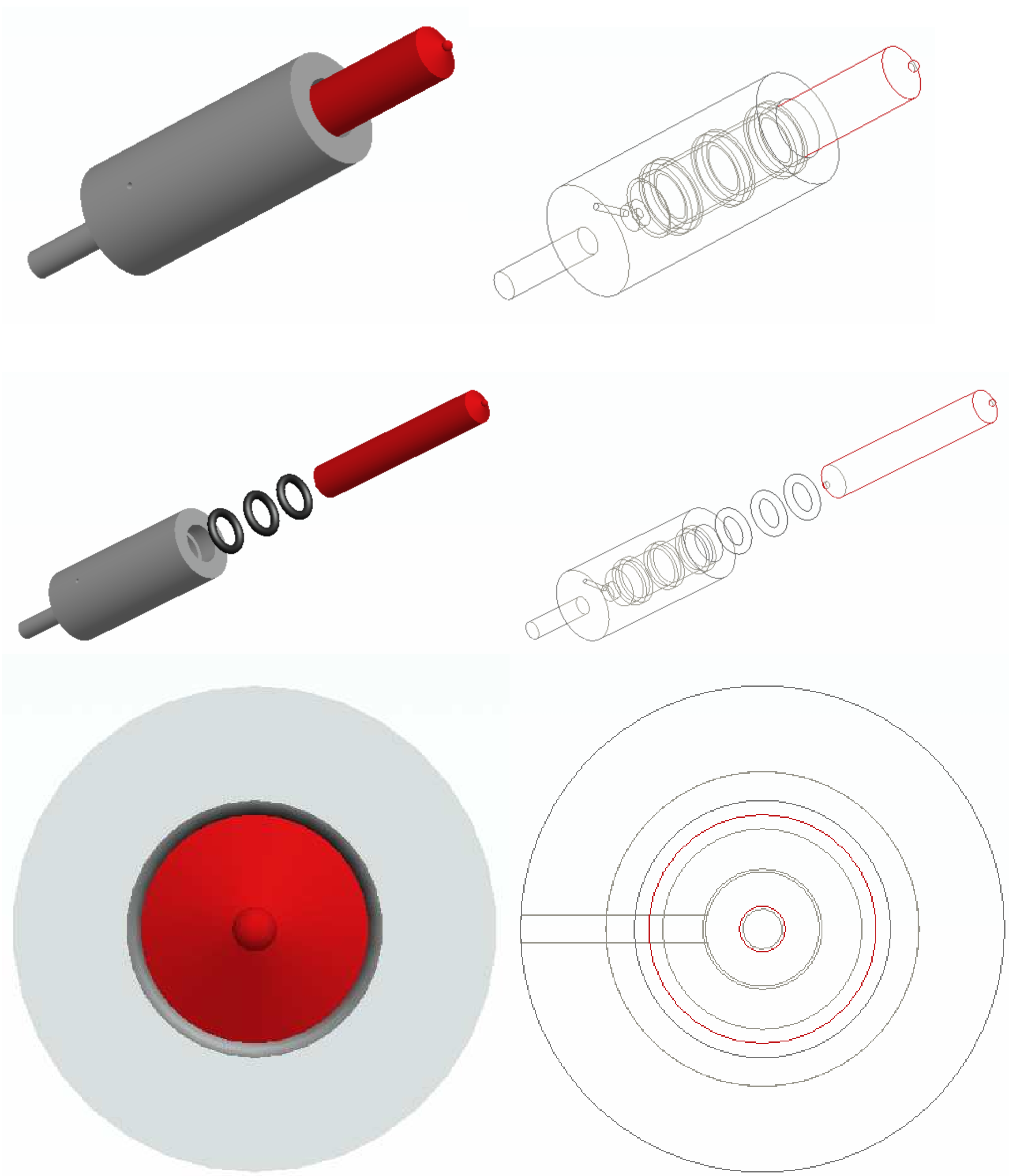
Slip-fit stone holder, exploded.

Above is a Pro-Engineer model of the finished product. This holder was designed to accommodate a ruby stone of diameter 0.25” and a length of 1.50” (falling under the “long” category). With the use of standard easy-to-find o-rings, this holder should provide a snug grip around the ruby stone, as shown in the assembled view below.



Slip-fit stone holder, assembled.

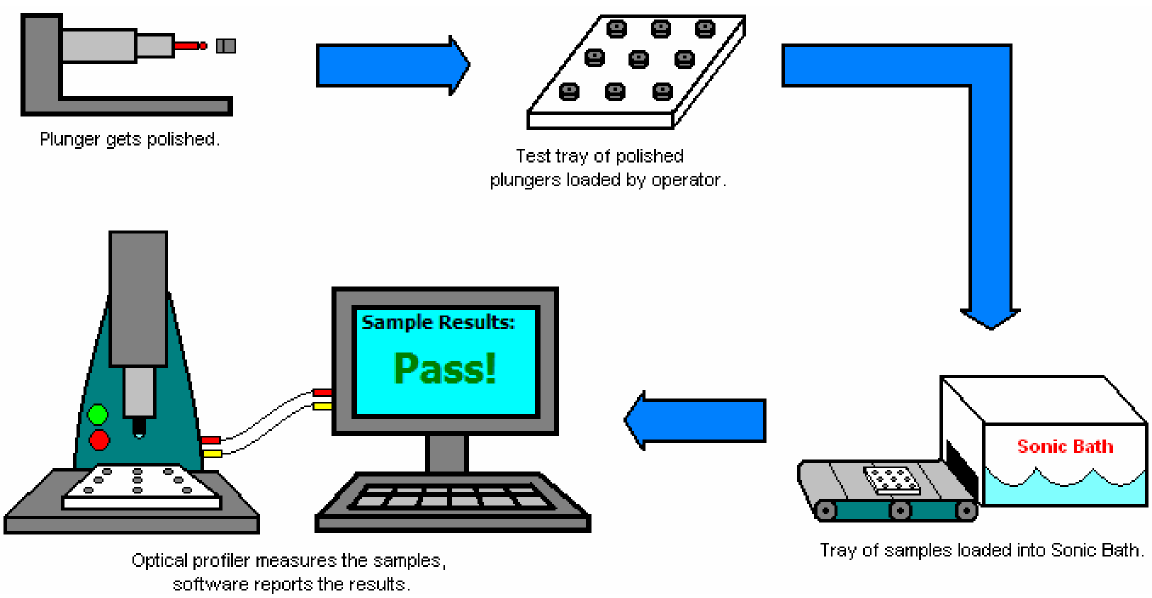
With three points of contact along the stone, versus the original holder’s one point, this holder will eliminate any chance of stone wobbling. And replacing the stone becomes a breeze. An air relief hole located at the bottom of the cavity allows for easy insertion and extraction of the ruby stone without air pressure or suction working against it. This specific design will be suitable for all stones classified as “long”, and another, very similar model can be created for the “short” stones. Possibly with one less o-ring support, or just with the o-rings moved closer together. If GT decides that they want to have this holder manufactured and implemented, we will cross that bridge at that time. Below are alternate views of this holder.



6.0 Conclusion

6.1 Proposed Plunger Polishing and Quality Control System

The following diagram illustrates our final proposed polishing and testing procedure. This four step process will not only allow GT to test more polished plungers, but it will also produce quantitative data on the polished surfaces. And that has always been a top goal for us to achieve since day one of this project.



The first step of the process is polishing the plungers. Not much will be changed here except for the stone holder. From there, the operator loads a tray of polished plungers. We'd recommend this test batch not exceed 20 plungers; just to prevent tray loading from becoming a time consuming chore. Even with this 20 plunger limit, this is a large step up from the 3 or 5 plungers out of every 500 that are currently being tested. The increased batch size will give GT a better idea of the quality of all of their polished plungers.

Once the tray is loaded, the operator runs the samples through an ultrasonic bath. The purpose of this is to remove any dirt, debris, and/or lubricant from the plunger seats before they are scanned by the optical profiler. The profiler is a very sensitive piece of machinery; small obstructions can have quite a large affect on the measurements it acquires. After the ultrasonic bath, the tray of samples is placed on the deck of the profiler and a start button is pushed to commence the scanning operation. The profiler's deck will be programmed to move and position each plunger under the lens, one by one until each plunger is measured. After all parts are scanned, computer software will determine if a plunger seat passes or fails. All quantitative data will be saved and archived for any future analysis GT may want to do.

6.2 Recommendations

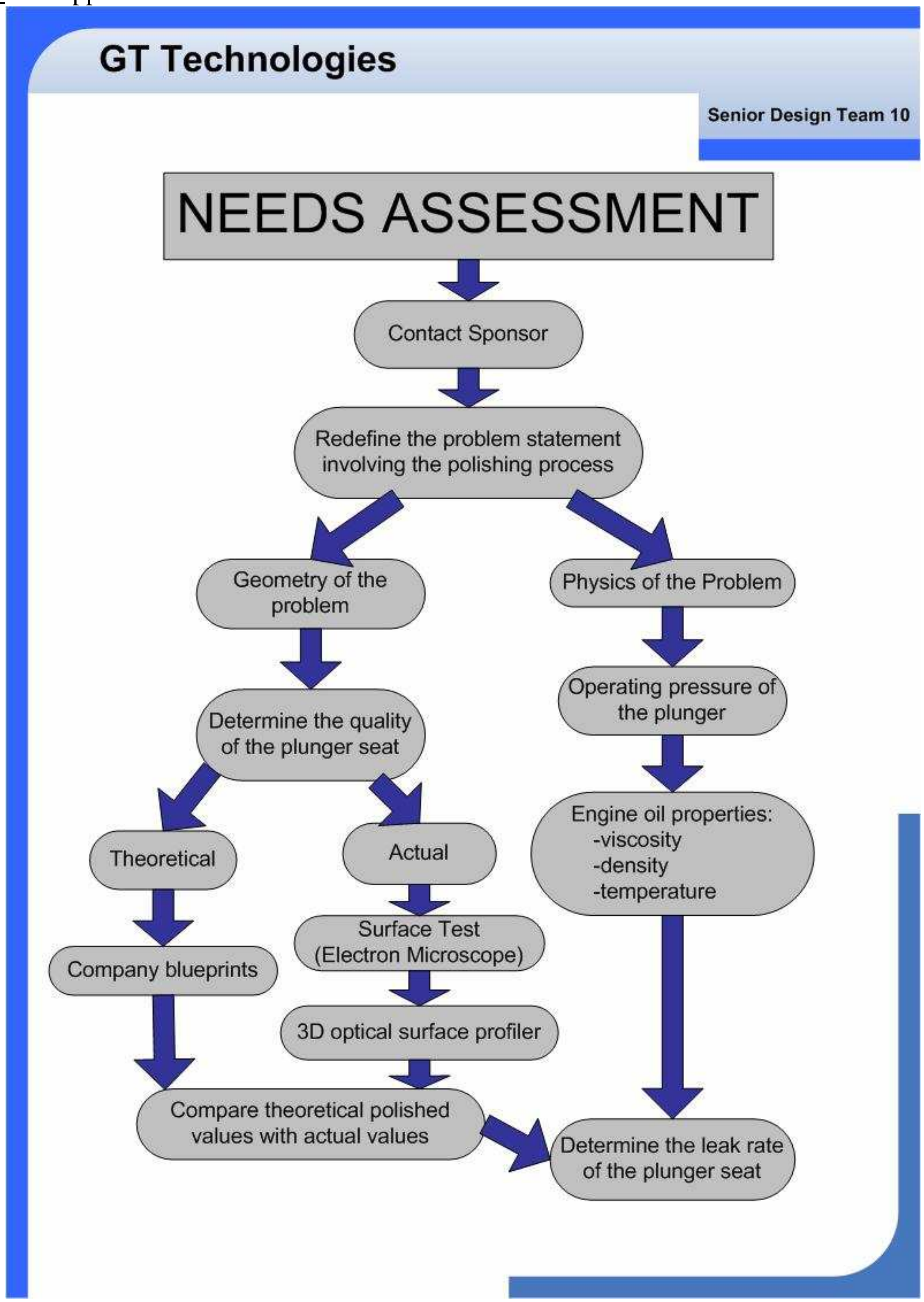
This project has found one improvement that shows promise to improve the surface finish of the seat and that is the fine grit ruby stone. The increased cost of $5 per stone, which polishes roughly 30,000 to 35,000 parts, does not significantly increase the cost of production. Yet preliminary results show a slight improvement in surface finish. Experiments in super abrasive synthetic diamond and cubic boron nitride might also be tested using the same procedure. These materials could reduce machine down time by demonstrating longer service life due to the increased material hardness. This group recommends continued testing with the fine grit ruby stone with detailed analysis to determine surface quality and shape characteristics. This will determine if the seat polish is consistently improved over a full cycle of parts.

A possible quality control system has been conceived with all the necessary hardware listed and a procedure described. The proposed system would give quantitative data on the surface finish and shape profile of each sample plunger tested. Larger sample batches could be tested with an automatic record of all tests being kept. Optical profiling technology has the potential to provide a highly detailed quality control analysis and should be pursued further. Though the instruments may be affected by floor vibration, systems such as air bearing tables already exist to overcome this obstacle.

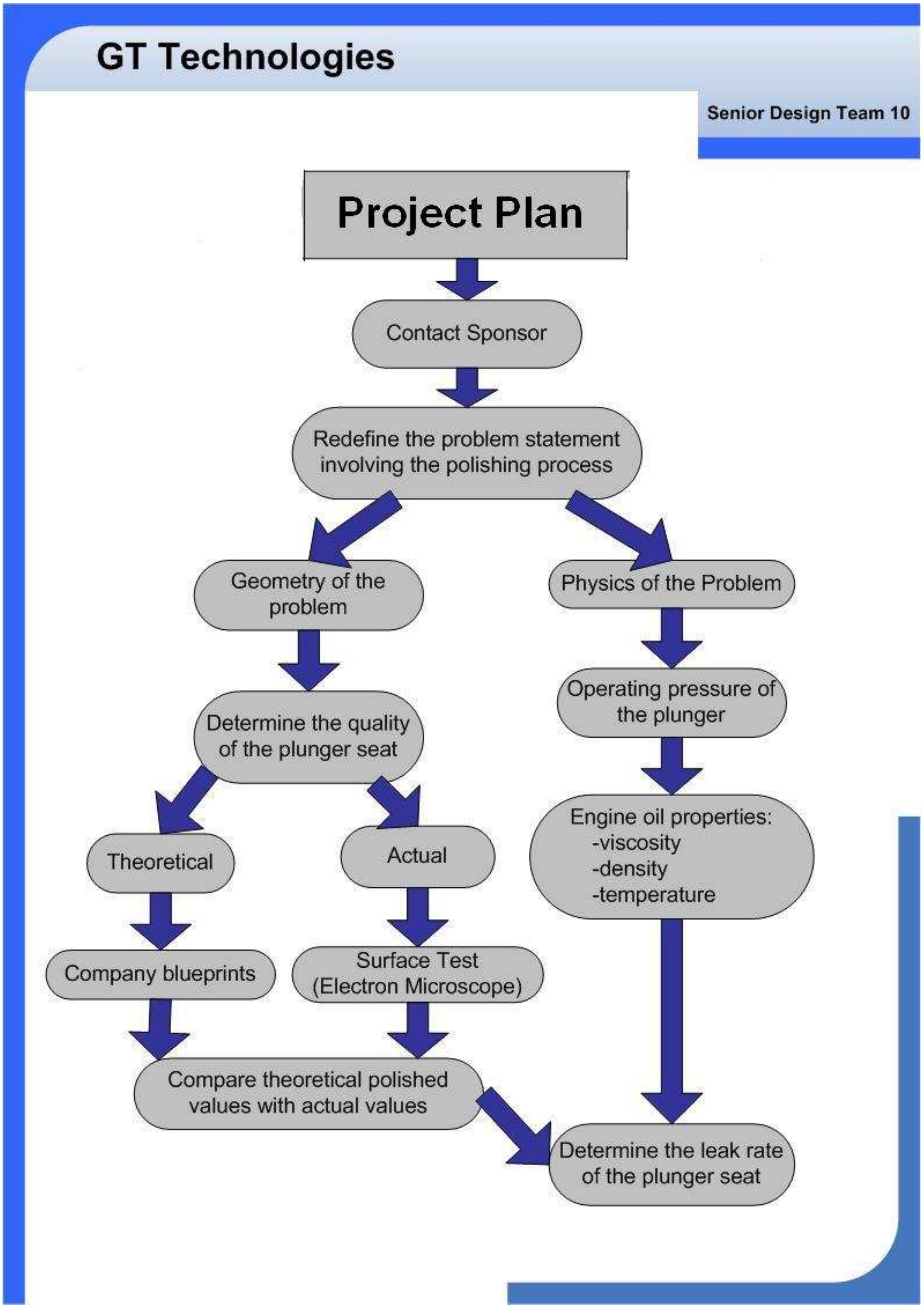
The group was not successful at establishing manufacturing specifications and tolerances for roughness and roundness, but this would require an intensive study into microscopy techniques, micro-surface characterization, and lubrication theory fluid dynamics. While it is possible to these tolerances, it would require more time and fully dedicated human resources.

7.0 Appendices

7.1 Appendix A – Needs Assessment



7.2 Appendix B – Project Scope



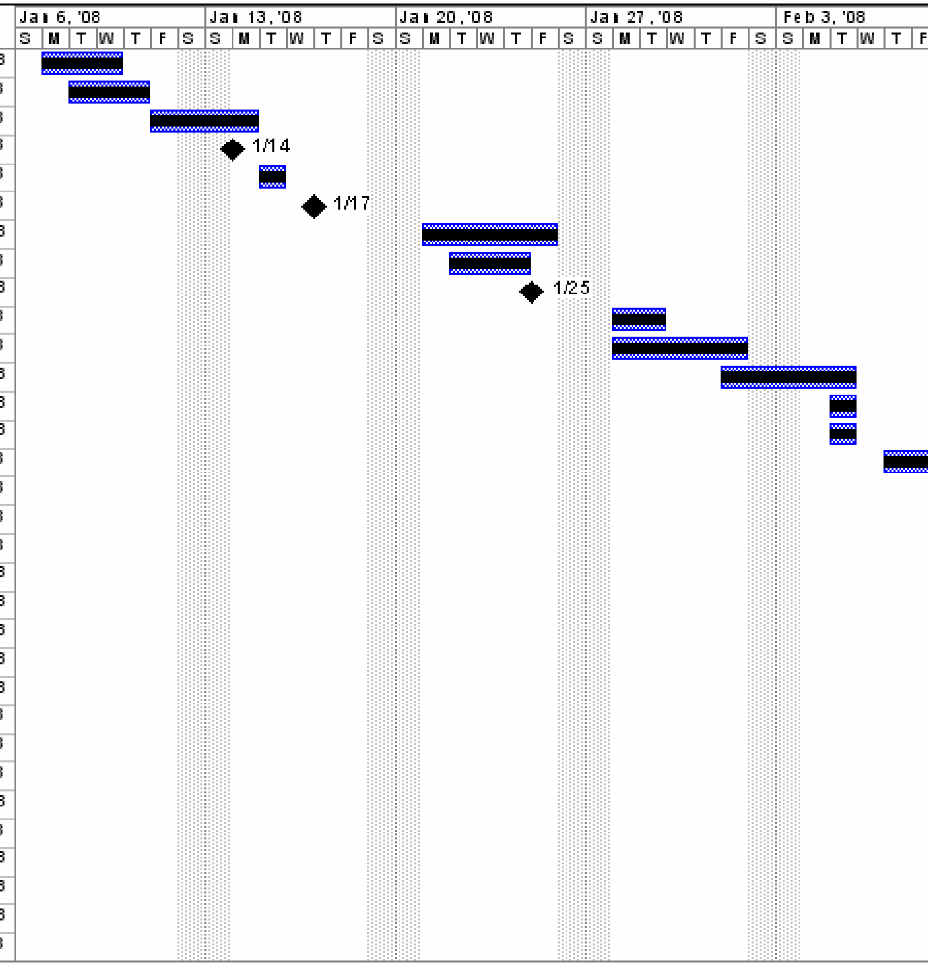
7.3 Appendix C – Product Specifications

GT Technologies has asked us to design a test apparatus that could effectively test the clearances/seal quality between a ball and plunger set that is being used in a hydraulic lash adjustor assembly. The product itself has to follow a set of guidelines:

1. Test clearances between the ball and plunger close to 35 millionths of an inch
2. Determine the eccentricity of a circle, representative of the spherical shaped ball seat, to within 1 ten-thousandth of an inch
3. The tester should be able to perform two tests in less than five minutes in order to keep up with the production line.
4. It cannot contain any known carcinogens or materials that are harmful to human health
5. Provide operation conditions/scenarios that are similar to those in a working internal combustion engine.
6. The design should be able to accurately tell the amount of test fluid that is leaking in between the test object and plunger. An experiment will then be set to find out whether the grinding of the plunger seat is even necessary to the production of the hydraulic lash adjuster.
7. Display quantitative data on the quality of the seal between the seat and plunger.
8. Set an effective "pass" or "fail" system for the leak tolerances of each plunger.
9. The machine has to able to fit on top of a standard 18'' X 4' work bench
10. Has to meet the ISO/TS 169 49:200 Quality Assurance Systems standards.
11. The systems must be user-friendly, which means that its operation can be taught to an employee within minutes.

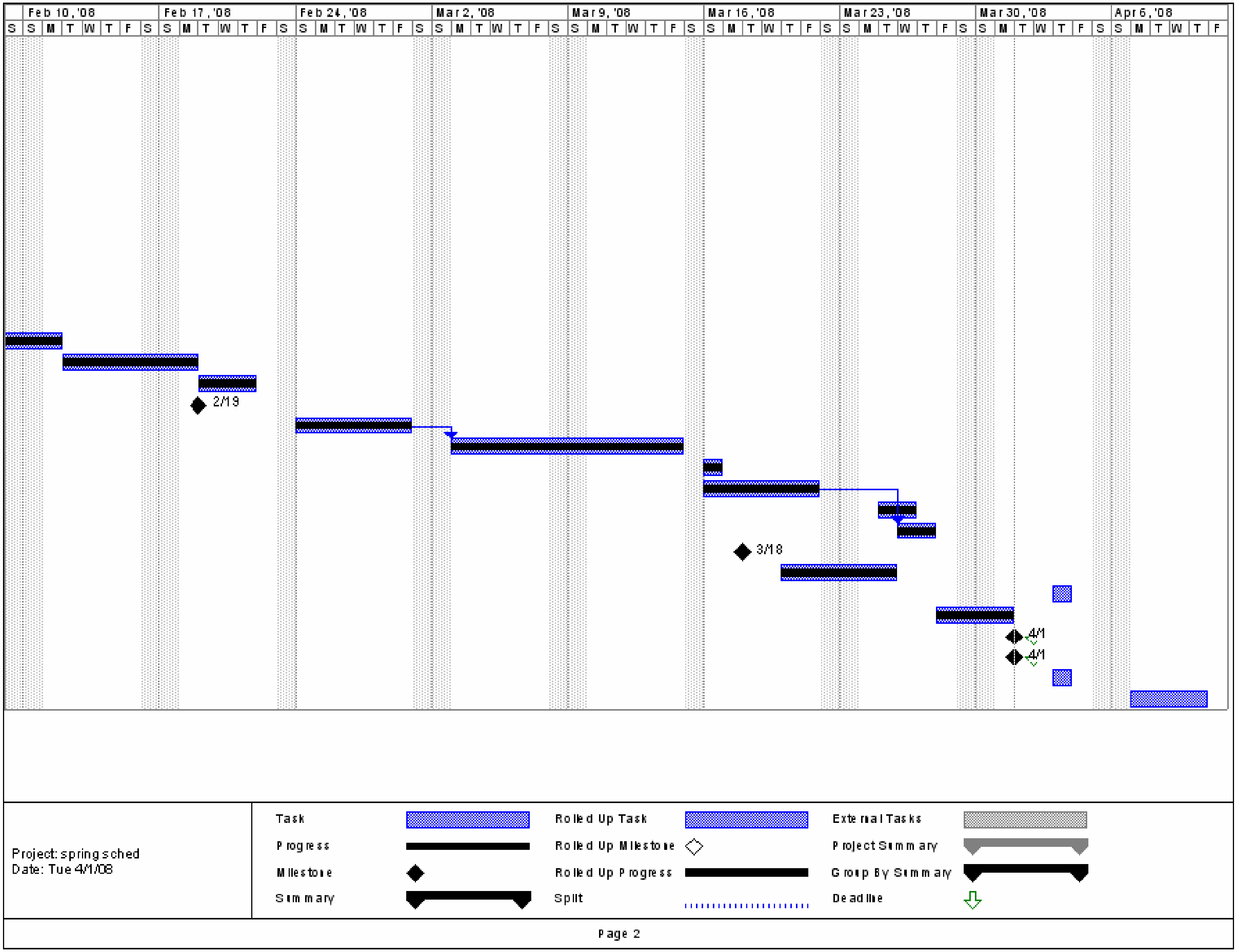
7.4 Appendix D – Spring Schedule

ID	Task Name	Duration	Start	Finish
1	Prepare Restated Project Plan/S	3 days	Mon 1/7/08	Wed 1/9/08
2	Contact Nick @ Mag Lab	3 days	Tue 1/8/08	Thu 1/10/08
3	Develop Testing Procedure	2 days	Fri 1/11/08	Mon 1/14/08
4	Divide Tests between group	0 days	Mon 1/14/08	Mon 1/14/08
5	Staff Meetings	1 day	Tue 1/15/08	Tue 1/15/08
6	Restated Project Scope/Plan	0 days	Thu 1/17/08	Thu 1/17/08
7	Surface Tests @ Mag Lab	5 days	Mon 1/21/08	Fri 1/25/08
8	First Presentation of the Semes	3 days	Tue 1/22/08	Thu 1/24/08
9	Present Surface Test results to	0 days	Fri 1/25/08	Fri 1/25/08
10	Acquire Plungers from GT	2 days	Mon 1/28/08	Tue 1/29/08
11	Leak Testing @ GT	5 days	Mon 1/28/08	Fri 2/1/08
12	Compile surface test Results	3 days	Fri 2/1/08	Tue 2/5/08
13	Staff Meetings	1 day	Tue 2/5/08	Tue 2/5/08
14	Third Team Evaluation	1 day	Tue 2/5/08	Tue 2/5/08
15	Compile leak test Results	3 days?	Thu 2/7/08	Mon 2/11/08
16	Research thin flow theory and S	1 wk	Tue 2/12/08	Mon 2/18/08
17	Implement thin flow calculation	3 days	Tue 2/19/08	Thu 2/21/08
18	Second Presentations	0 days	Tue 2/19/08	Tue 2/19/08
19	Test Polishing Improvements @	1.2 wks	Sun 2/24/08	Fri 2/29/08
20	Mail Parts to Aveeco and Wait f	2 wks	Mon 3/3/08	Fri 3/14/08
21	Analysis at Mag Lab	1 day	Sun 3/16/08	Sun 3/16/08
22	Prepare Final Reports	6 days	Sun 3/16/08	Fri 3/21/08
23	Finalize Website	2 days	Tue 3/25/08	Wed 3/26/08
24	Present Final Product to GT	2 days	Wed 3/26/08	Thu 3/27/08
25	All Analysis Done	0 days	Tue 3/18/08	Tue 3/18/08
26	Prepare final presentation	4 days	Thu 3/20/08	Tue 3/25/08
27	Final Presentations	1 day	Thu 4/3/08	Thu 4/3/08
28	Last touches of final report	2 days	Fri 3/28/08	Mon 3/31/08
29	Website Due	0 days	Tue 4/1/08	Tue 4/1/08
30	Final Report Due	0 days	Tue 4/1/08	Tue 4/1/08
31	Open House	1 day	Thu 4/3/08	Thu 4/3/08
32	Exit Interviews	4 days	Mon 4/7/08	Thu 4/10/08

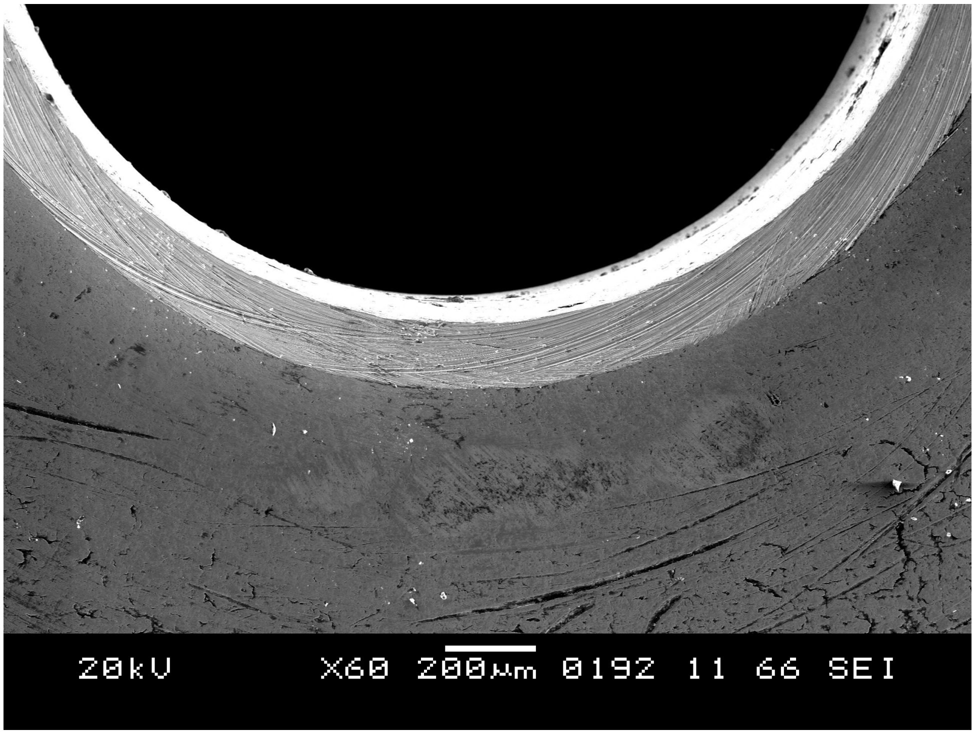


Project: spring sched
Date: Tue 4/1/08

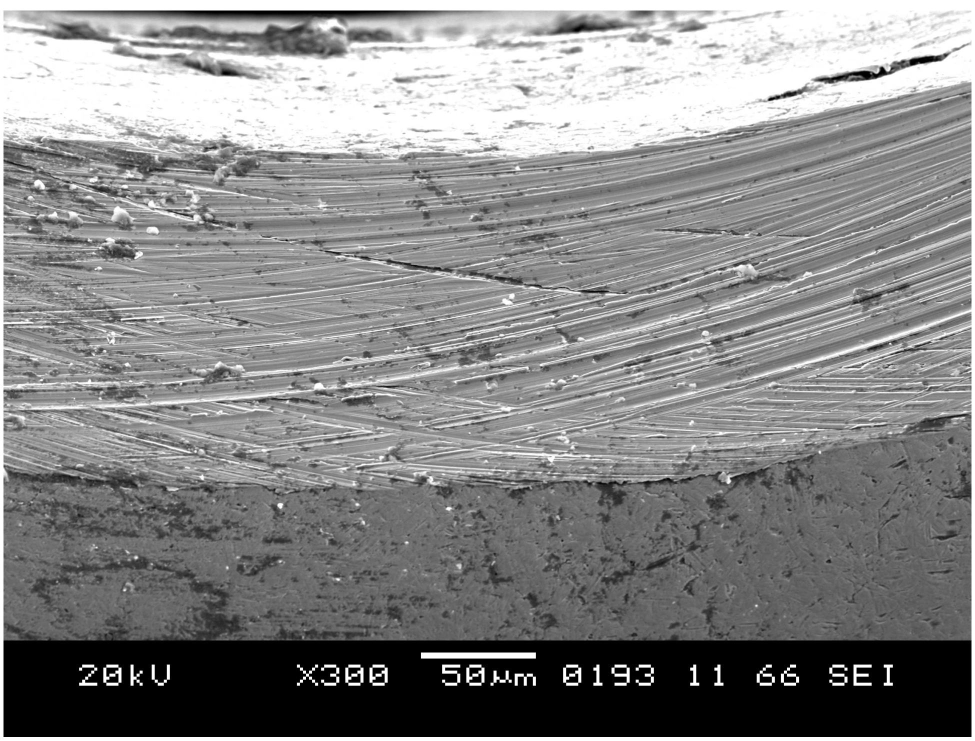
Task
Progress
Milestone
Summary
Rolled Up Task
Rolled Up Milestone
Rolled Up Progress
Split
External Tasks
Project Summary
Group By Summary
Deadline


Feb 10, '08
Feb 17, '08
Feb 24, '08
Mar 2, '08
Mar 9, '08
Mar 16, '08
Mar 23, '08
Mar 30, '08
Apr 6, '08
2/19
3/18
4/1
4/1
Project: spring sched
Date: Tue 4/1/08
Task
Progress
Milestone
Summary
Rolled Up Task
Rolled Up Milestone
Rolled Up Progress
Split
External Tasks
Project Summary
Group By Summary
Deadline
Page 2

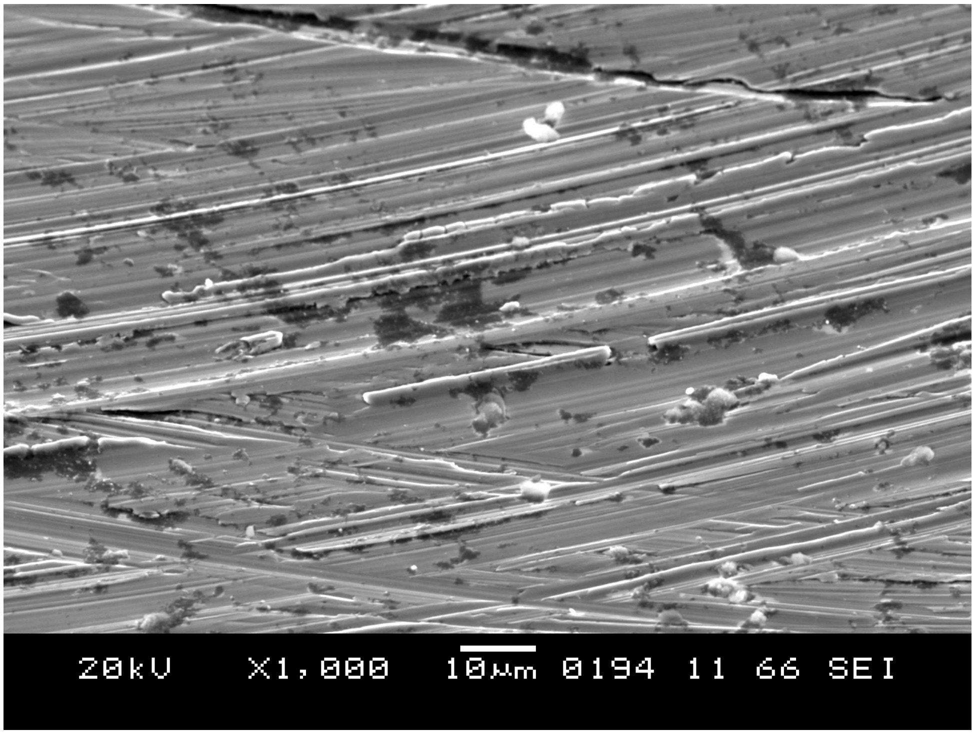
7.5 Appendix E – Microscopy Pictures of Plungers



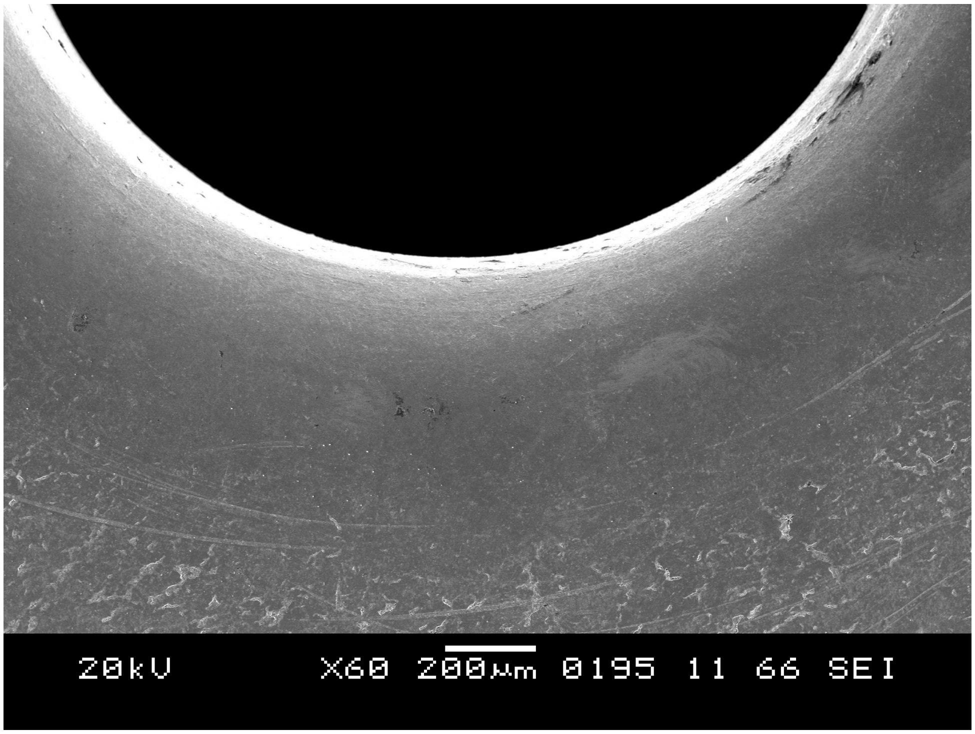
Scanning Electron Microscope (SEM) overhead pictures of Polished Plunger at 60x



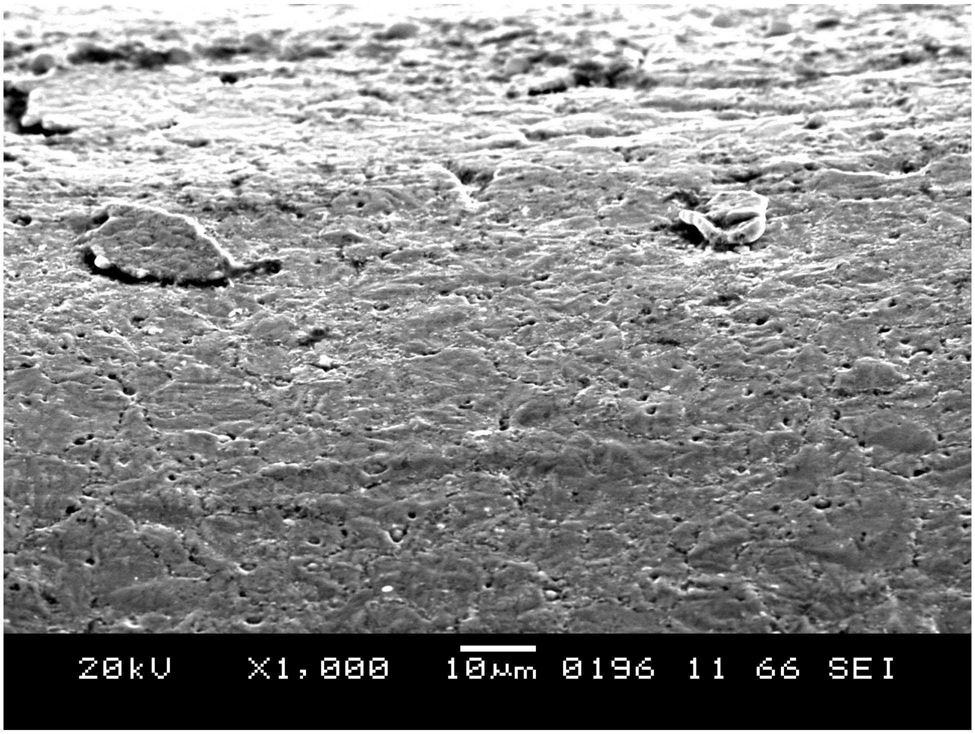
SEM overhead picture of Polished Plunger at 300x



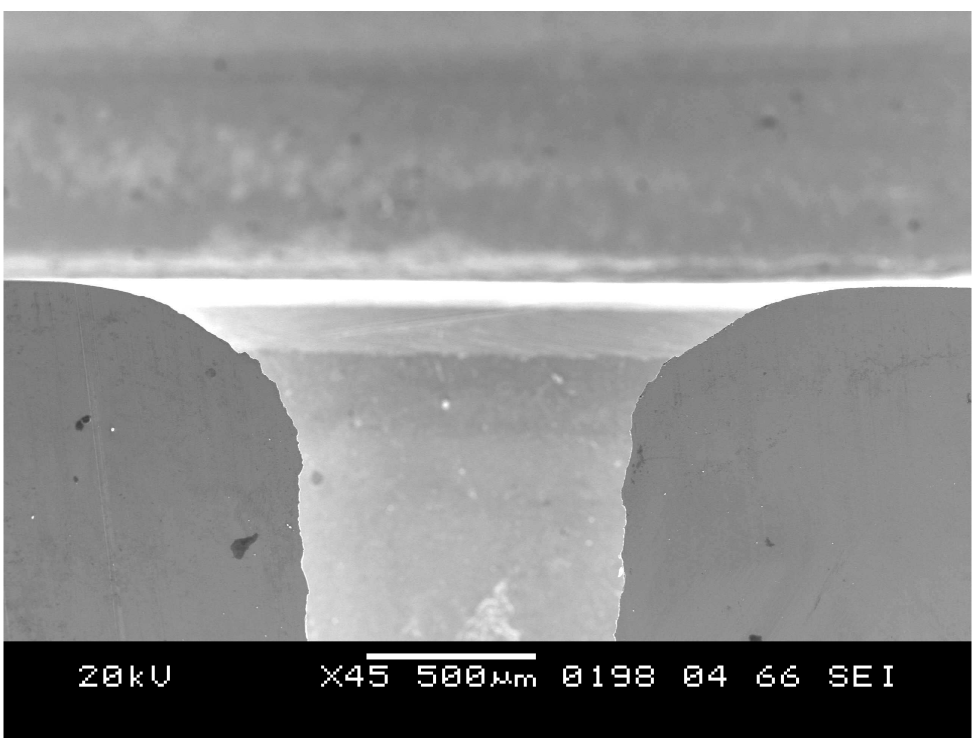
SEM overhead picture of Polished Plunger at 1000x



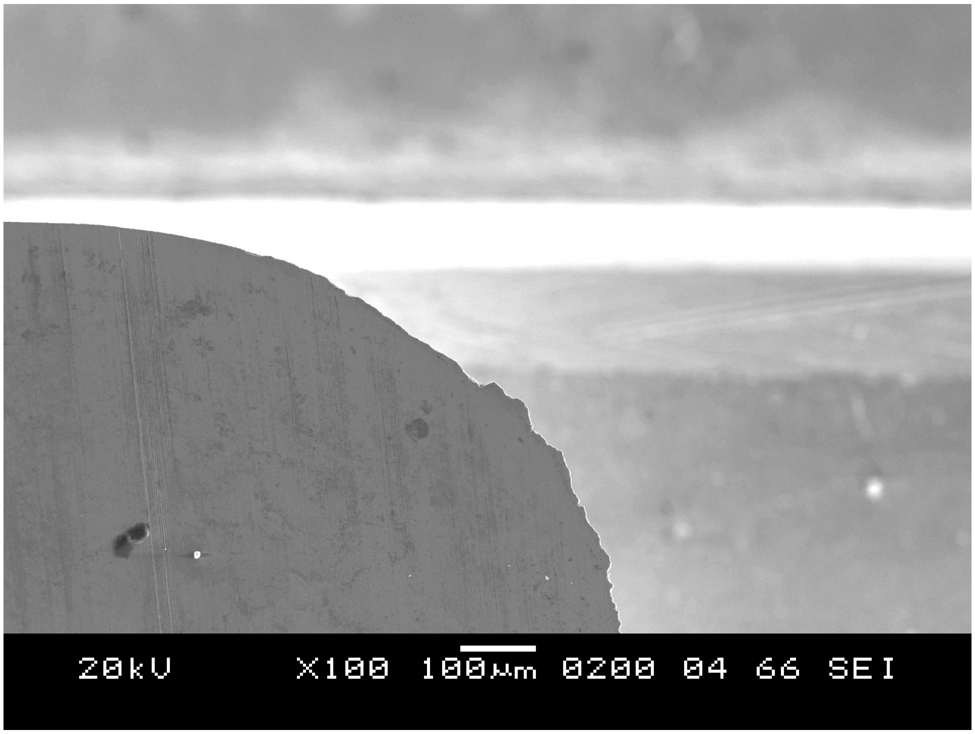
SEM overhead picture of unpolished plunger at 60x



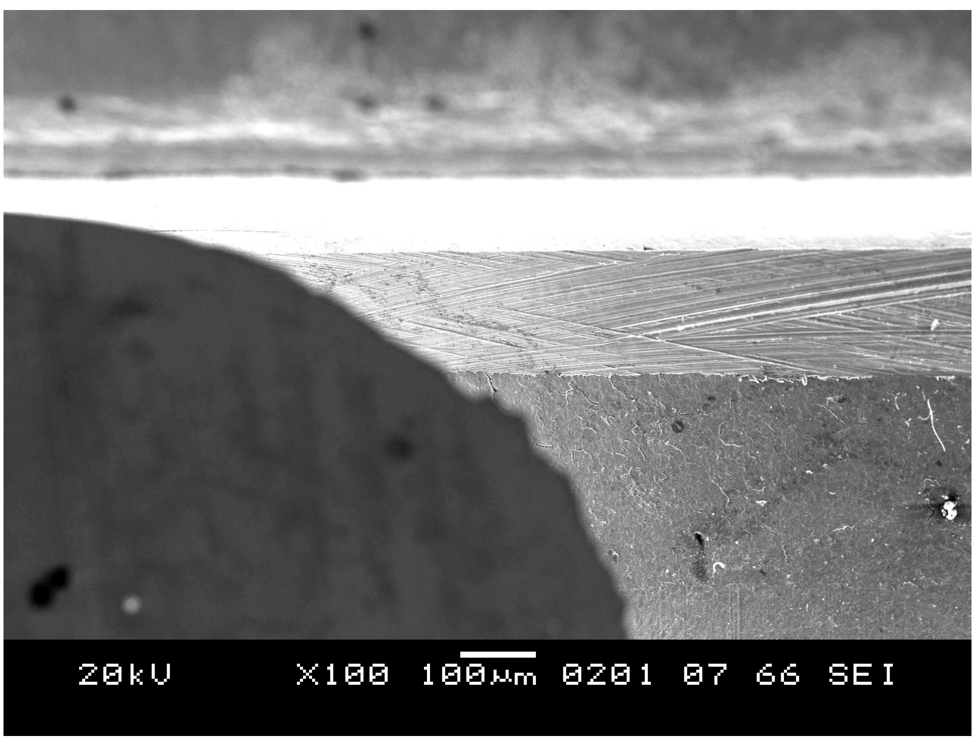
SEM overhead picture of unpolished plunger at 1000x



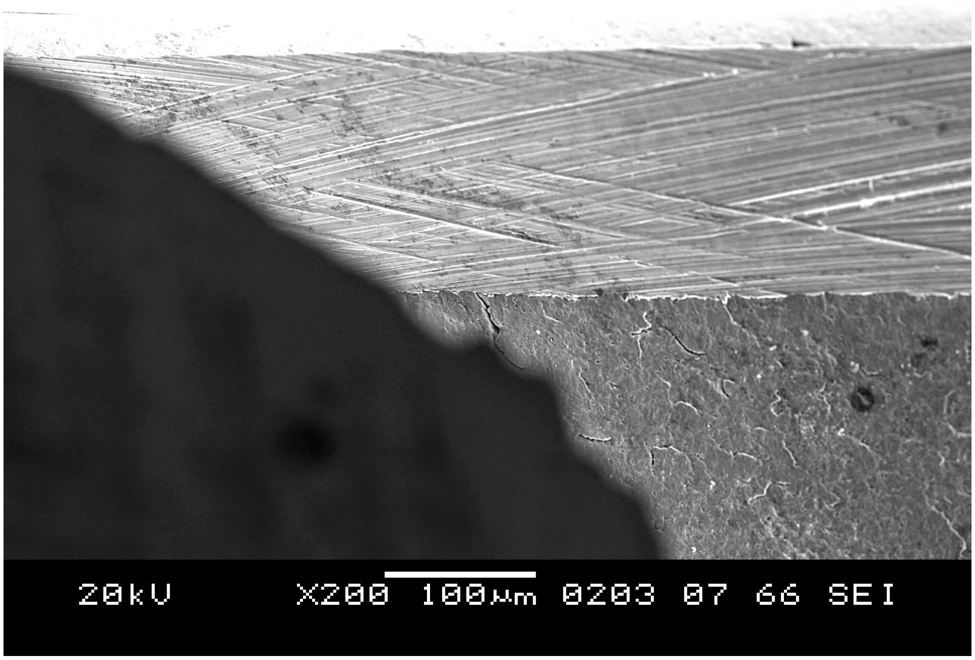
SEM vertical cross section picture of polished plunger at 45x

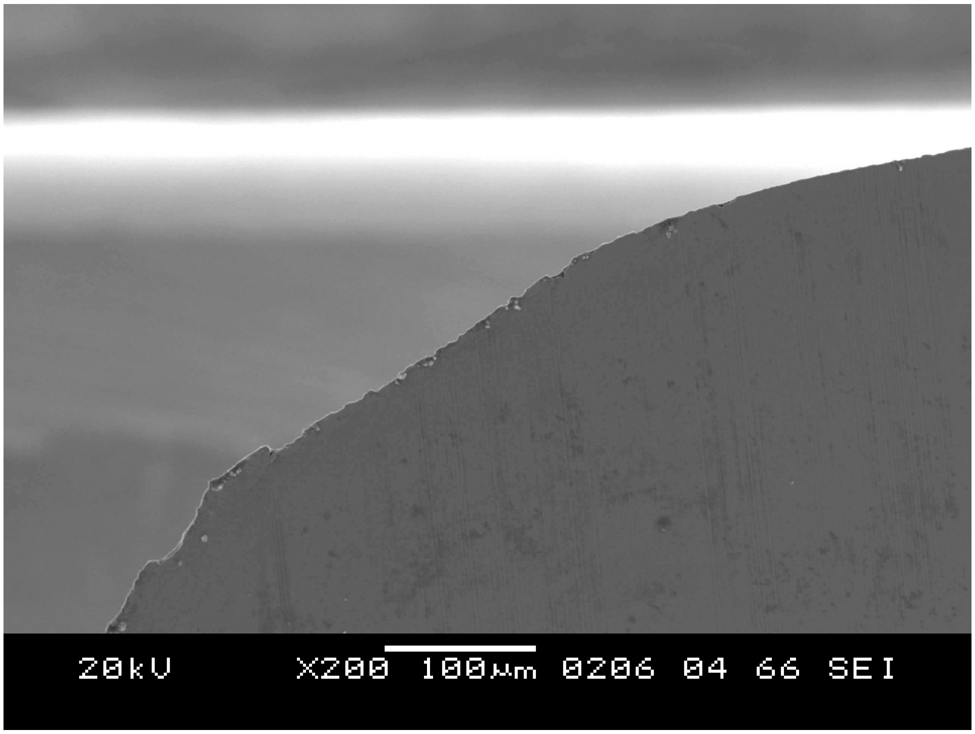


SEM vertical cross section picture of polished plunger at 100x

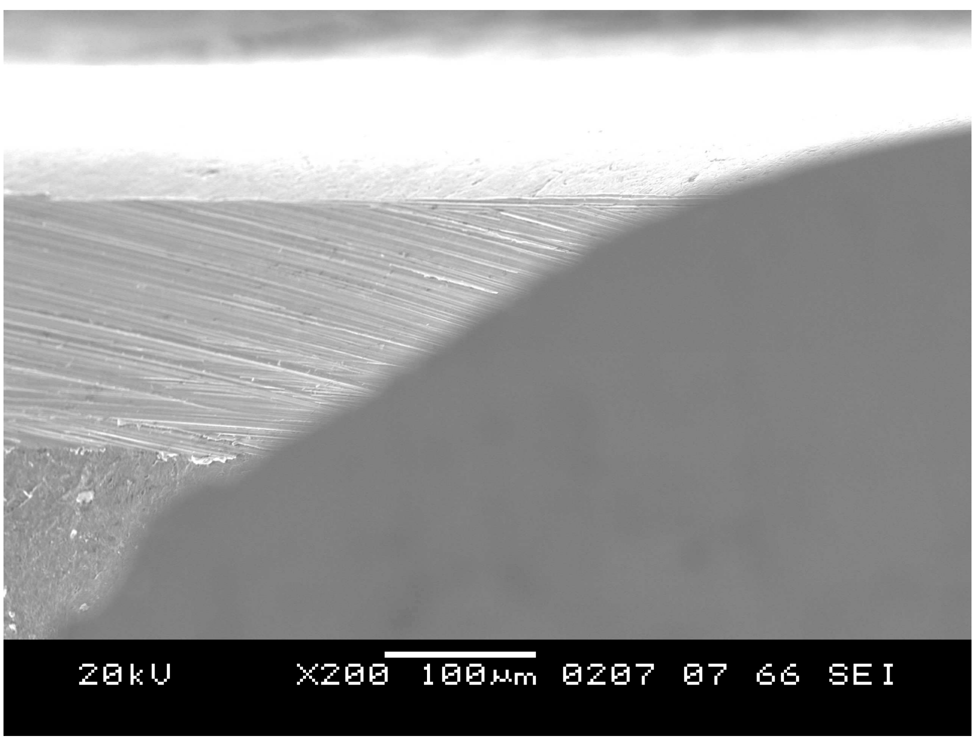


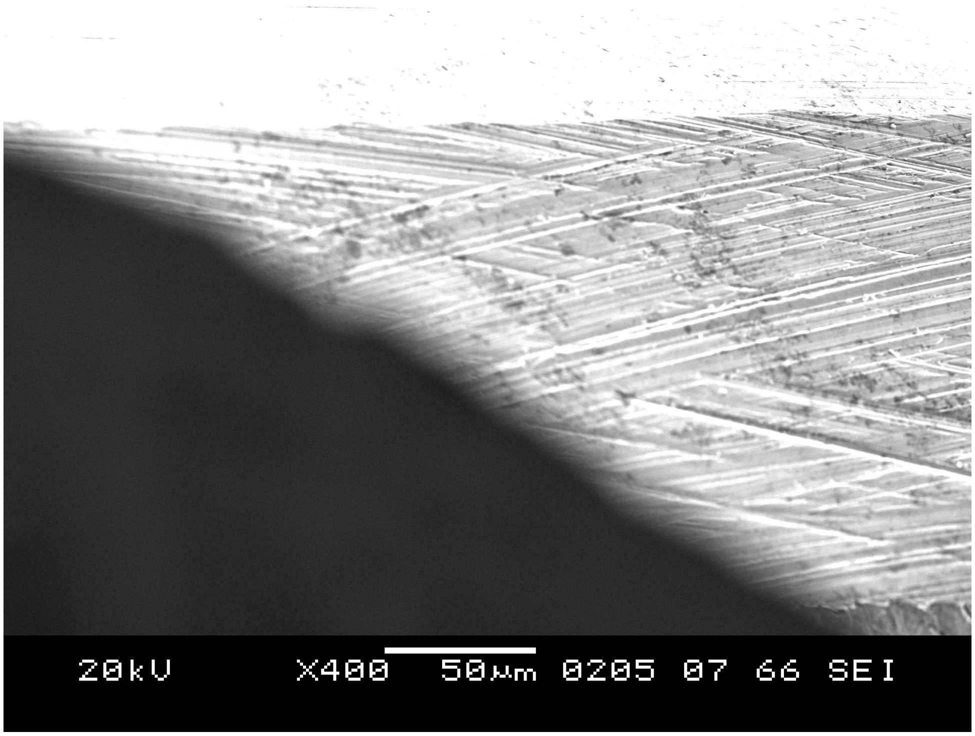
SEM vertical cross section picture of polished plunger at 200x



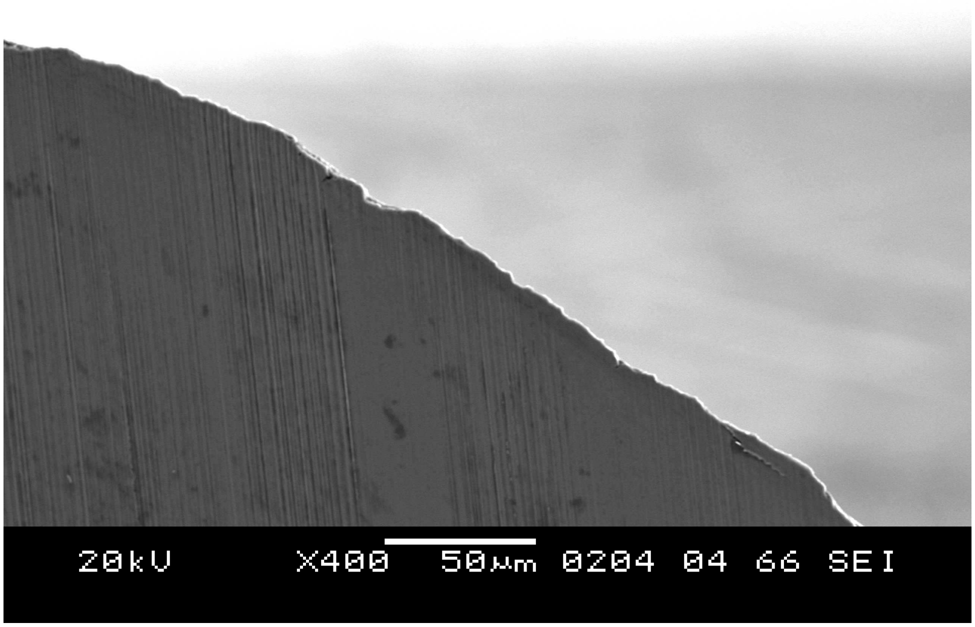


SEM vertical cross section picture of polished plunger at 200x

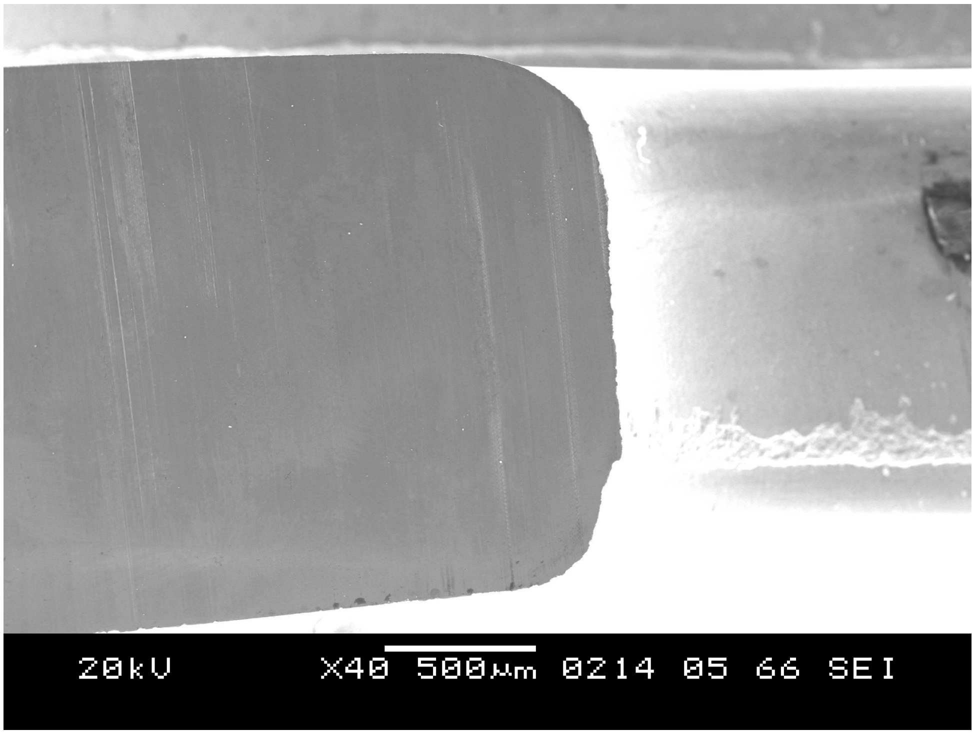




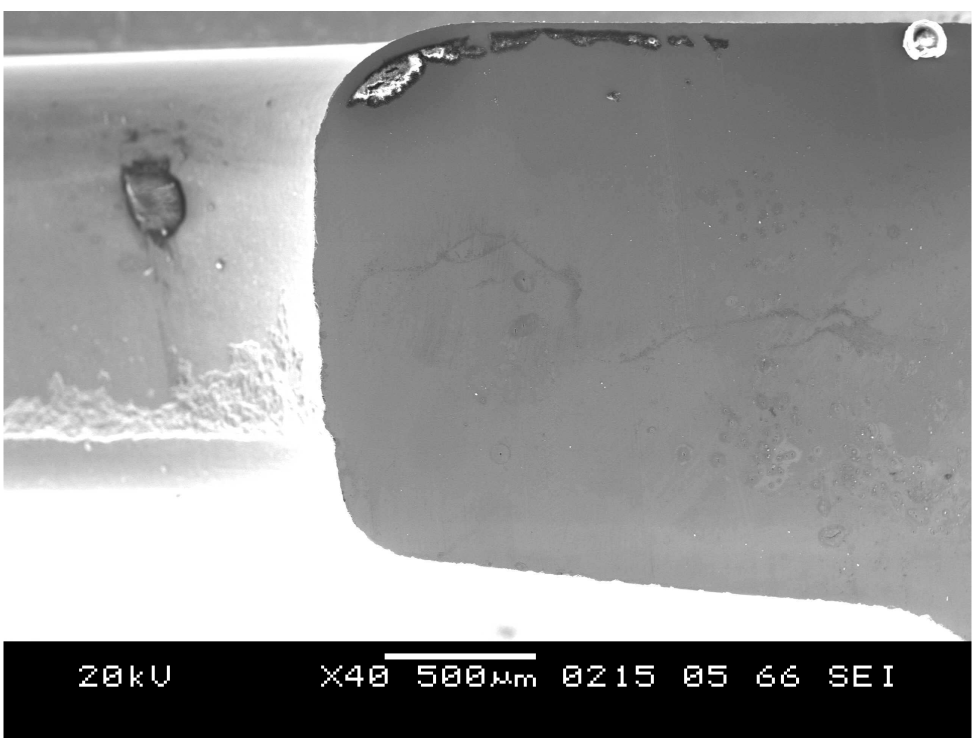
SEM vertical cross section picture of polished plunger at 400x

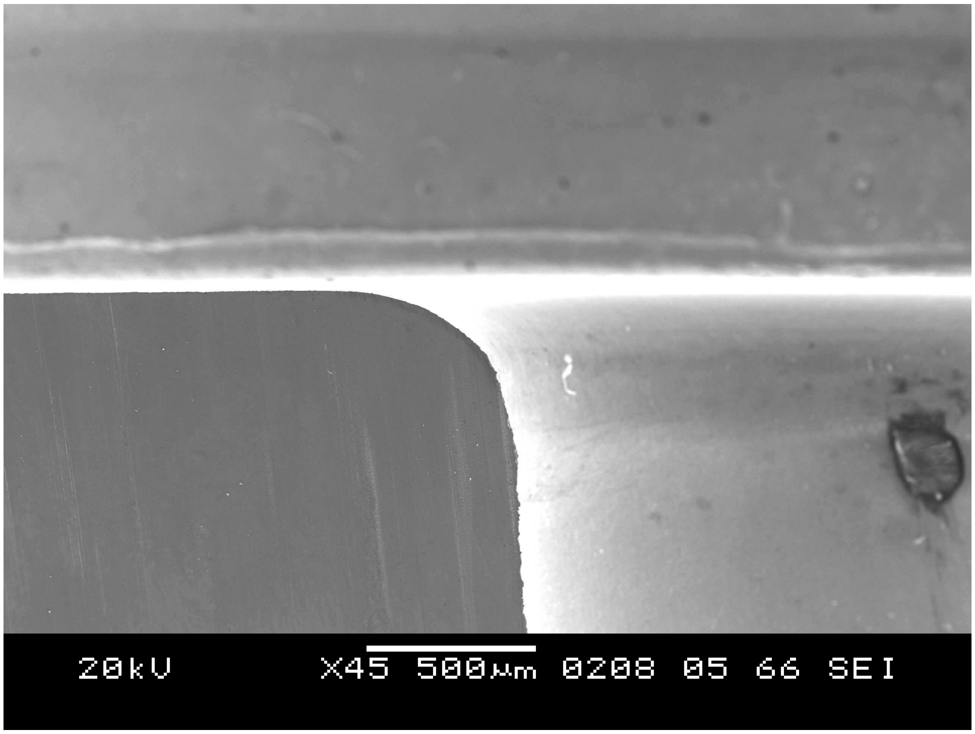


SEM vertical cross section picture of unpolished plunger at 40x

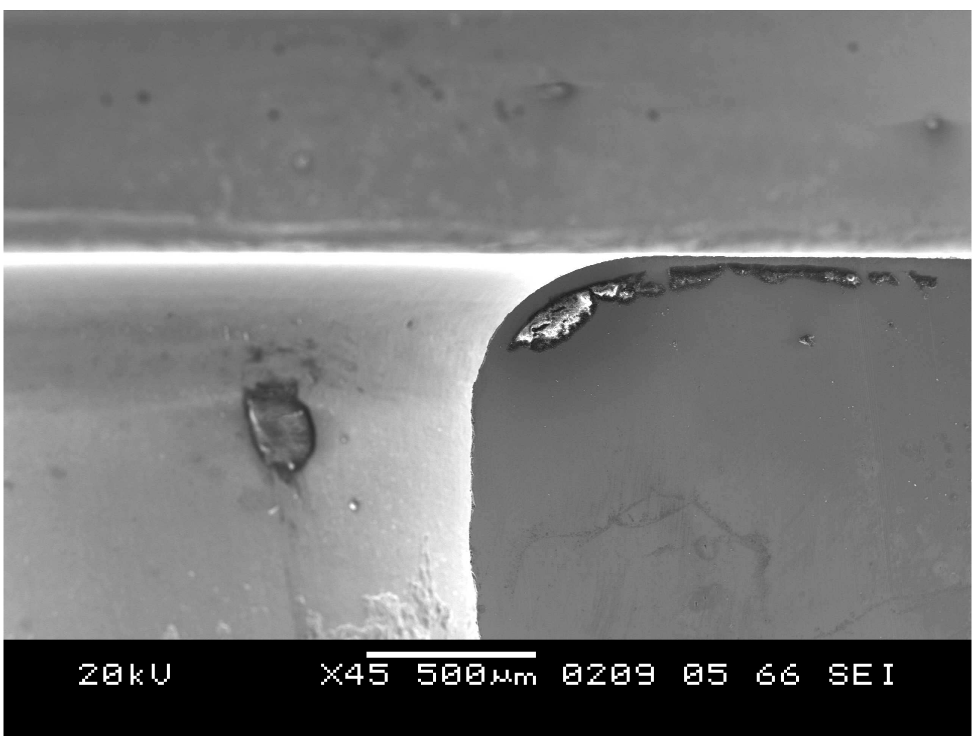


SEM vertical cross section picture of unpolished plunger at 40x

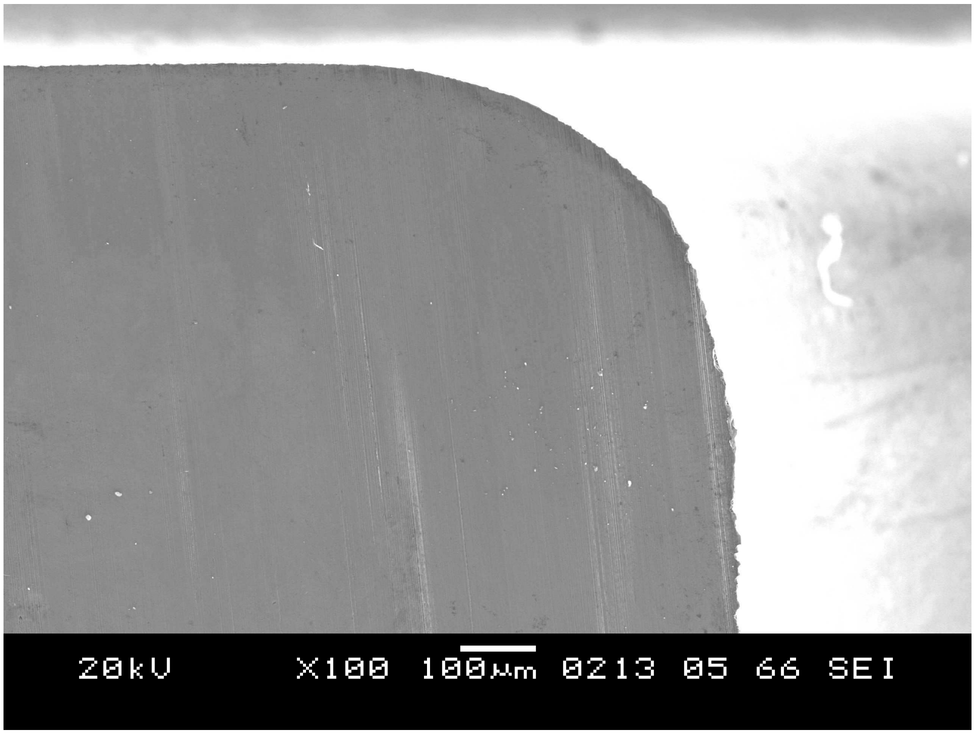




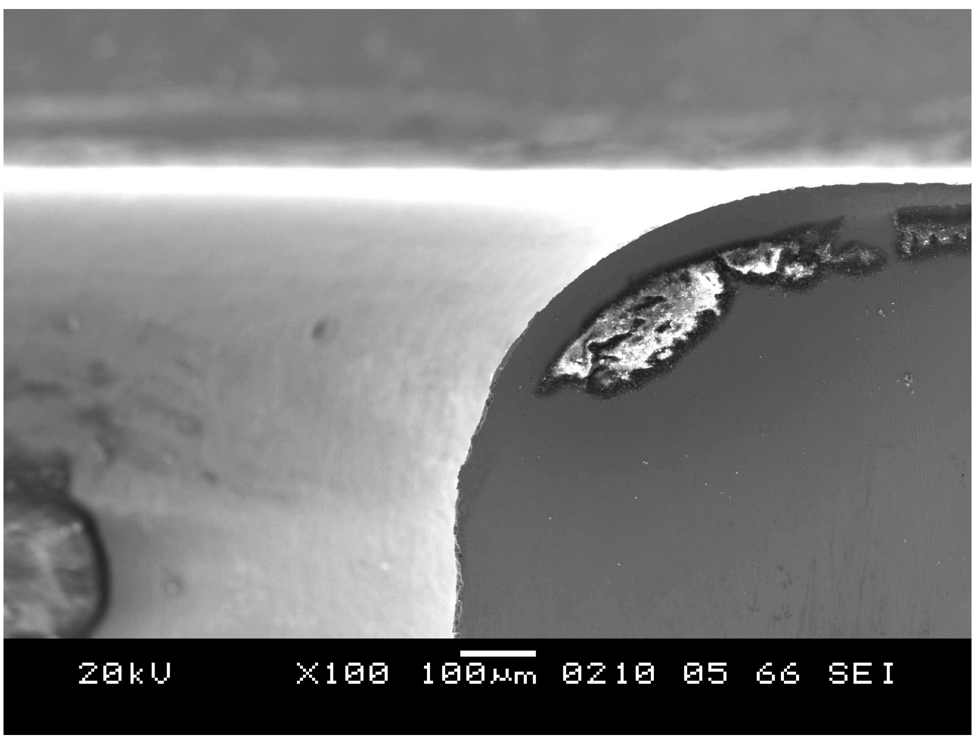
SEM vertical cross section picture of unpolished plunger at 45x



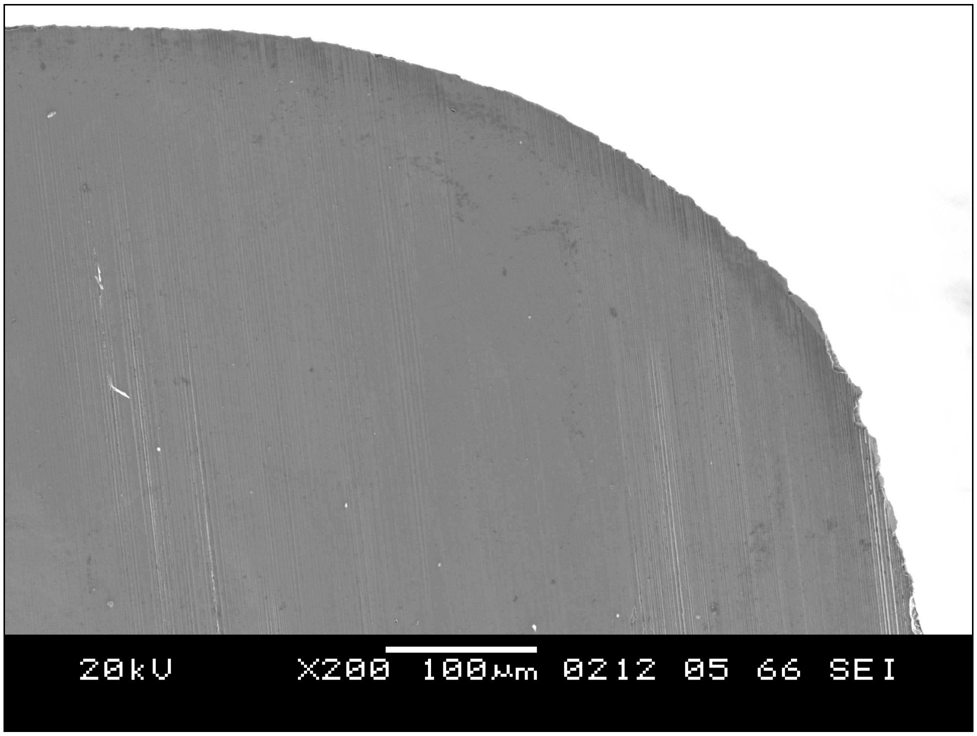
SEM vertical cross section picture of unpolished plunger at 45x



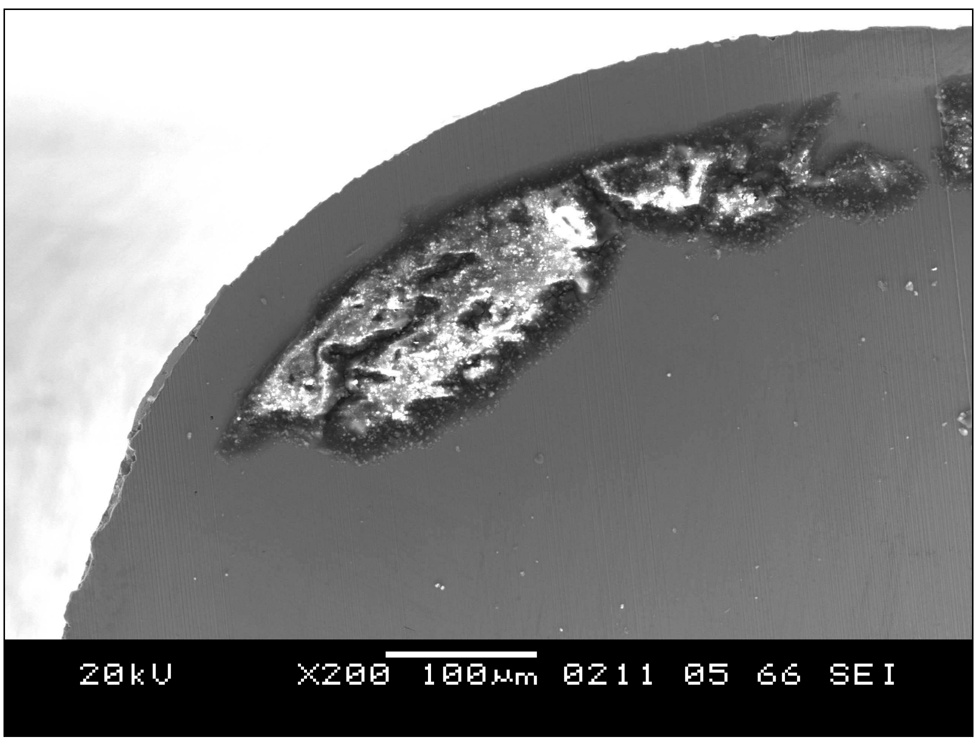
SEM vertical cross section picture of unpolished plunger at 100x



SEM vertical cross section picture of unpolished plunger at 100x

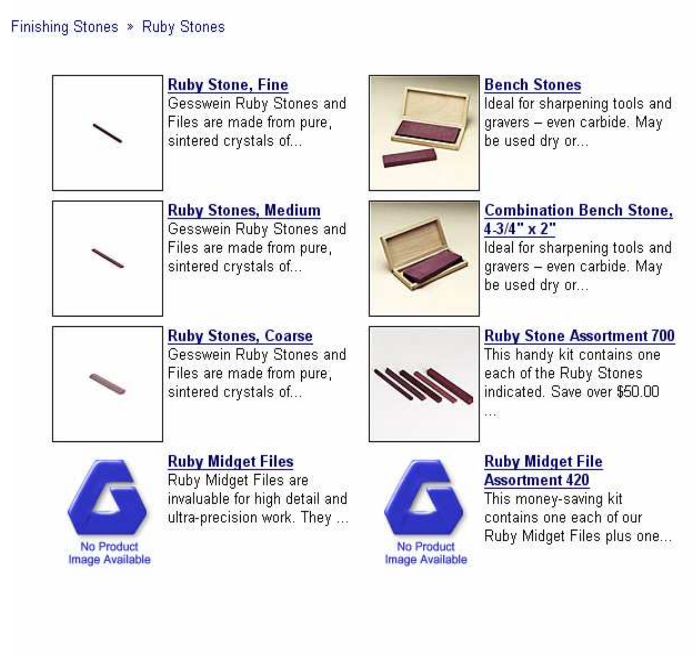


SEM vertical cross section picture of unpolished plunger at 200x



SEM vertical cross section picture of unpolished plunger at 200x

7.6 Appendix F - Gesswein™ Website



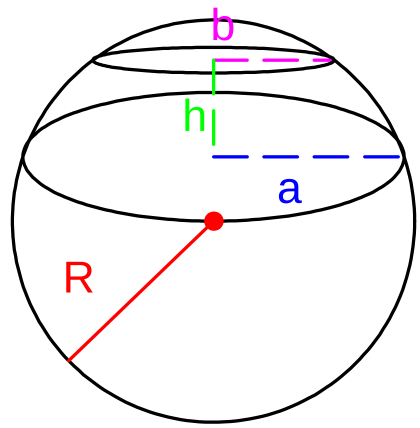
7.7 Appendix G - Evaluation of Valve Seat Geometry

Area of a Surface of Revolution: $S_{revolution} = \int_a^b 2\pi y \cdot \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx$

$S_{zone} = 2\pi r \cdot h$

Proof

Area of a Zone:



$$S = 2\cdot\pi\cdot\int x\cdot\sqrt{1\cdot\left(\frac{dx}{dz}\right)^2}\, dz$$

$$x = \sqrt{R^2 - z^2}$$

$$\frac{dx}{dz} = -z\cdot\left(R^2 - z^2\right)^{\frac{-1}{2}}$$

$$\left(\frac{dx}{dz}\right)^2 = \frac{z^2}{R^2 - z^2}$$

$$S = 2\cdot\pi\cdot\int_{\sqrt{R^2-a^2}}^{\sqrt{R^2-b^2}} \sqrt{R^2 - z^2}\cdot\sqrt{1 + \frac{z^2}{R^2 - z^2}}\, dz$$

$$S = 2\cdot\pi R\cdot\int_{\sqrt{R^2-a^2}}^{\sqrt{R^2-b^2}} 1\, dz$$

$$S = 2\cdot\pi\cdot R\cdot\left(\sqrt{R^2 - b^2} - \sqrt{R^2 - a^2}\right)$$

$$\sqrt{R^2 - b^2} = y_2 \qquad \sqrt{R^2 - a^2} = y_1$$

$$y_2 - y_1 = h$$

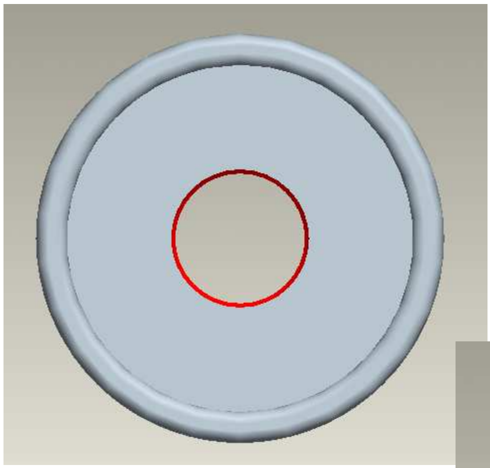
$$S = 2\cdot\pi\cdot R\cdot h$$

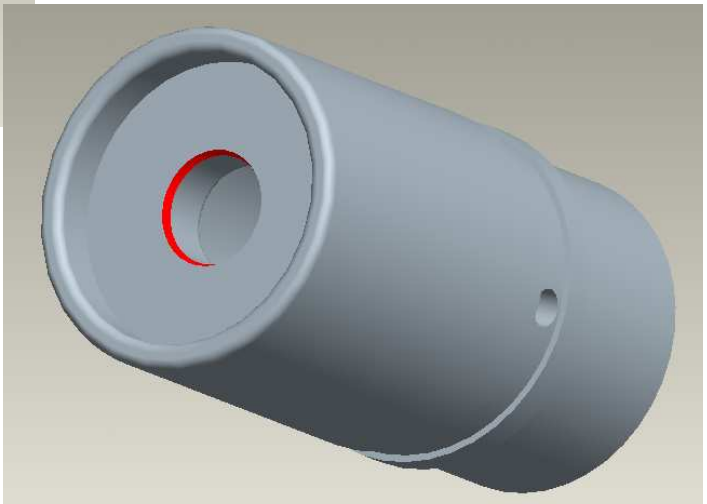
Thanks to Wolfram MathWorld
http://mathworld.wolfram.com/Zone.html

7.8 Appendix H – Economic Cost of Polishing

Labor Grade	3	4	5	5.2	6	6.2	7	7.2	8	8.2	9
Employee Cost	$9.49	$10.80	$12.38	$12.95	$13.88	$14.54	$15.88	$16.42	$17.45	$18.27	$18.83
Employee Fringe Benefits	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Overall Employee Cost	$13.38	$15.23	$17.46	$18.26	$19.57	$20.50	$22.39	$23.15	$24.60	$25.76	$26.55
Employee cost per machine	$4.46	$5.08	$5.82	$6.09	$6.52	$6.83	$7.46	$7.72	$8.20	$8.59	$8.85
Machine Cost per Hour	$9.17	$9.17	$9.17	$9.17	$9.17	$9.17	$9.17	$9.17	$9.17	$9.17	$9.17
Number of shifts	2	2	2	2	2	2	2	2	2	2	2
Hours per shift	8	8	8	8	8	8	8	8	8	8	8
Operating Cost per Day	$146.72	$146.72	$146.72	$146.72	$146.72	$146.72	$146.72	$146.72	$146.72	$146.72	$146.72
Total Machine and Employee Cost per Hour	$13.63	$14.25	$14.99	$15.26	$15.69	$16.00	$16.63	$16.89	$17.37	$17.76	$18.02
Daily Operating Cost per Machine	$218.08	$227.94	$239.82	$244.10	$251.10	$256.06	$266.14	$270.20	$277.94	$284.11	$288.32
Yearly Cost per Machine	$79,600.95	$83,196.64	$87,533.42	$89,097.96	$91,650.62	$93,462.19	$97,140.22	$98,622.42	$101,449.56	$103,700.30	$105,237.38
Total Daily Cost	$654.25	$683.81	$719.45	$732.31	$753.29	$768.18	$798.41	$810.60	$833.83	$852.33	$864.96
Total Yearly cost	$238,802.86	$249,589.92	$262,600.27	$267,293.88	$274,951.87	$280,386.58	$291,420.67	$295,867.25	$304,348.68	$311,100.89	$315,712.15

7.9 Appendix I – PRO-ENGINEER model and live picture of Plunger





7.10 Appendix J – Price Quote Charts

Engis Corporation
105 W. Hintz Road
P.O. Box 9046
Wheeling, IL 60090-9046 USA

Leaders in Superabrasive Finishing Systems

Telephone : (847)808-9400
Fax : (847)808-9430
1-800-99 ENGIS
www.engis.com

March 31, 2008

Anthony Heberlein
1701 W. Pensacola St.
Tallahasee, FL 32304

Fax#
Tele# 850-368-0111

Quote# 6000632108

Dear Anthony

Thank you very much for your recent quotation request; we are pleased to submit the following for your review and approval:

Qty.	Description	Price	Estimated Ship Date
1	CBN plated full radius pin 1/16" radius - 1/4" x 2 " shank 80/100 or 200/230 grit	$216.00	4 Weeks
5	Same as above	$76.00	"
10	Same as above	$64.00	"
25	Same as above	$46.00	"
50	Same as above	$40.00	"

Please contact me so that we can review your application

Prices stated are FOB Wheeling, Illinois. Shipping dates will be confirmed at time of order. Our terms of payment are net 30 days with approved credit. This quotation is valid for 60 days. Standard terms and conditions apply.

We appreciate the opportunity to quote your requirements. Should you require any additional information or have any questions, please feel free to contact us.

Regards,

Jim Rovano
Inside Sales Manager

Engis®
Leaders in Superabrasive Finishing Systems

Engis Corporation
105 W. Hintz Road
P.O. Box 9046
Wheeling, IL 60090-9046 USA

Telephone : (847)808-9400
Fax : (847)808-9430
1-800-99 ENGIS
www.engis.com

March 31, 2008

Anthony Heberlein
1701 W. Pensacola St.
Tallahasee, Fl. 32304

Fax#
Tele# 850-368-0111

Quote# 6000632064

Dear Anthony

Thank you very much for your recent quotation request; we are pleased to submit the following for your review and approval:

Qty.	Description	Price	Estimated Ship Date
1	Diamond plated full radius pin 1/16" radius - 1/4" x 2" shank 80/100 or 200/230 grit	$216.00	4 Weeks
5	Same as above	$76.00	"
10	Same as above	$64.00	"
25	Same as above	$46.00	"
50	Same as above	$40.00	"

Engis will not guarantee the tool performance. Mixing & matching of grit sizes to achieve quantity pricing is prohibited.

Prices stated are FOB Wheeling, Illinois. Shipping dates will be confirmed at time of order. Our terms of payment are net 30 days with approved credit. This quotation is valid for 60 days. Standard terms and conditions apply.

We appreciate the opportunity to quote your requirements. Should you require any additional information or have any questions, please feel free to contact us.

Regards,

Jim Rovano
Inside Sales Manager

7.11 Appendix K – Leak down MathCAD, supplied by GT Tech Engineering

$Gr := .000035 \cdot in$

$F := 1500 \cdot newton$

$SG := .795$

L=Length of piston
h=gap between piston and cylinder
D=Diameter of piston
μ=Viscosity of fluid
Trav=Piston travel

$h := \frac{(.00023 \cdot in + 3.5 \cdot Gr)}{2}$

$\rho_{water} := 62.4 \cdot \frac{lb}{ft^3}$

$L := .25 \cdot in$

$\nu := \left(70 \cdot 10^{-2}\right) \cdot stokes$

$\rho_{fluid} := SG \cdot \rho_{water}$

$\mu := \nu \cdot \rho_{fluid}$

$D := .355 \cdot in$

$Trav := .5 \cdot mm$

$$Time := \frac{\pi \cdot L \cdot \mu \cdot D \cdot \left[3 \cdot \left(\frac{D}{h}\right)^2 + 12 \left(\frac{D}{h}\right) + 16\right] \cdot Trav}{F \cdot 4 \cdot h}$$

$stokes = 0.001\ ft^2 \cdot sec^{-1}$

$Time = 2.271\ sec$

$h = 0.00017625 \cdot in$

$\nu = 70 \cdot \frac{mm^2}{sec}$

7.12 Appendix L - Images from *Theory and Practice of Lubrication for Engineers* by *Dudley Fuller*

FACTORS THAT AFFECT VISCOSITY 55

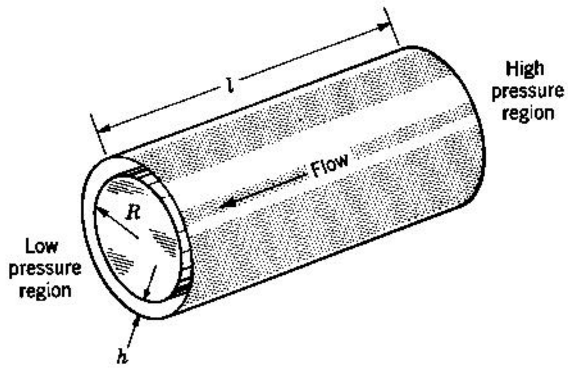


FIG. 2-18. Capillary seal.

Capillary seal model represents flow between plunger and plunger body

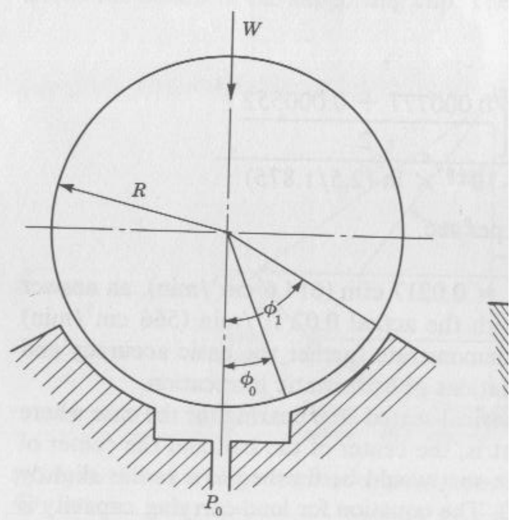


FIG. 3-20. Spherical step bearing.

Step bearing model represents flow between check ball and valve seat

7.13 Appendix M – MathCAD functions for Oil Flow

Capillary Seal Model

Flow between plunger and plunger body

Q = flow (cu. in/min)
ΔP = Pressure difference between high pressure chamber at atmospheric pressure
R = inside cylinder (plunger) radius = 0.178"
h = clearance = 0.00035"
μ = viscosity (reyns [lb-sec/in^2])
L = length of capillary (in)

for different plungers L will change

$$Q = \frac{\Delta P \cdot \pi \cdot R \cdot h^3}{6 \cdot \mu \cdot L}$$

$$\Delta P := \frac{1500N}{0.33in^2} \qquad \Delta P = 1.022 \times 10^3\,psi$$

$$L := 0.352in$$

$$R := 0.165in$$

$$h_1 := 0.000035in$$

$$\nu := 60\,\frac{stokes}{100} \qquad \rho := 880\,\frac{kg}{m^3} \qquad reynolds := 6894.76Pa \cdot sec$$

$$\mu := \nu \cdot \rho \qquad \mu = 7.658 \times 10^{-6}\,reynolds$$

$$Q := \frac{\Delta P \cdot \pi \cdot R \cdot h_1^{\,3}}{6 \cdot \mu \cdot L} \qquad \boxed{Q = 1.380614 \times 10^{-3}\,\frac{cm^3}{min}}$$

Step Bearing Model
Flow between check ball and seat

Q = flow (cu. in/min)
ΔP = Pressure difference
R = check ball radius = 0.0625"
h = clearance of checkball = solve for this value
μ = viscosity (reynolds [lb-sec/in^2])
L = width of contact band = 0.004"

$$Q = \frac{\Delta P \cdot \pi \cdot R \cdot h^3}{6 \cdot \mu \cdot L} \qquad Q_{capillaryseal} := Q$$

$$Q_{checkball} := \frac{1}{10} \cdot Q_{capillaryseal} \qquad Q_{checkball} = 1.381 \times 10^{-4} \frac{cm^3}{min}$$

$$\mu = 7.658 \times 10^{-6} \, reynolds$$

$$R := \frac{0.125}{2} in \qquad L := 0.1mm$$

$$h_2 := \left(Q_{checkball} \cdot \frac{6 \cdot \mu \cdot L}{\Delta P \cdot \pi \cdot R} \right)^{\frac{1}{3}}$$

$$\boxed{h_2 = 0.128 \, \mu m}$$

+

$$Q = \frac{\Delta P \cdot \pi \cdot R \cdot h^3}{6 \cdot \mu \cdot L}$$

Formula applies to both models

$$\frac{\Delta P \cdot \pi \cdot R_{cylinder} \cdot h_{capillaryseal}^{\ 3}}{6 \cdot \mu \cdot L_{capillaryseal}} = FS \cdot \frac{\Delta P \cdot \pi \cdot R_{checkball} \cdot h_{checkball}^{\ 3}}{6 \cdot \mu \cdot L_{contactband}}$$

This essentially states that if the designed leakage (left side) is proportional to the allowable leakage (right side), and the Pressure and viscosity are equal on both sides, the leakage out of the high pressure chamber is only a function of geometry.

$$FS := \frac{1}{10}$$

Arbitrarily set the allowable leakage past the checkball to be 1/10 of the leakage between the plunger and plunger body.

$$L_{contactband} := 0.1mm$$

The approximate width of the polished band of the valve seat.

$$L_{capillaryseal} := 0.352 \cdot in$$

The shortest plunger has this length between the high pressure chamber and relief port on the side of the plunger body.

$$R_{cylinder} := 0.178in$$

Radius of the plunger

$$R_{checkball} := \frac{1}{2} \cdot \frac{1}{8} \cdot in$$

Radius of the checkball

$$h_{capillaryseal} := 35 \cdot 10^{-6} in$$

$$h_{capillaryseal} = 0.889\ \mu m$$

Designed clearance between the plunger and plunger body.

$$\frac{R_{cylinder} \cdot h_{capillaryseal}^{\ 3}}{L_{capillaryseal}} = FS \cdot \frac{R_{checkball} \cdot h_{checkball}^{\ 3}}{L_{contactband}}$$

After mathematically cancelling similar terms on both sides of the equation.

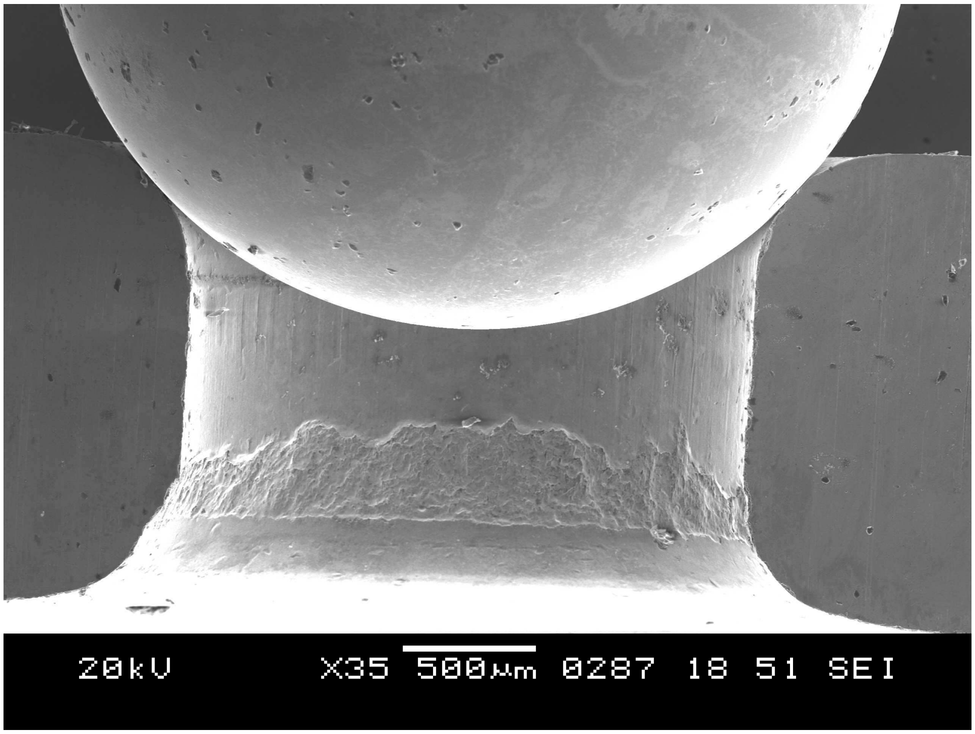
$$h_{checkball} := \left(FS \cdot \frac{L_{contactband}}{L_{capillaryseal}} \cdot \frac{R_{cylinder}}{R_{checkball}} \cdot h_{capillaryseal}^{\ 3}\right)^{\frac{1}{3}}$$

Solving backwards for clearance of the checkball.

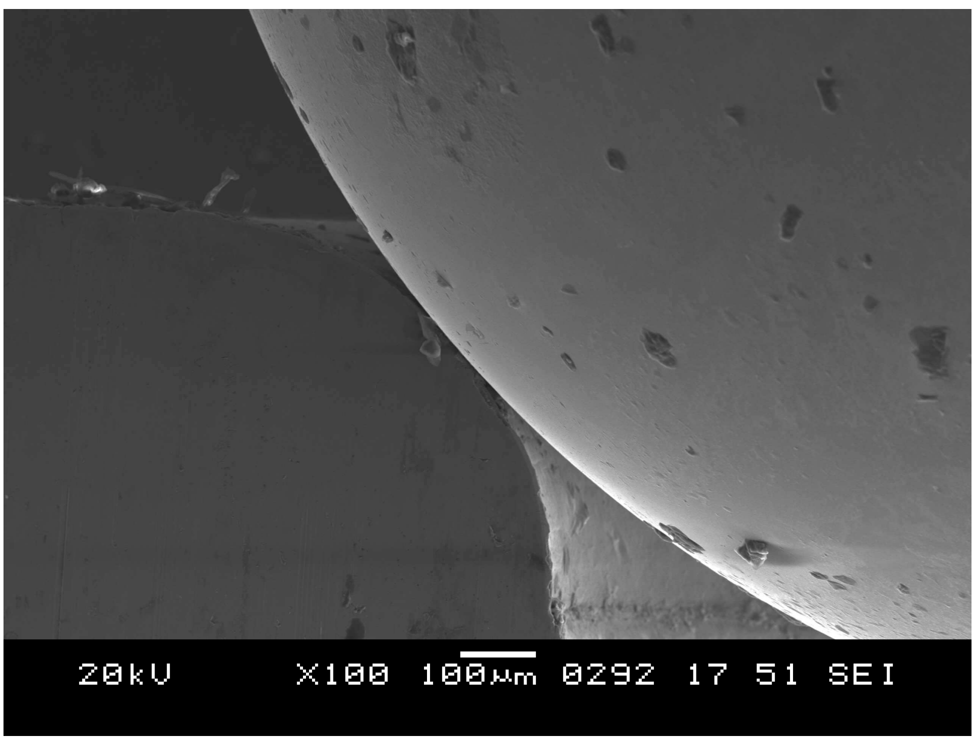
$$h_{checkball} = 0.131\ \mu m$$

Clearance of checkball that will allow specified amount of leakage.

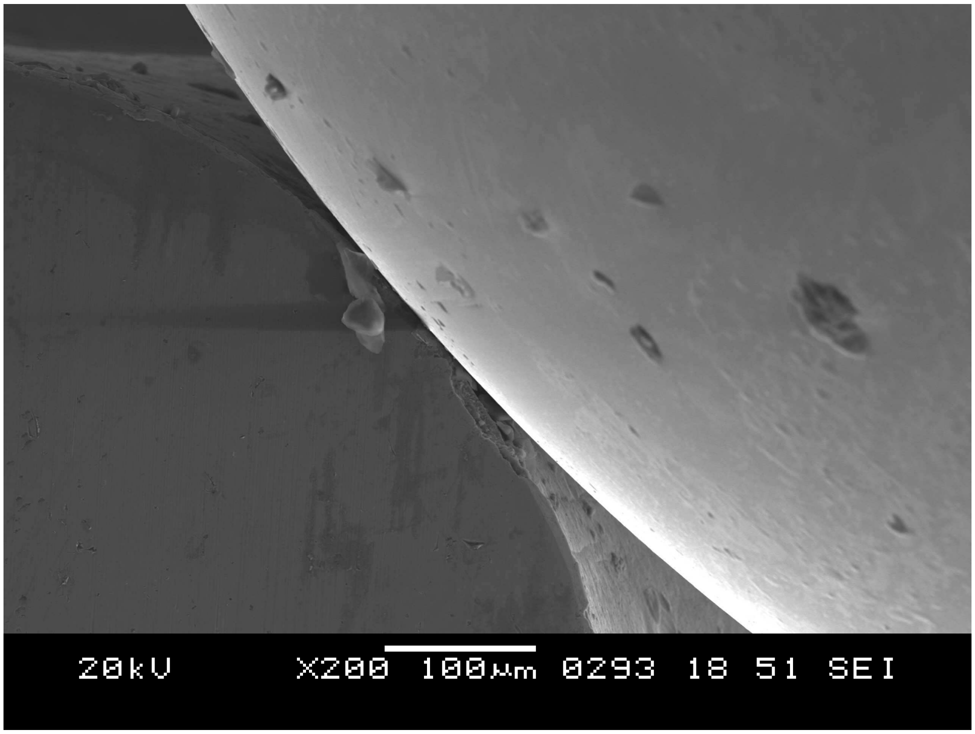
7.14 Appendix N – SEM Pictures of check ball and seat



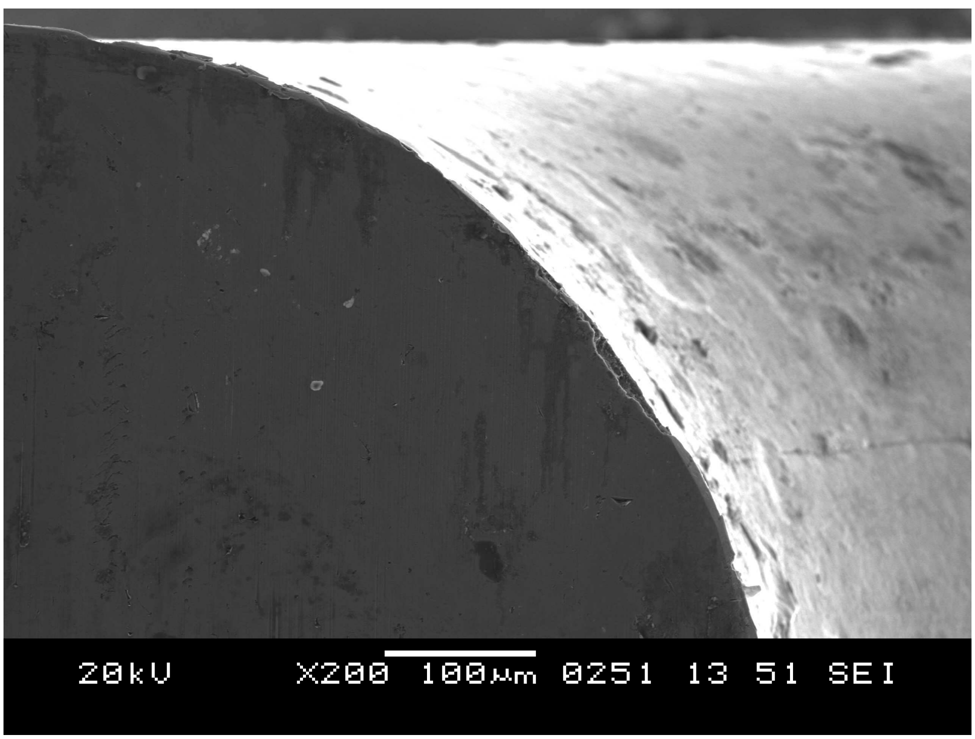
Unpolished seat 35x



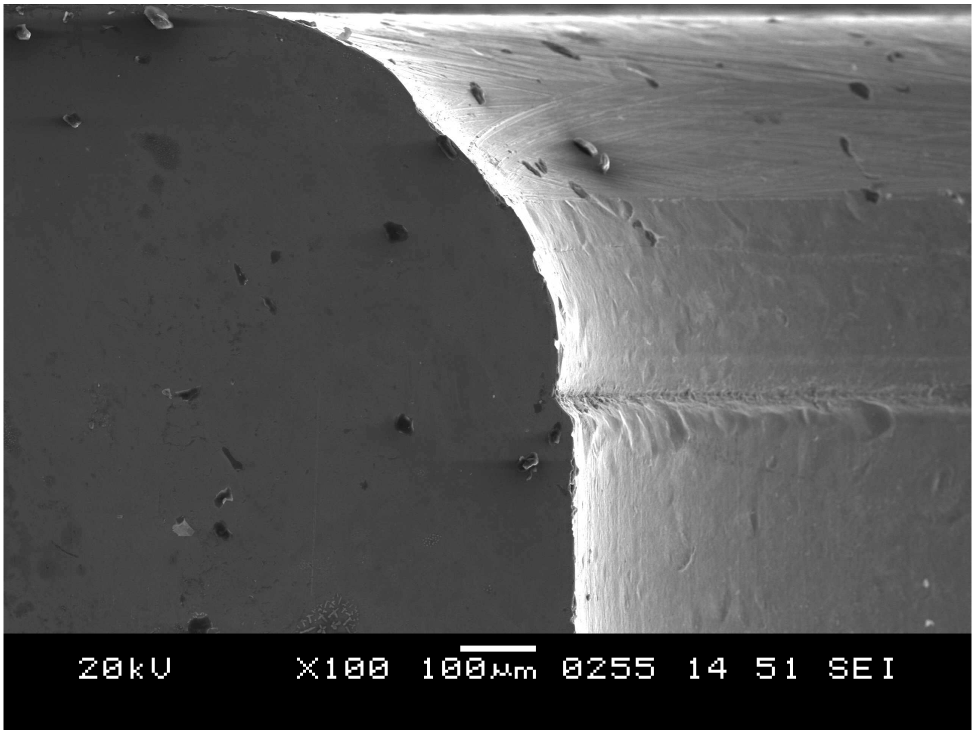
Unpolished seat 100x



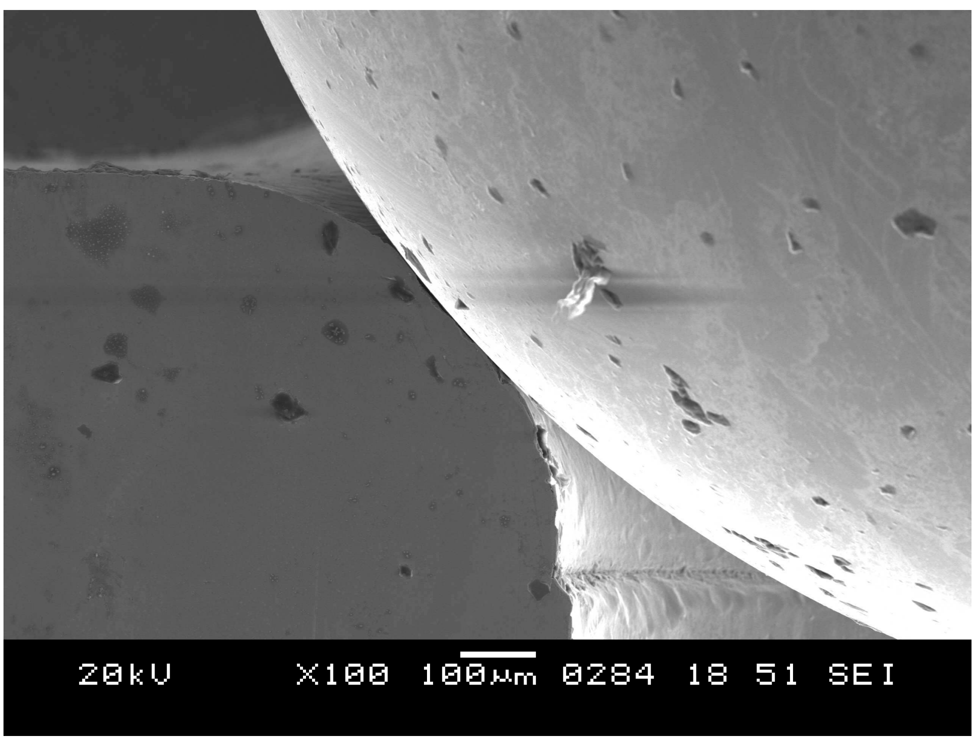
Unpolished Seat 200x



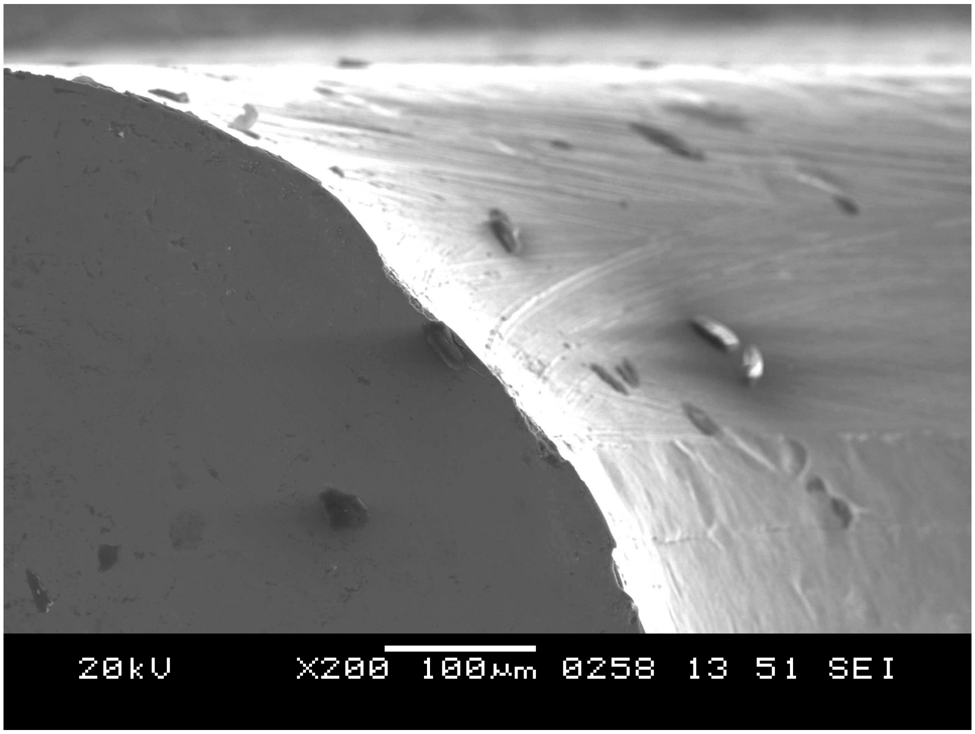
Unpolished Seat 200x



Polished w/fine grit, first 10 of 500 parts, 100x



Polished w/fine grit, first 10 of 500 parts, 100x



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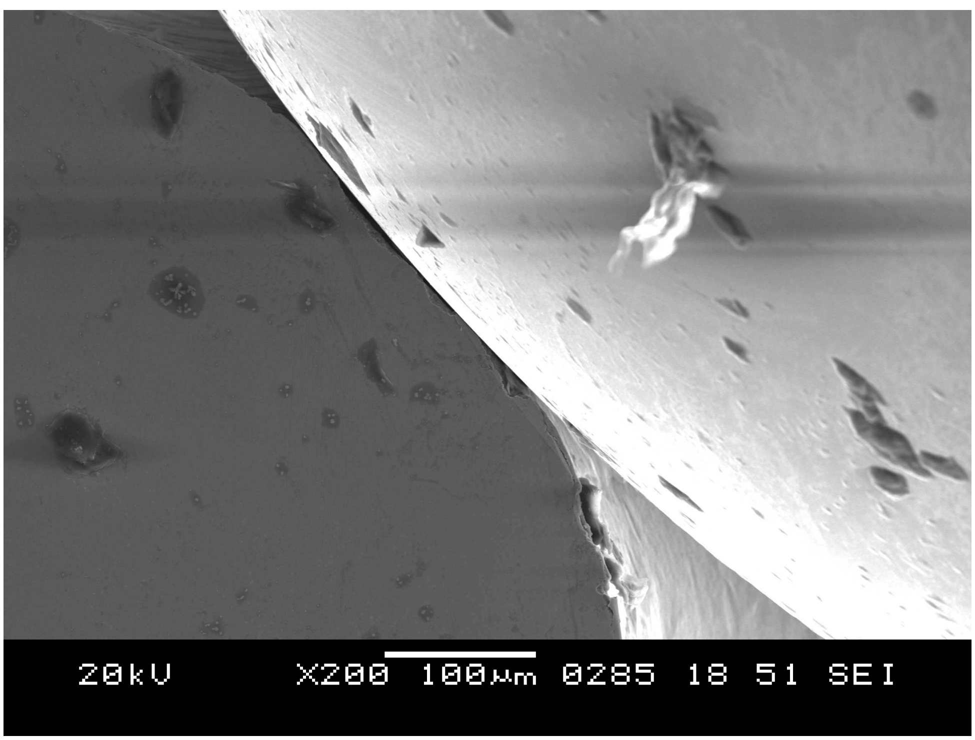

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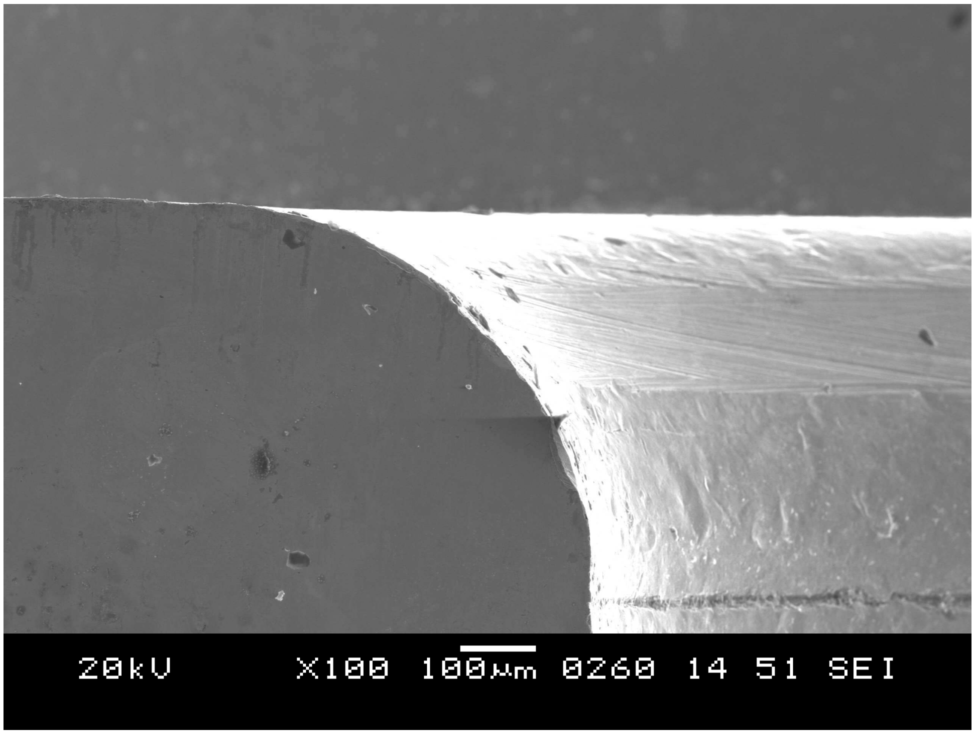

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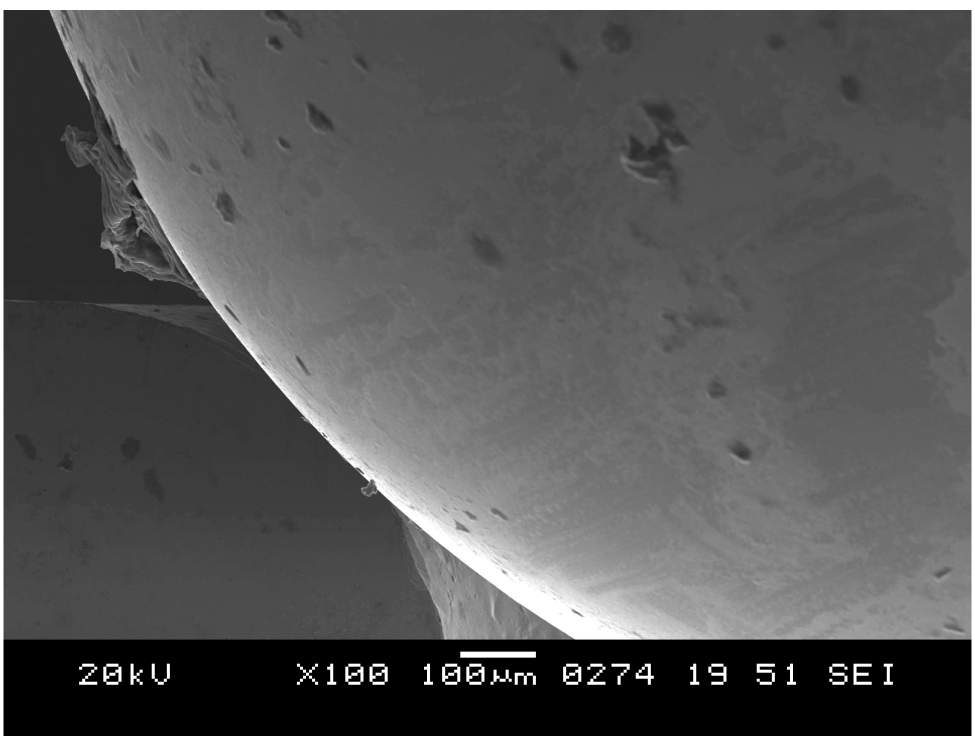

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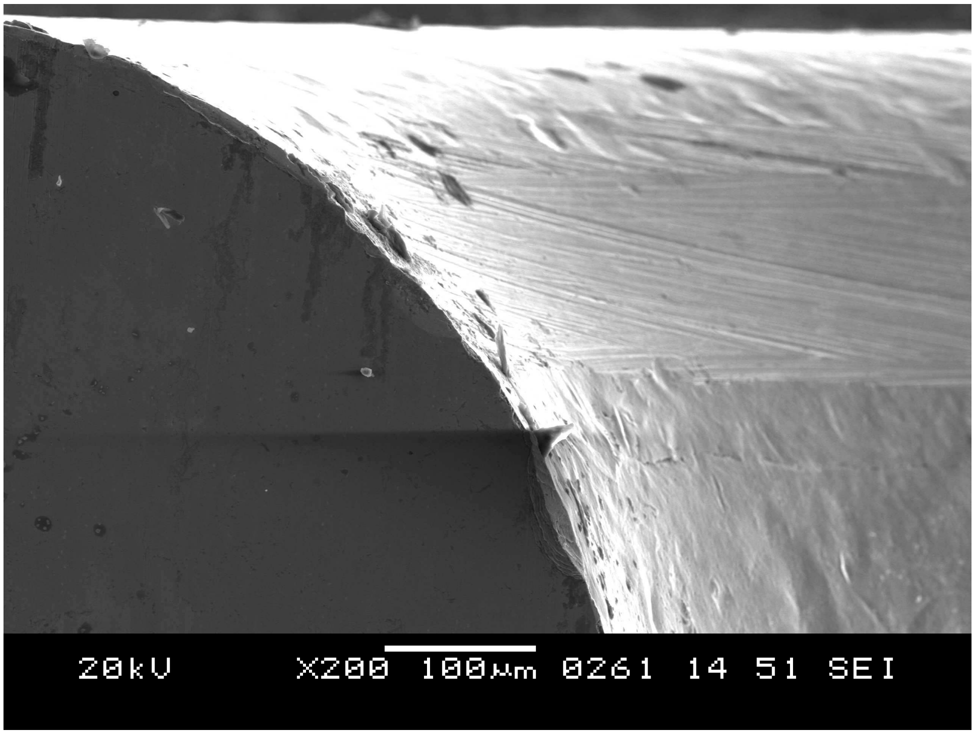

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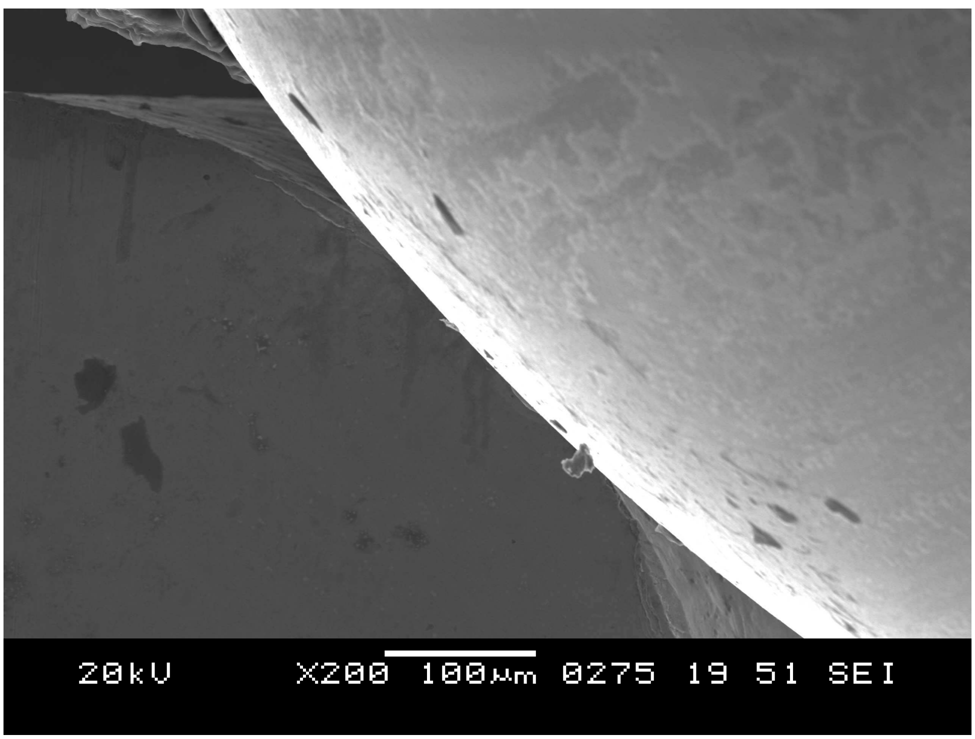

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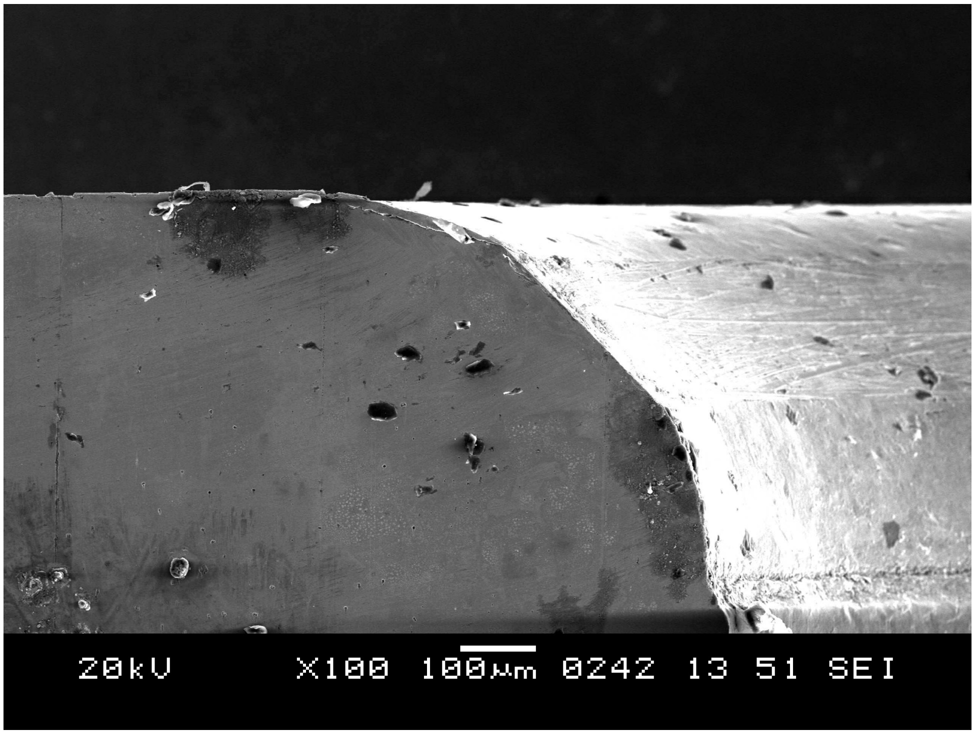

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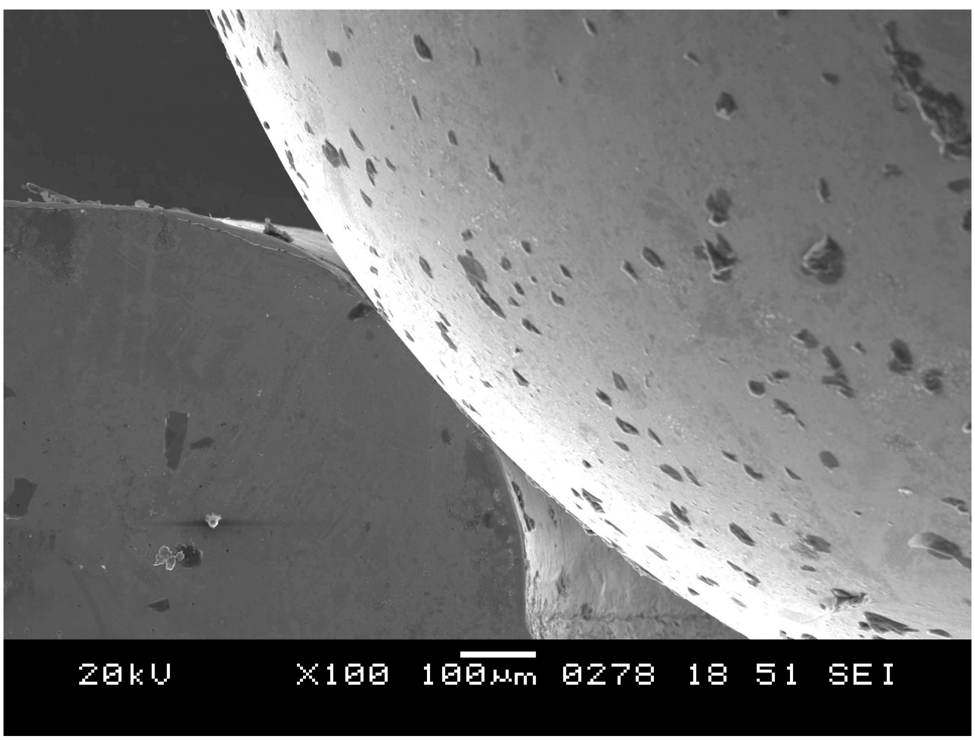

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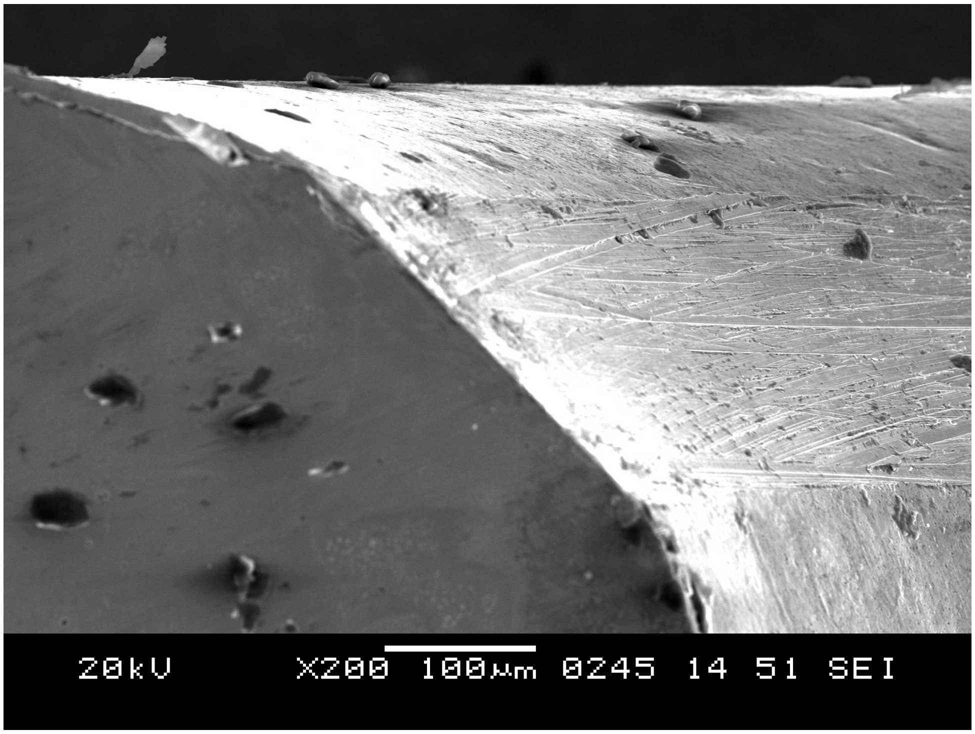

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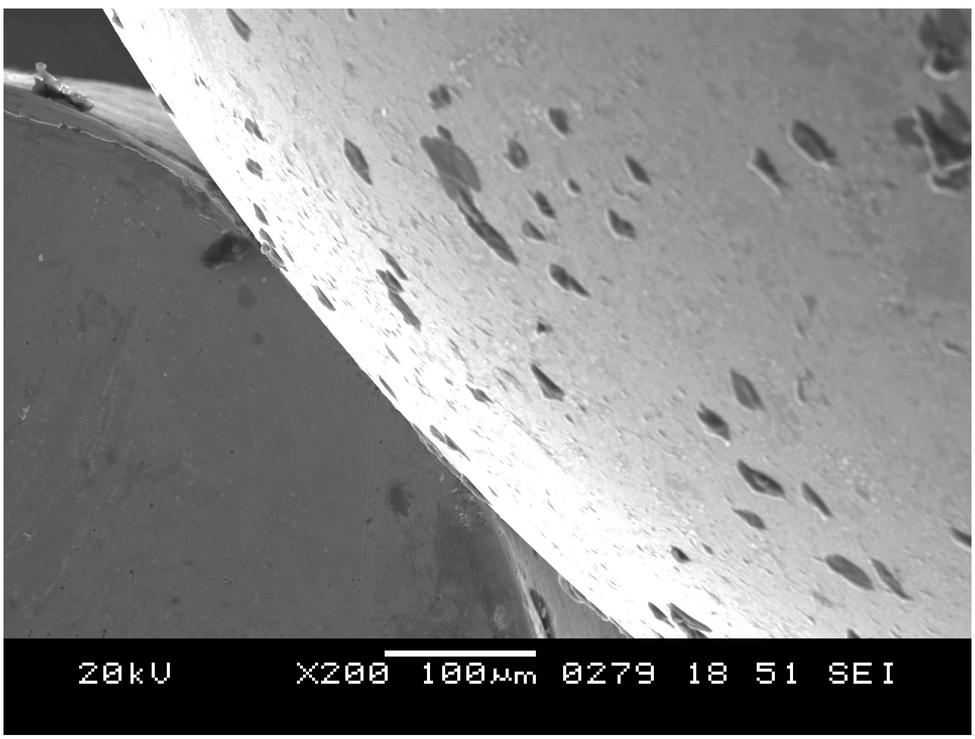

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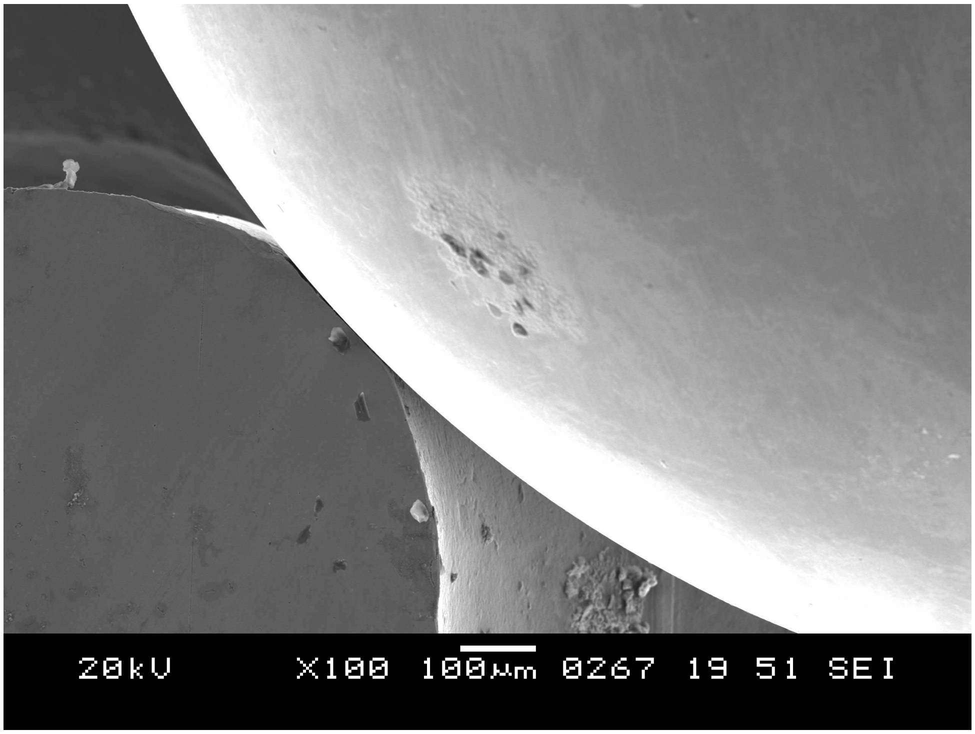

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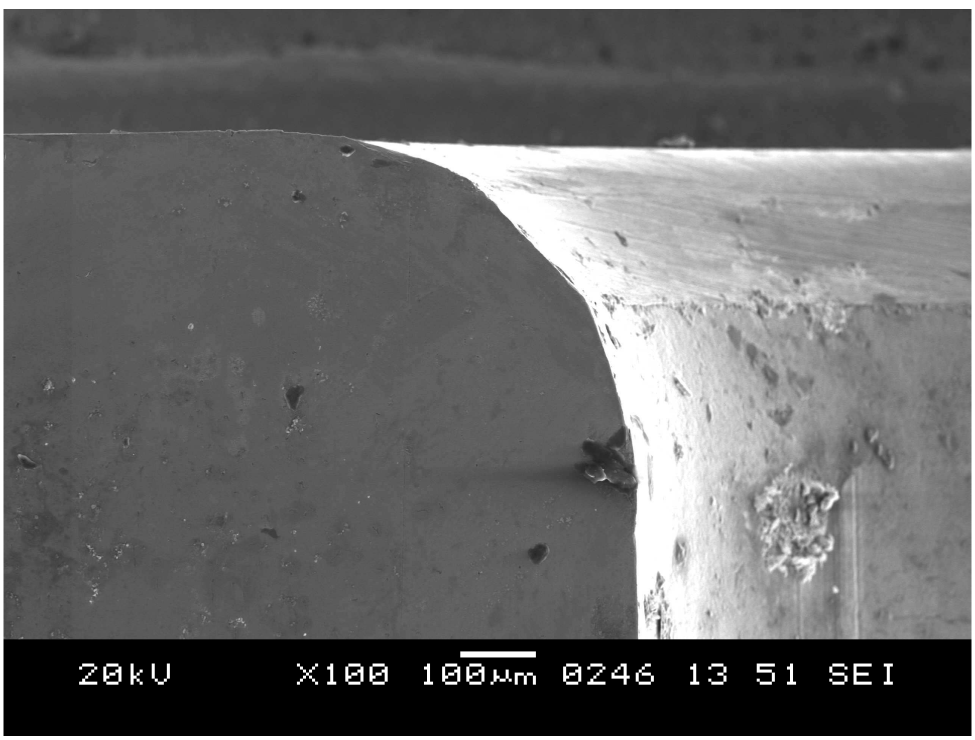

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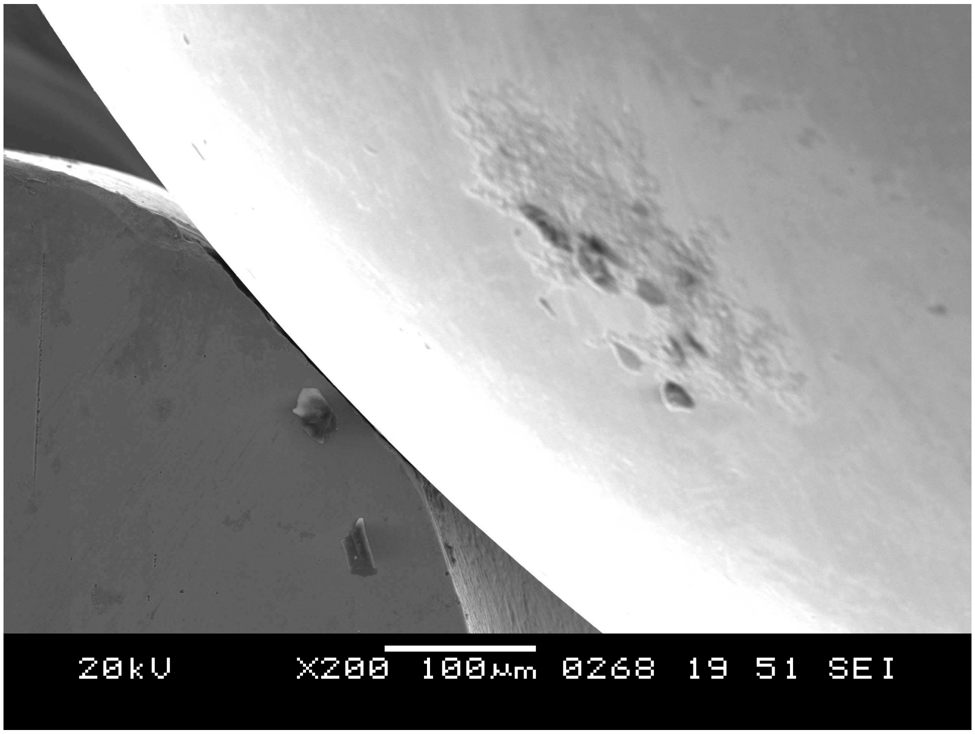

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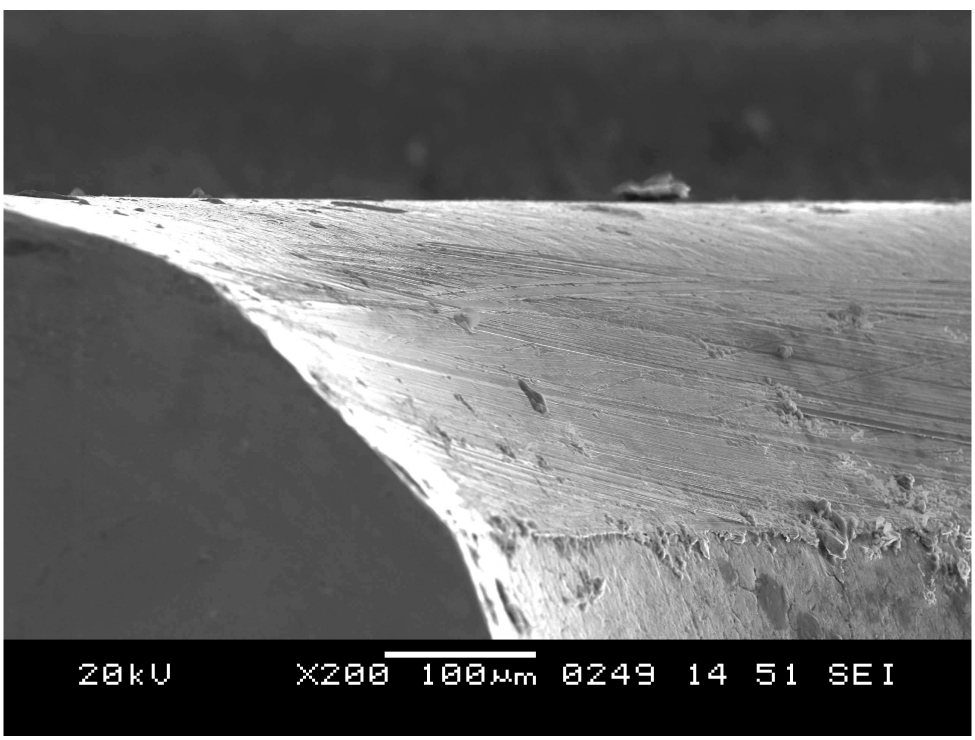

Polished w/course grit stone, last 10 of 500 parts, 200x

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