ME 597 Independent Study

Hard-Turning Lens Project Report

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Introduction

The objective this past semester has been to improve upon past efforts to machine the lens mold cavity shown below in Figure 1. The diameter of the lens and the depth of the lens make precision machining techniques paramount. MATLAB code used to define the desired surface geometry can be found in Appendix X.
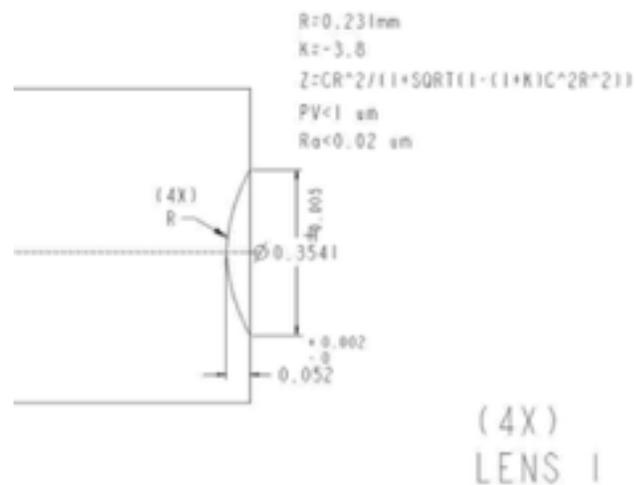

R=0.231mm
K=-3.8
Z=CR^2/(1+SQRT(1-(1+K)C^2R^2))
PV<1 um
Ra<0.02 um

(4X)
R

Ø0.3541

+0.002
-0
0.052

(4X)
LENS I

Figure 1. Lens geometry provided by FoxConn Interconnect Technologies.

The turning machine used to achieve turning geometries is shown below in Figure 2. The lever arm is rotated about the pivot about the z-axis shown. A spindle holding the work piece shown in Figure 3 translates with respect to the z-axis with sign conventions following the orientation shown in Figure 2. An overview of the tool and tool holder design will be presented. Following this, efforts to achieve the target geometry as well as practical steps are outlined.
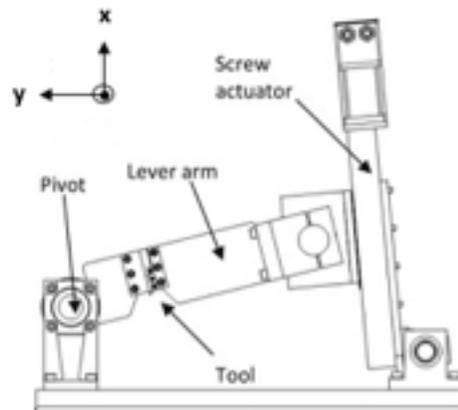
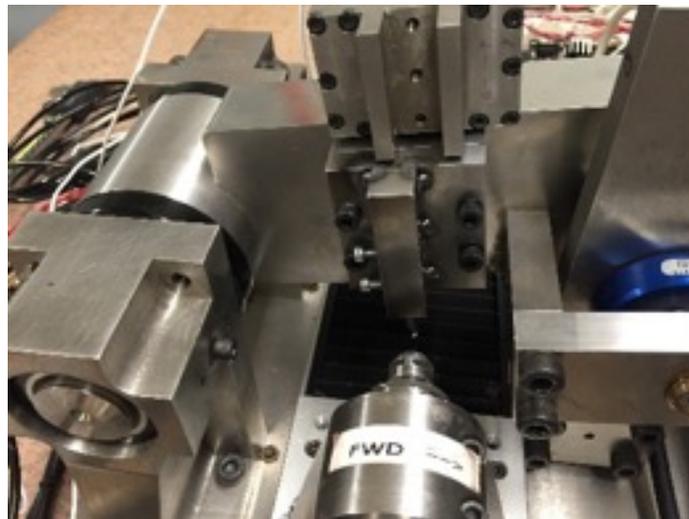**Figure 2.** Front profile schematic of turning machine [1]

Figure 3. Turning machine with spindle and tool holder shown.

Design

Design of the tool holder and tool has focused on two major objectives:

1. Cutting the targeted lens geometry specified in Figure 1.

2. Achieving a low surface roughness of less than .

The current tool holder has been designed with the idea of allowing manual horizontal adjustment along the axis of the tool arm. This is the y-axis when the lever arm is parallel to the ground; i.e. roughly at its resting position. The sliding grooves that allow the top plate of the tool holder to slide with respect to the bottom plate are shown in Figure 4. Four M5 screws along with washers secure the front plate to the back plate. Because of the holes in the front plate are much larger than the diameter of the M5 screws, the front plate can move with respect to the back plate.
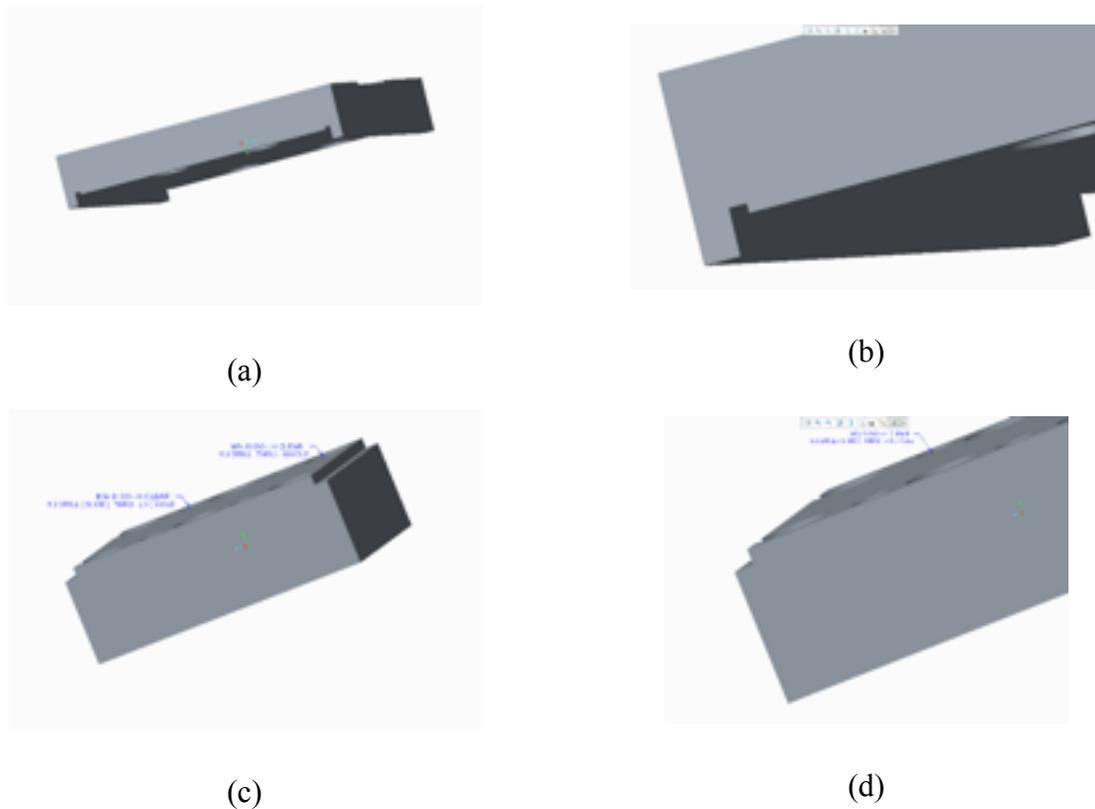

(a)

(b)

(c)

(d)

Figure 4. CAD design (a) front plate zoomed out (b) front plated zoomed in (c) back plate zoomed out (d) back plate zoomed in

Another critical feature of the tool holder design is the addition of a high resolution micrometer. Each turn on the knob represents and allows for critical fine setting of position along the lever

arm axis. If the axis of the micrometer is precisely oriented along the lever arm axis, the

adjustment is the true degree of adjustment. However, if it is at an angle, as shown in the picture,

it is less than. The angled plate and c clamp merely allows the micrometer to get aligned into

position. Note that the micrometer should not under any circumstances be used to impart force

onto a tightened front plate as this can ruin the threads of the micrometer and is beyond the

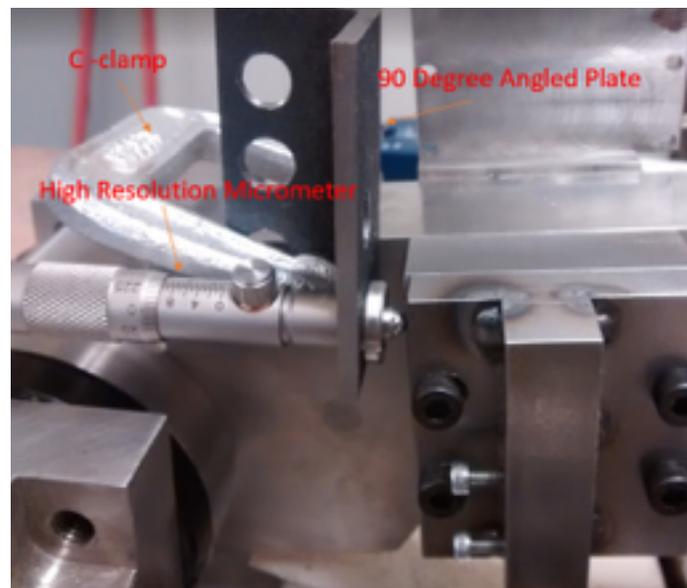intended application of the device. Hardware specifications for the micrometer are given in

Appendix X.

Figure 5. Tool holder shown with micrometer adjustment.

Consequences of even the slightest off center alignment along the lever arm are severe. The

intended cut path is labelled as the target in Figure 6. However, given an off center alignment for

example of , the tool path will travel first along leg 1. Upon reaching the actual center of the

work piece, it will then travel along leg 2. The resulting cut is shown as the black line in Figure
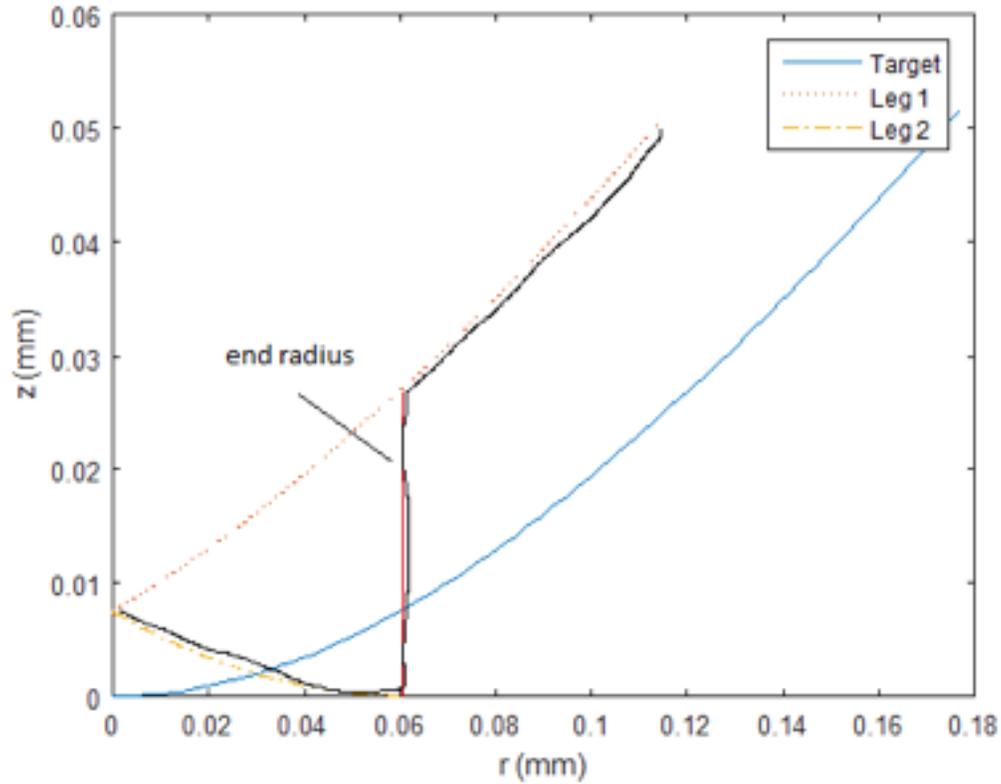
6.

Figure 6. The results of off-center alignment shown by the black line.

In fact, if a line depth scan of the surface profile is taken, one can see the influence of this off-center alignment as shown in Figure 7. An off-center alignment of roughlyis evident.
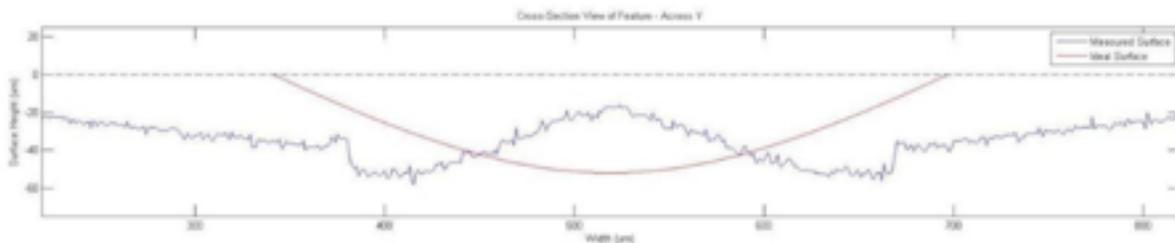

Figure 7. Cross-section view of machined lens mold with off center alignment.

One further defect evident in Figure 7 is an insufficient rake angle. The rake angle is essentially the slope of the target geometry. The slope of the target geometry is along the periphery and

decreases to at the center of the work piece. Consider the sample tool geometry shown in Figure 5 of a boring bar from J&M Diamond. The rake angle of the tool is.
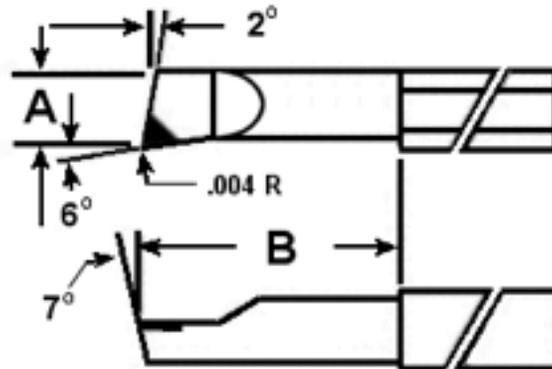

Figure 5. Tool bit geometry [3]

This means that the maximum slope of a target geometry is. We decided to acquire single point threading tool bits with a rake angle of (Appendix X). This accommodates the maximum rake angle that we want to achieve for the wok piece. In addition the AlTiN+ surface coating is highly suitable for cutting hard alloys such as titanium. Note however, that the carbide cores of these cutting tools is highly unsuited to the task of cutting at large depth of cuts (beyond) and cannot withstand high force impacts.

Results

The correct offset along the lever arm, which we will call the y offset, was achieved in several facing operations. Here we define facing as the operating where the lever arm travels through its complete range of motion about the z-axis, as defined by Figure 2, along the workpiece. If the y offset is sufficient, no part of the workpiece before the facing operating should remain. To enable differentiation between cut regions and uncut regions, we used new workpieces for each sample. Figure 7 depicts the outcomes of successive facing operations taking on the microscope

at 1x. Depending on the measured diameters of the remaining regions adjustments were made accordingly.
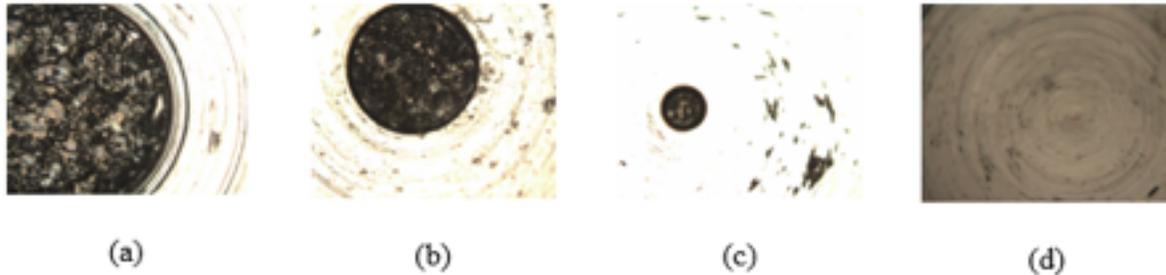

Figure 7. Successive facing operations reaching y offset.

Achieving the correct x-offset involved a similar series of operations, this time involving cutting rings. We chose to face the workpiece before each operation. The sequence of successive ring cutting operations is depicted below in Figure 8.
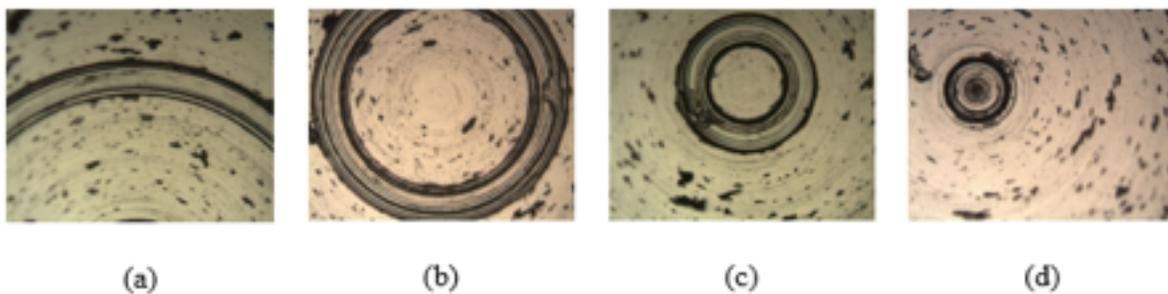

Figure 8. Successive ring cutting operations reaching z offset.

In each ring cut, a finite width is observed. This is essentially the edge radius of the tool. Thus, the smallest ring, Figure 8(d) is a circle. Ideally, the diameter of the smallest ring is equal to twice the edge radius. These ring cutting operations also allowed us to calibrate the relationship between ring diameter and machine count position.

Cutting the actual geometry of the lens cavity mold involved several iterations involving changes in machining strategy. The first attempt is shown in Figure 9. These profiles were found by using the Keyence laser confocal scanner. Successive depth cuts were taken to achieve this geometry. In addition to varying from the desired geometry in a non-linear manner, the sides of the surface are shown to exhibit undesirable fluctuations.
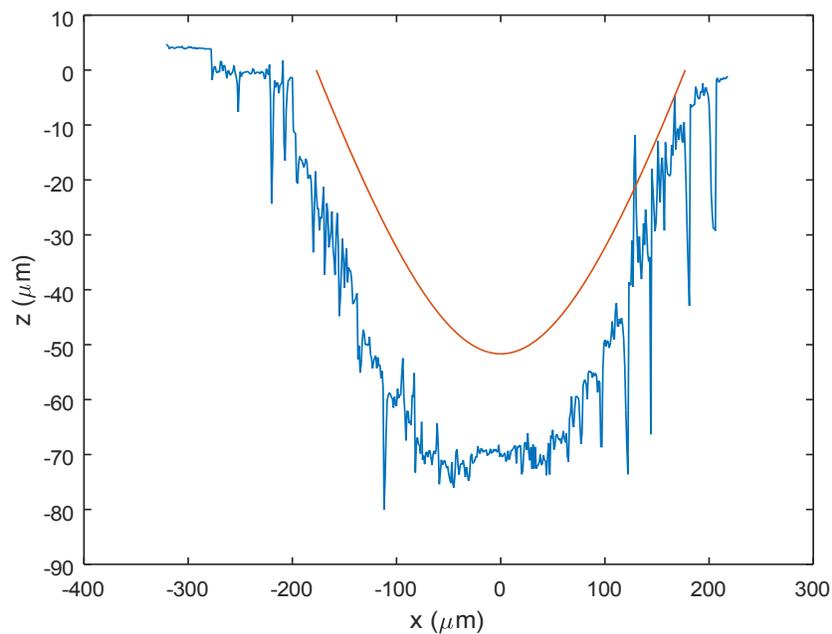

Figure 9. Lens mold cut trial one.

The second attempt to cut the lens mold is shown in Figure 10. In this trial, the lens cavity was cut as a sequence of five successively deepening cavities. Although the geometry is seen to be

closer to the desired shape, and the roughness has decreased, there is still evidence of undesirable

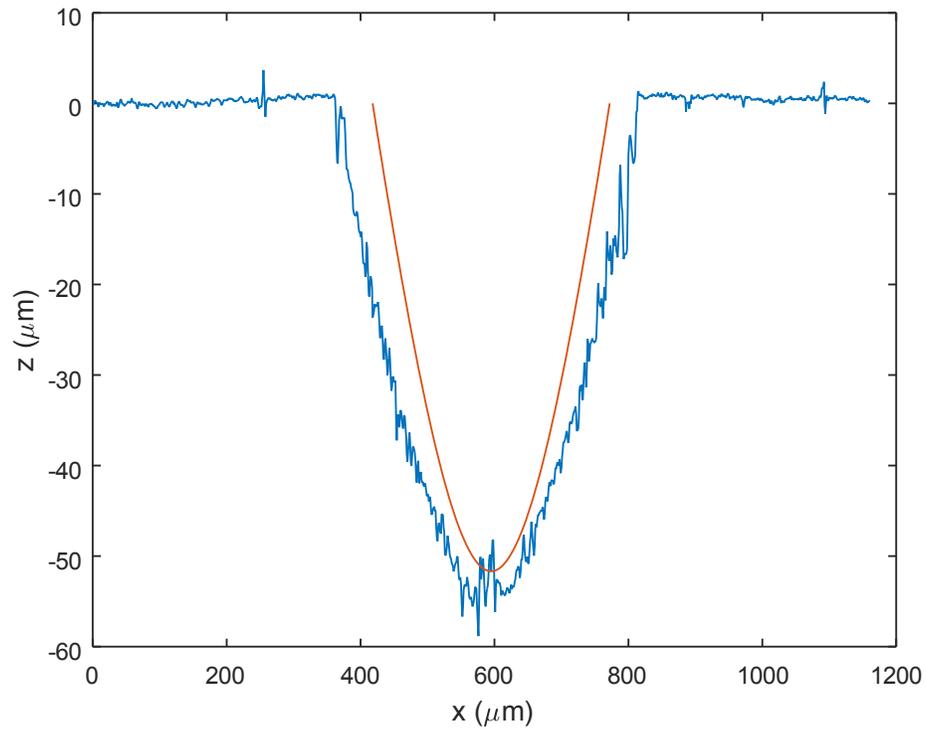instability particularly towards the bottom of the lens mold cavity.

Figure 10. Lens mold cut trial two. Depth of cut, spindle set to 3000 RPM.

Figure 11 is the 3D version of successive slices over the top of the lens mold cavity. As can be

seen, the fluctuations at the bottom are not outliers, but true formations that result from

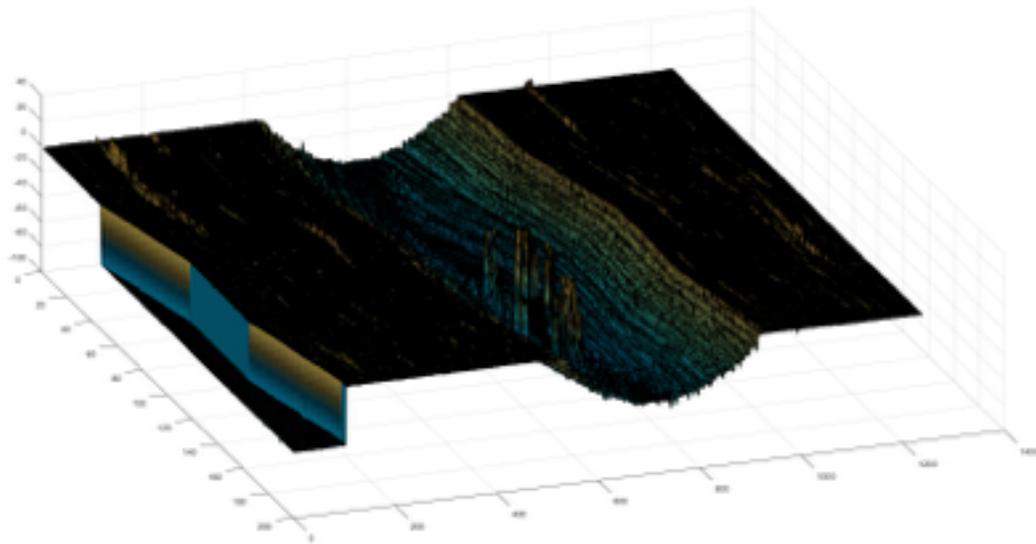instabilities in the cutting process.

Figure 11. 3D surface profile of the surface geometry at depth of cut, spindle speed of 3000

RPM.

The final profile cut of titanium is shown in Figure 11. The main difference is that the depth of

cut has been reduced to in order to reduce the surface instabilities. As shown in Figure 12, the

surface projections on the bottom of the cavity were eliminated. A further modification on the

process was to modify the actual cutting path to get closer to the true geometry
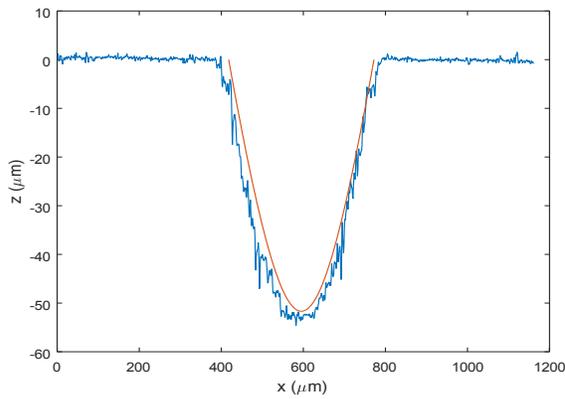
(a)
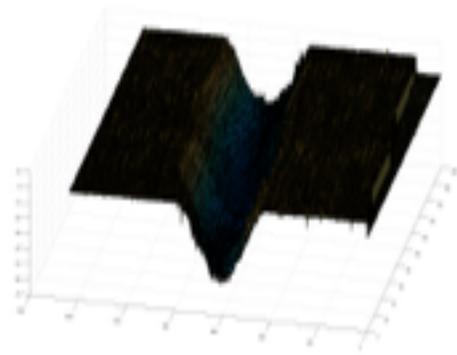
(b)

Figure 12. Lens mold cut trial three. Depth of cut , spindle set to 3000 RPM. (a) Middle line profile (b) 3D surface profile.

Diagnosis

When cutting rings such as in Figure 8, it is often easy to falsely assume the next smaller diameter ring you have cut is ever closer to the center, when in fact it is often the case that you have traveled past the center. One particularly helpful feature of turning, is that depending on the depth of cut, feed rate, and spindle speed, and face diameter position being cut, a different type of surface will materialize. This type of analysis was essential in developing intuition for surface roughness.

The first place to begin the discussion is in analyzing the edge radius of the tool itself as shown in Figure 13. The long square end of the tool is approximately The actual cutting corners that extending at 30 degrees to the horizontal, are Thus any cut that the tool makes on any face should be at least in width. Of course, the deeper a part is cut, the greater the cutting radius due

to the 30 degrees. Another aspect of analysis that can be perplexing, is the sensitivity of the microscope itself to the level of focus. When different areas of a part are varying in depth, their size as observed on the microscope will also vary depending on the microscope focus level set. This is easily observable when going between preset focus levels. But even at any given preset level, variation is also noticeable. This is why it is helpful often to define what features are most important, and making sure they are most prominent at the highest resolution level possible before choosing a lower resolution setting.
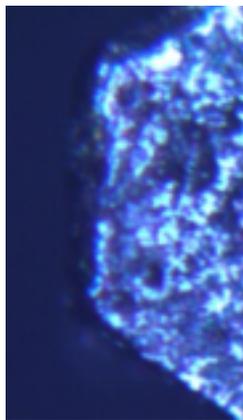

Figure 13. Edge profile of tool. The long edge is perpendicular to the lever arm.

We will review a few cases of machining to give some sense of other parameters at play. Consider the centering ring shown in Figure 14. For this cut, the tool cut into the workpiece at only one location, yet several rings are observed. For a depth of cut, rubbing is not a significant issue at the cener of the cut. The reason we see multiple rings here is because of the slow feed rate of the cut. The widest part of the ring is cut when the tool is deepest. Thus the widest part is the shallowest part. Figure 14 also shows the clear difference between dark spots resulting from burning, and dark areas resulting from rubbing. In the case of burning, the surface will take on a

charred appearance. Flecks that result from burning are not uncommon to see. In the case of rubbing, more often, dark circles will form uniformly without the presence of ashy residue. The circles towards the center are the result of rubbing. Rubbing can result from excessive dwelling, and spindle speed. Burning is usually the result of excessive depth of cut or feed rate.
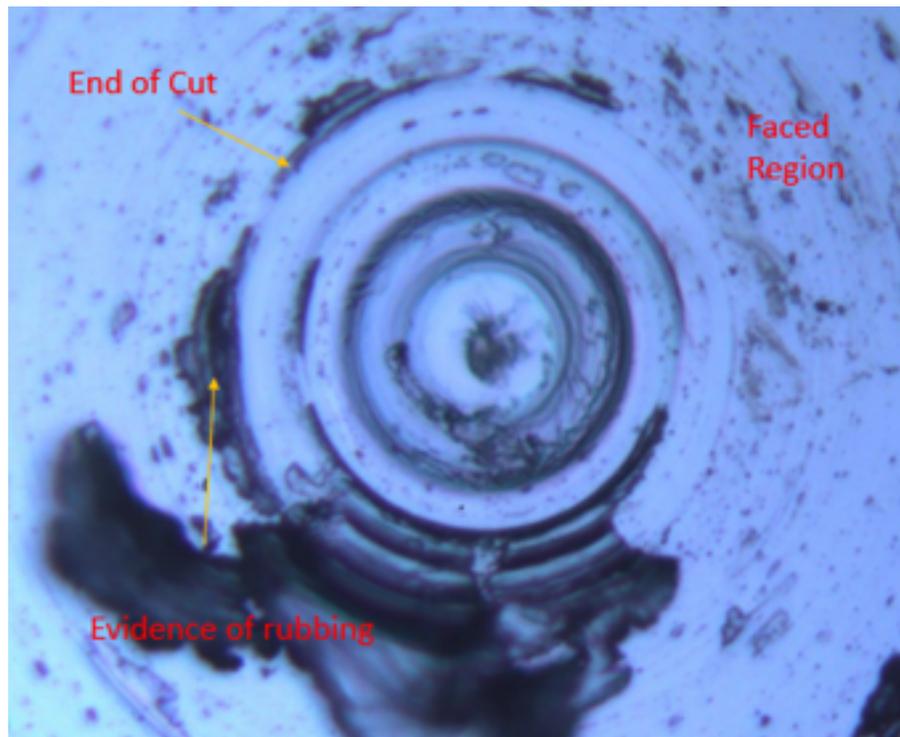

Figure 14. Center ring cut atdepth of cut at feed rate of 1 mm/min and 3000 rpm. No swell at end of ring cut. Faced region cut before ring cut.

Surface Roughness

Improving the surface roughness of the part proved to be the most challenging aspect of this project. This was mostly due to the need to recalibrate the x and z positions for the new collet. Every instance of turning had its own variations. Understanding microscope images was

critical in determining methods for better surface roughness. Our main approach for improving

surface roughness involved using bulk metallic glass (BMG) given its abilities to be liquid-like at

sub 500 K temperatures (crystallization is likely at over 500 K). A microscope image of a BMG

cut is shown in Figure 15. Two different images, of the same lens mold cut are shown in Figure

15 at different focus levels. In Figure 15 (a) rubbing on the outer edges is quite clear, as the

pattern is uniformly black, and speckles are not overtly scattered. Towards the center, some

speckling is evident along. A close of shot of Figure 15 (b) would also show what appear to be

melted pools of BMG.
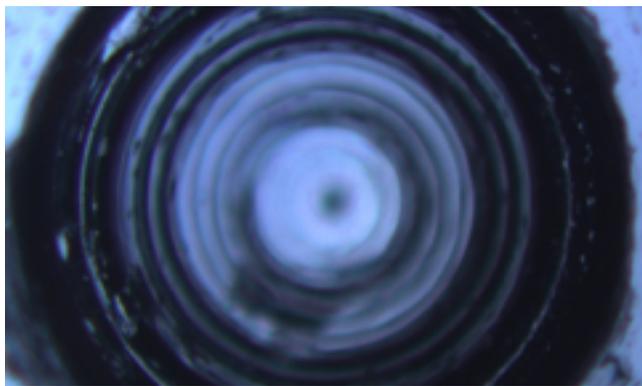
(a)   Outer geometry focus.
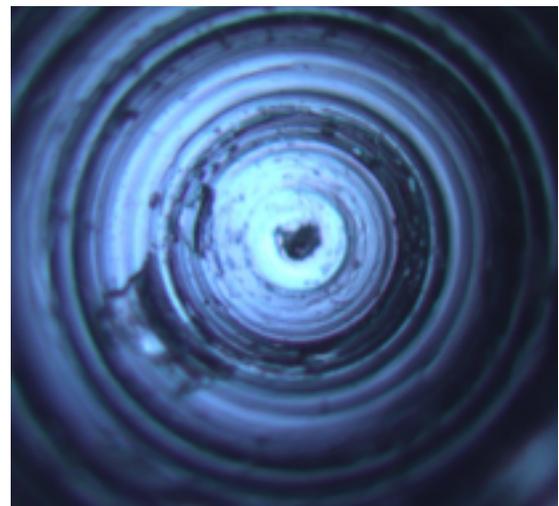
(b) Inner geometry focus.

Figure 15. First attempt at cutting geometry with BMG at 7000 RPM, feed rate of 4 mm/min, ad

depth of cut of

Noticing the varied response of our material to cutting conditions depending on cutting radius, we decided to vary feed rates from low values (approx.) on the outside of the cavity, to high values (approx.. 4.7) on the inside of the cavity. The results are shown in Figure 16.
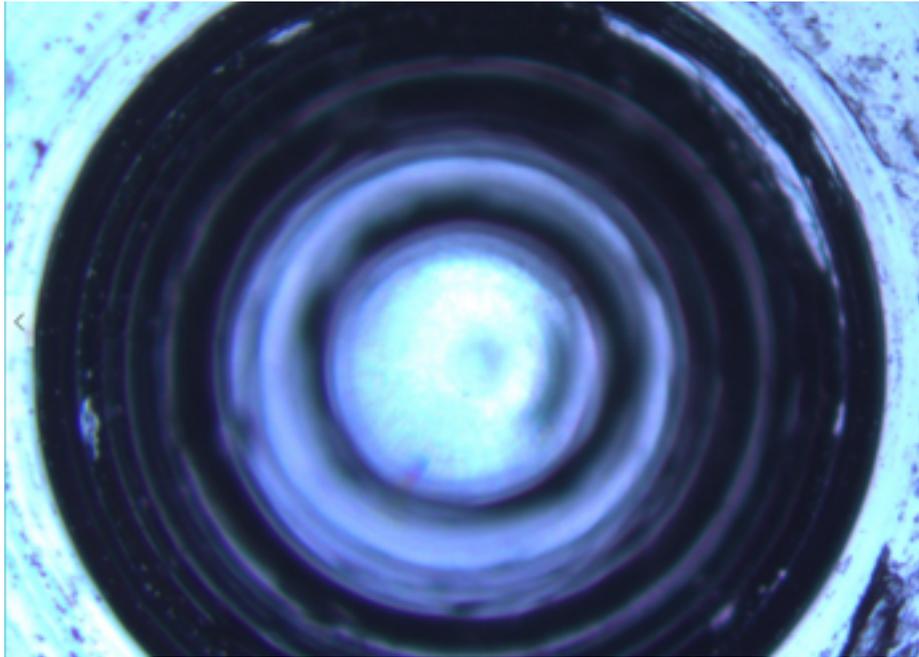

Figure 16. Second attempt at cutting BMG with prescribed geometry. BMG at 7000 RPM, feed rate varies from [3.2,4.7] mm/min, ad depth of cut of

A laser scan of the same attempt is shown in Figure 17 as a 3D surface plot and in Figure 18 as a cross section plot. As with the titanium sample, we are again able to reach similar levels of geometric conformance, however roughness persists to be an issue towards the upper portions of the surface. One encouraging feature is the smoothness along the bottom of the shape. If burning and rubbing can be avoided in the upper parts of the geometry.
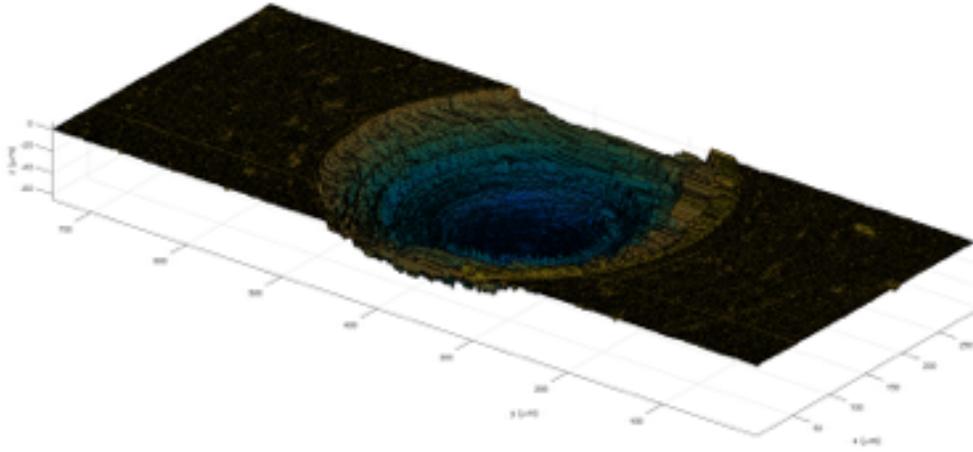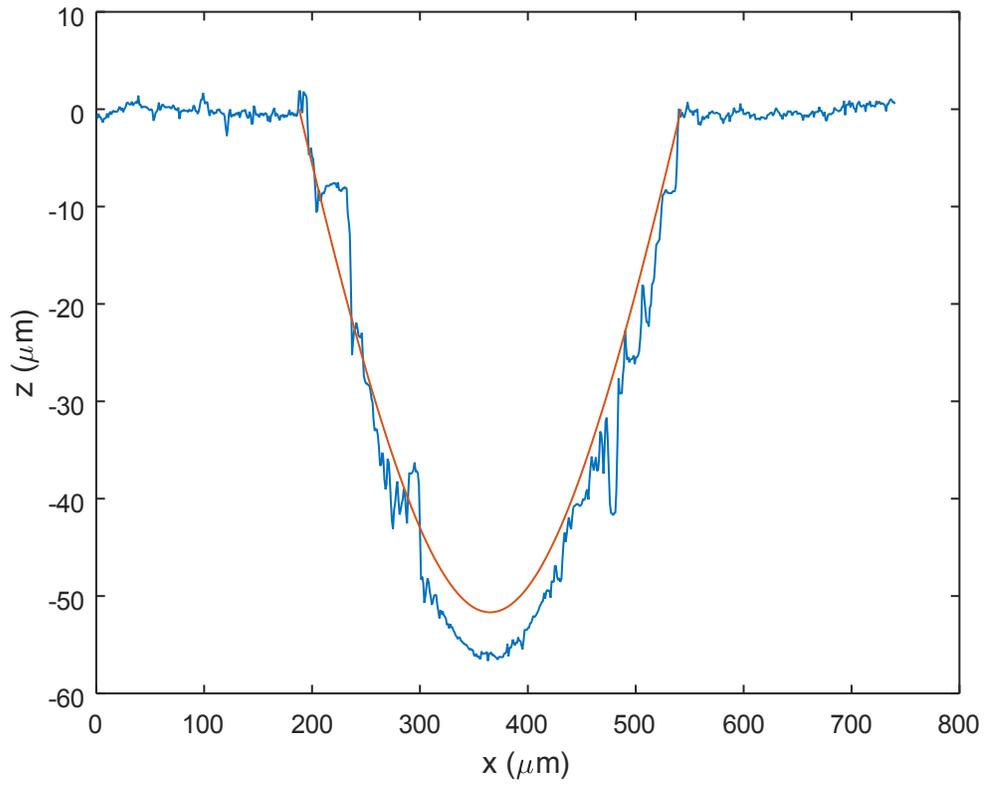
Figure 17. Laser scanned plot of BMG cut.

Figure 18. Cross section plot

Conclusions

      A combination of manual fine adjustment and microscopy yielded the desired geometry. The choice of Bulk Metallic Glass, though not immediately yielding smooth surfaces everywhere, nonetheless, showed a possible path to smoother surfaces, particularly with respect to operating conditions along the bottom surface of the part. Manual adjustments for centering both along the lever arm axis and the vertical, x-axis proved to be extremely time consuming.

      Future work in this area might look into ways to characterize the visual states of BMG towards an optimal smooth surface. Furthermore, much work could be done to incorporate sensors with feedback to streamline the centering process, though achieving satisfactory center positions was possible with adequate effort.

Appendix A: Turning Instructions

Hard Turning Machine Setup

1. The homing program must be run in order to get the turning machine ready. First make sure the tool holder and tool are not attached to the machine. There is a risk of the homing program breaking the tool bit off, so the tool and tool are best left unattached. Note: you must manually unlock (#2k) then lock motor #2 (#2j/ in command line) in the HIGH position before running the homing routine.

2. Running the homing routine.

   a. File-> Download. Select HomingProgv1.txt

   b. Close loops in motor 1 and motor 2

      command line: input #1j/, enter, input #2j/

   c. Run the homing routine by entering b101r in the command window. This will run a homing routine.

   d. Wait at least 30 seconds after the homing routine finishs. There is a long dwell (20 sec) in this program.

3. LOADING the kinematics.txt file. You MUST load the kinematics.txt file. This is technically program 24. If you fail to do this, your spindle will ram right into the tool bit and break it.

a. *10) Click File-> Download. Select the Kinematics.txt file.*

Turning

The usual sequence of events are:

1. Touch-off

2. Facing

3. Turning of geometry/part

Touch-off: (Manual)

Getting a feel for the touch off operation is a critical first step.

1. The starting position is for the lever arm for motor #2 to be in a high position such as 130,000 and the spindle, motor #1 to be at a positive position.

2. Jog motor #2 to 68,000, this is usually off center enough so you can see some flakes if contact is made, but not too on the very edge.

3. Make CERTAIN that the "incremental" check box is ticked. If not, you are facing certain disaster, and likely your tool bit getting rammed by the spindle. While doing any jogging operation, it is quite possible for you to accidentally uncheck this box by mistake. Try to be aware of this possibility so that you can avoid costly tool bit breakage.

4. Jog motor #1 in negative steps of 1000 cts until a small opening is observed.

5. Jog motor #1 in negative steps of 100 cts until even a smaller opening is observed.

6. …. 10 cts (5 microns)

7. ….. 4 cts (2 microns)

8. Look for flakes to form on the very end of the tool bit. The moment you observe one, it is sufficient to set this position for motor #1.

9. Note the motor #1 position. You will need this for subsequent work.

Facing

1. Use the motor #1 position you gathered from step 9 above. You will enter this value where it says Zero_Z in the code for the facing program (facing.txt).

2. Note, you must have properly centered the lever arm axis (manually) by this point, or you will not actually be able to face. A black post will be left in the middle if you try. This is the first step towards centering the lever arm axis coincidentally (making the black post smaller).

3. The Zero_X value is the center value based on motor #2 and the P8014 value you see on the front screen.

4. Run your facing program, with special attention paid to make sure you do not exceed depth of cut and a feed rate of 10.

   a. Note: You can use a fast feed rate of 100, provided you have carefully made sure the tool is not in contact with the work piece during maneuvers.

5. When you are finished facing, you usually have a new Zero_Z value for your geometry

   program which you should record.

Turning of Geometry

1. Turning of the geometry is remarkably similar to the process for facing, only you now

   have a new Zero_Z program. In order to make your file, the only parts you need to

   usually change from the facing program are the middle bits of G01 code. MATLAB can

   be useful for constructing such code. Here is my code:

```
1. %Cut Lens Mold Cavity
2. R=0.231;
3. c=1/R;
4. K=-3.8;
5. lim=150;
6. jlim=50;
7. r=linspace(0.3541/2,0,lim);
8. rnew=-6.52200336038368*r.^3+1.365484584370070*r.^2+1.095406226295
   230*r;
9. rnew2=-6.52200336038368*r.^3+1.365484584370070*r.^2+1.09540622629
   5230*.76*r;
10.% adjustment
11.rnew=rnew2;
12.z=c*r.^2./(1+(1-(1+K)*c^2*r.^2).^.5);
13.z=abs(z-max(z));
14.plot(rnew,z,rnew2,z);
15.xcenter=11.57317;
16.format long e
17.offset=0.4126464;
18.%%
19.diary gcode.txt
20.diary on
21.% Go to center position
22.for j=1:jlim
23.    disp('G01 X(Zero_X) Z(Zero_Z+1) F10');
24.    for i=1:lim
25.        disp(strcat('G01 X(Zero_X+',num2str(rnew(i),'%15.8f'),')
   Z(Zero_Z-',num2str((j/jlim)*z(i),'%15.4f'),') F10'));
26.    end
27.    disp('DWELL 1000');
28.end
29.diary off
```

Appendix B: Sample Code

Top code common to all sections

; definitions

```
#DEFINE Zero_X        P1001
#DEFINE Zero_Z        P1002
#DEFINE Cur_Pass  P1003
#DEFINE Max_Pass  P1004
#DEFINE i         P1005
#DEFINE R         P1006
#DEFINE C         P1007
#DEFINE K         P1008
#DEFINE width         P1009
#DEFINE D         P1010
```

; intializations
; use speed of 3000 RPM

```
Zero_Z  = -11.154; define with touchoff operation (CRITICAL!)
Zero_X  = 11.29464233; define with centering operation (CRITICAL!)
Cur_Pass    = 1
Max_Pass    = 5
i           = 0
```

```
R = 0.231; mm
C = 1/R; 1/mm
K = -3.8
```

width = 0.052; mm

D = 0.3541/2; mm

; … insert your G01 code here

; move clear of the cut

G01 Z(Zero_Z + 5) F100

G01 X(Zero_X + 5) F100

CLOSE

Appendix C: Manuals

High Resolution Micrometer Specifications found at http://search.newport.com/?

x2=sku&q2=HR-13

Made in USA - Single Point Threading Tools Thread Type: Internal Material: Solid Carbide

MSC Part #: 67878272   ☆☆☆☆☆   Write the first review

| Price: | $64.10 ea. |
| Qty: | 1 |

☑ **Register** today and receive up to **25%** off your first order!

Item Notes   **$64.10**

Add to Cart ▾

Single Point Threading Tool Specifications found at

http://www.mscdirect.com/product/details/67878272
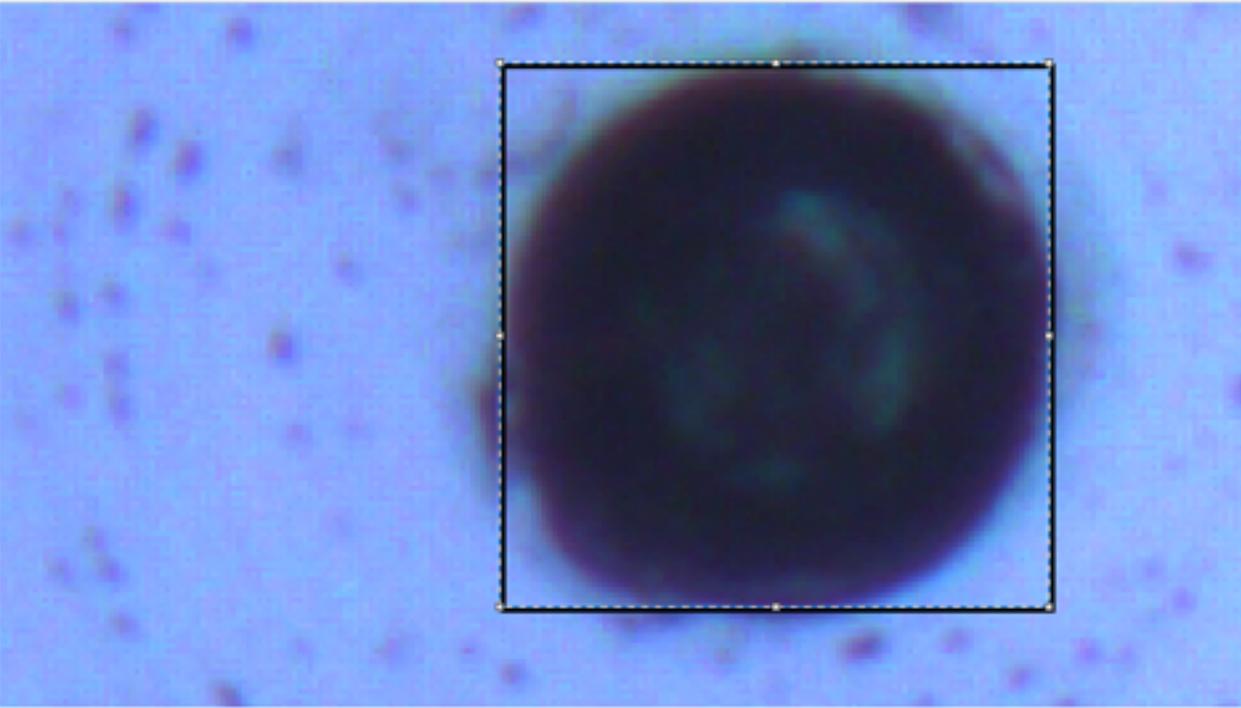
Appendix D: Using the Microscope

Using the microscope usually involves some combination of MS Paint as shown below and some finesse which you just have to learn. Learning to diagnose what your microscope images are telling you is ESSENTIAL.