Engineered Defect SNL Targets

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April 23-26

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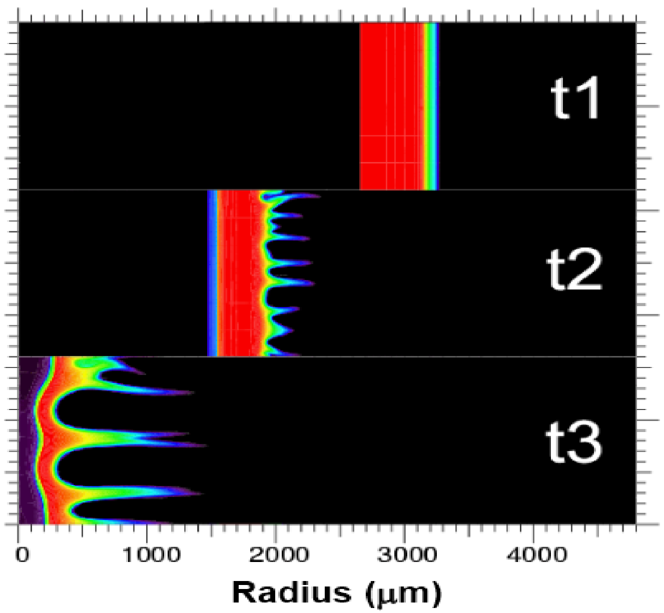
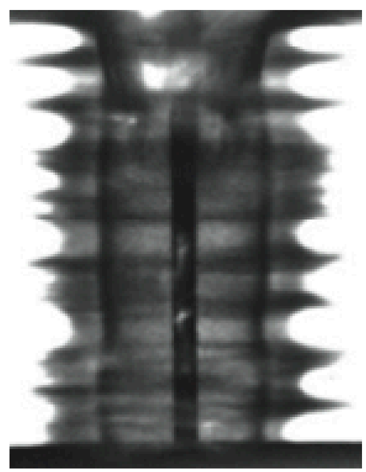
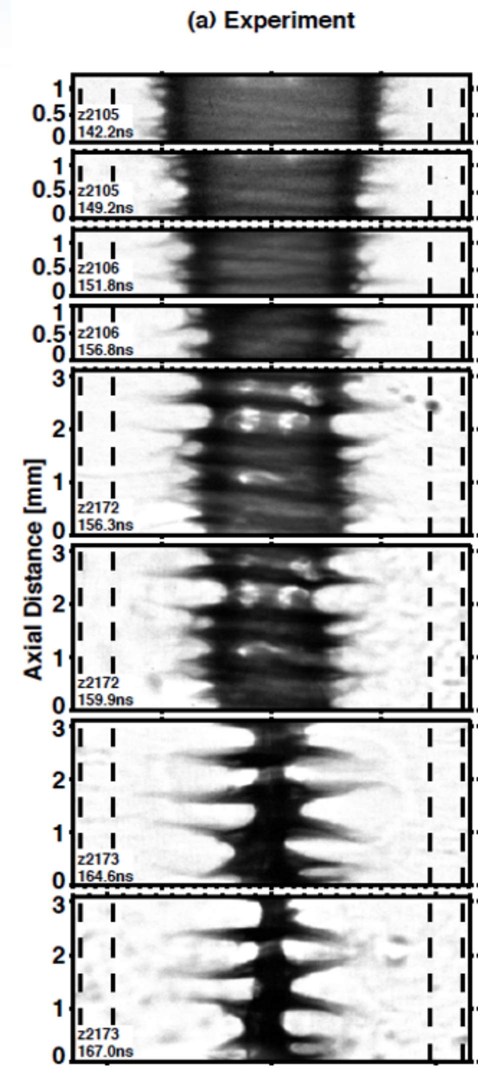
Fusion In Magnetically-Driven Z Pinches Is Reduced By The Magneto-Rayleigh Taylor (MRT) Instability

Since the 1950s, much z-pinch research has been rooted in understanding and mitigating MHD instabilities.





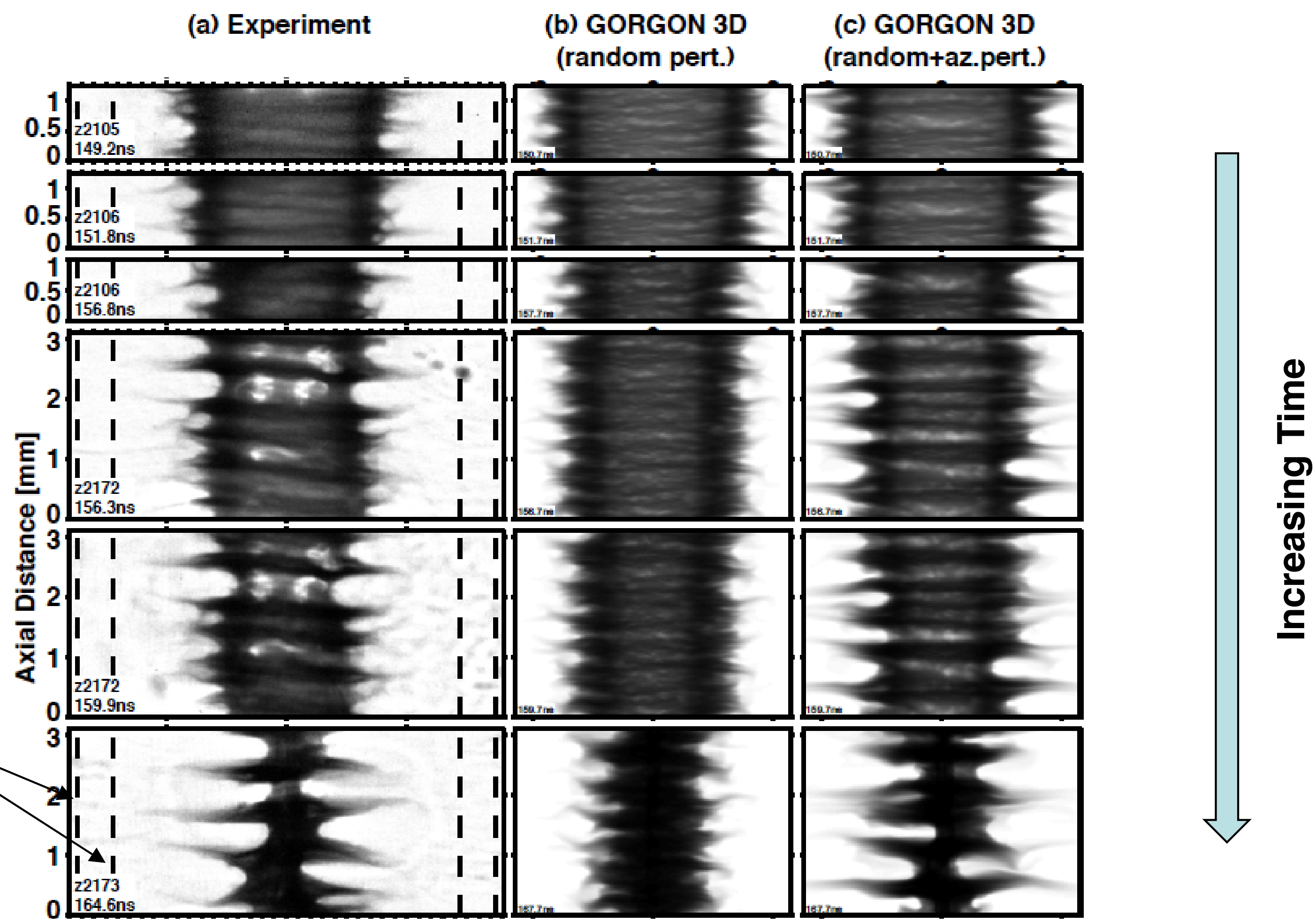
Imploding Be liner on Z



R.D. McBride *et al.*, PRL 109, 135004 (2012)

Simulations Of Imploding Liners Match Experiment Only When An Artificial Azimuthal Seed Perturbation Is Added

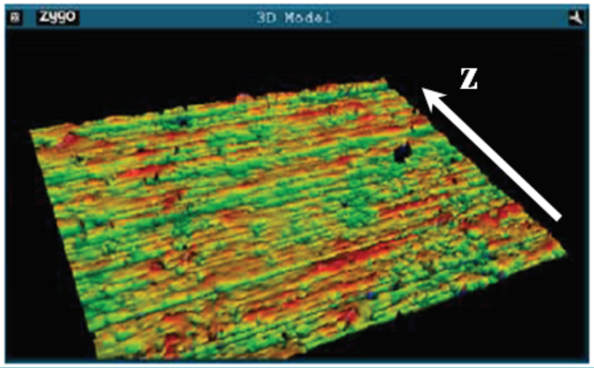
Original location of outer and inner walls of liner

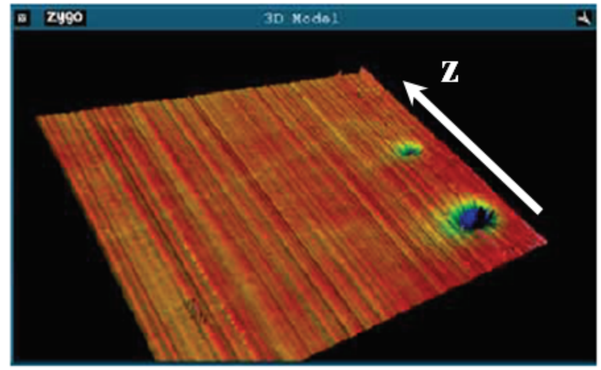


R.D. McBride *et al.*, PRL 109, 135004 (2012)

What seeds the unexpected large amplitude and azimuthally symmetric MRT?

A 2013 Z-Campaign Evaluated Turning vs. Axial Broaching To Determine Effect Of Initial Surface Texture

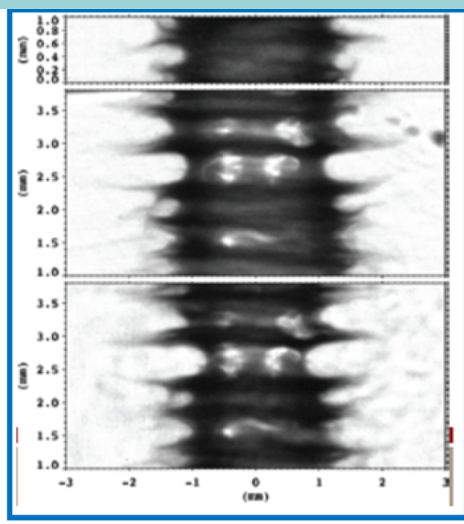


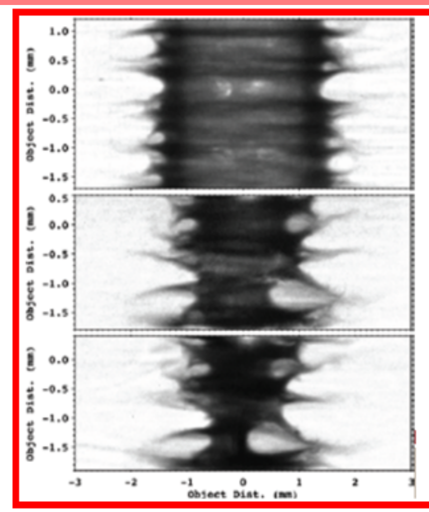


Turned OD Surface: 50nm RMS

Broached OD Surface: 50nm RMS

Experimentally observed MRT development resembles lathe grooves, so machined texture was initially suspected as the seed.



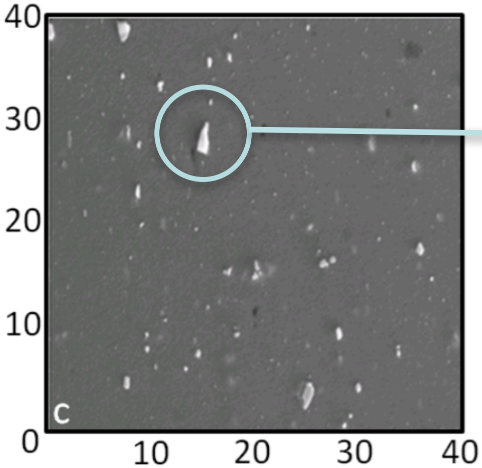


D.B. Sinars *et al.*, Phys. Rev. Lett. 105, 185001 (2010)

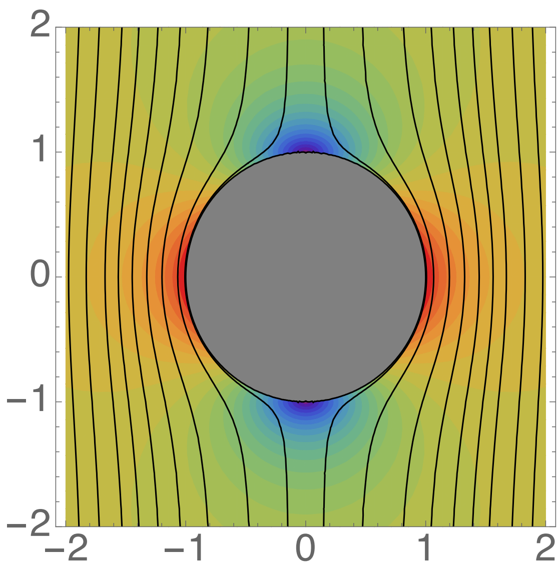
Modified Fabrication Process: Changing the orientation of the machining grooves from azimuthal (lathe) to axial (broaching) had little impact on MRT development.
CONCLUSION: INITIAL OUTER SURFACE TEXTURE IS NOT THE MRT SEED

Could The Electrothermal Instability (ETI) Provide The Seed For the MRT Instability?

SEM characterization of Al 6061 rod surface



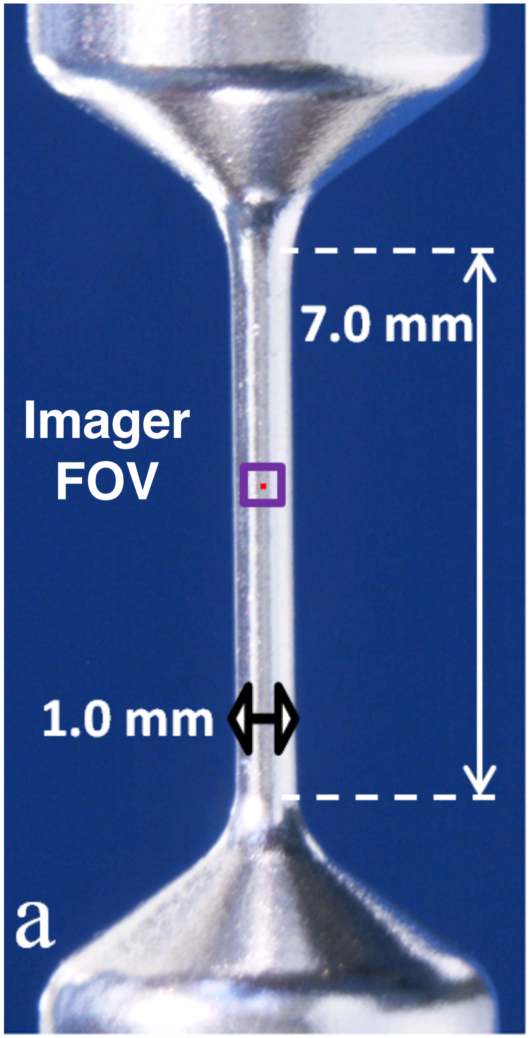
5 μm inclusions of lower conductivity (Si, Mg)



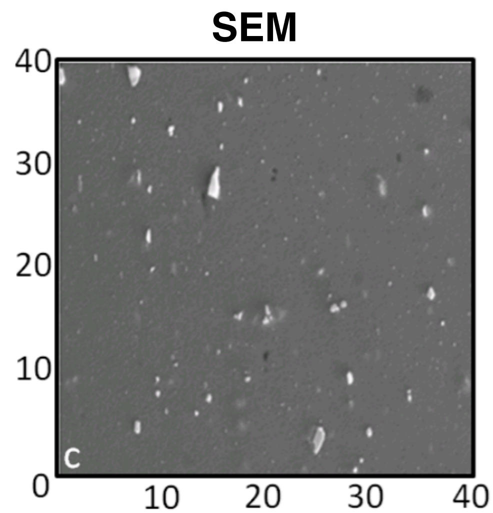
<u>ETI Theory</u>:

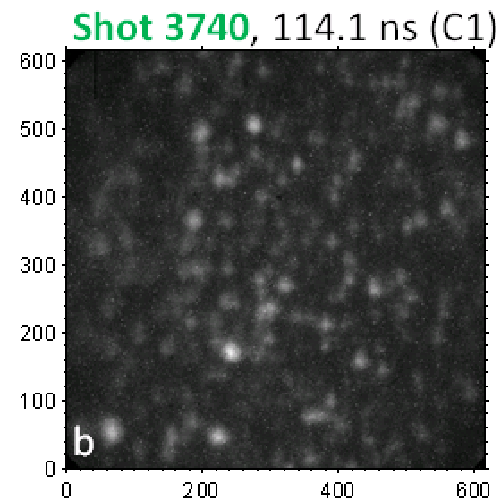
1. **Near inclusions, current is amplified, causing hot spots.**
2. **Conductivity decreases with increasing T, so a feedback loop results, causing runaway hot spots.**

Experiments At U of Nevada, Reno Zebra Facility Support The Theory That Surface Defects Cause Hot Spots



Al 6061:
Diamond Turned & Electropolished



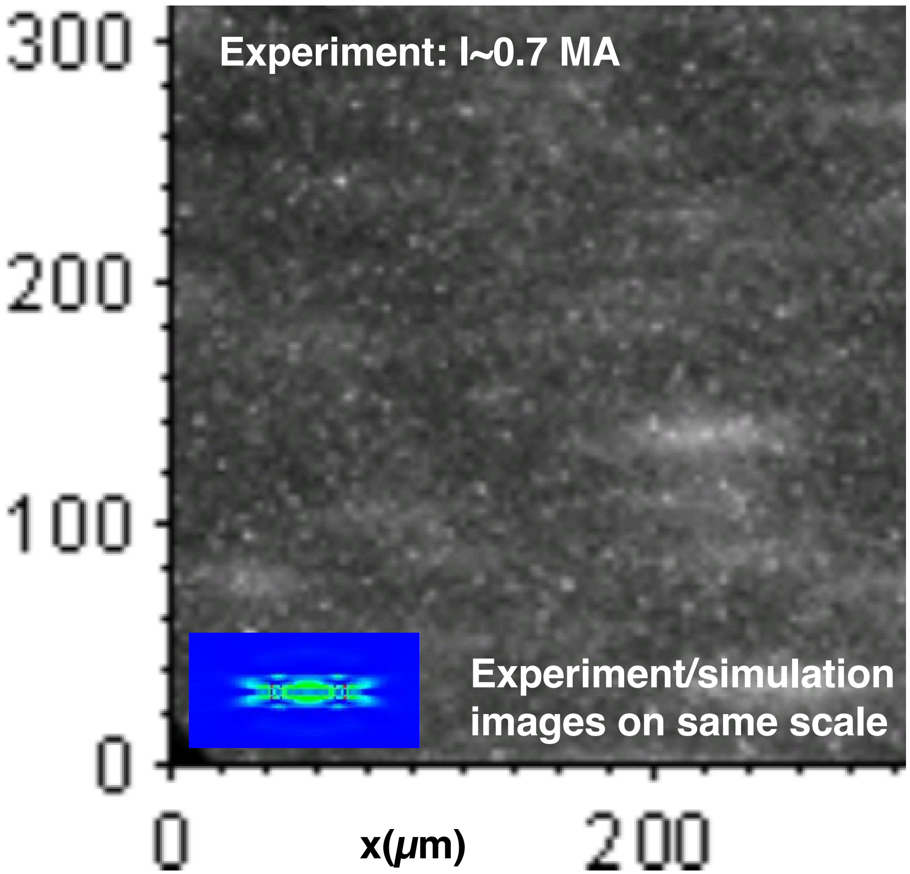


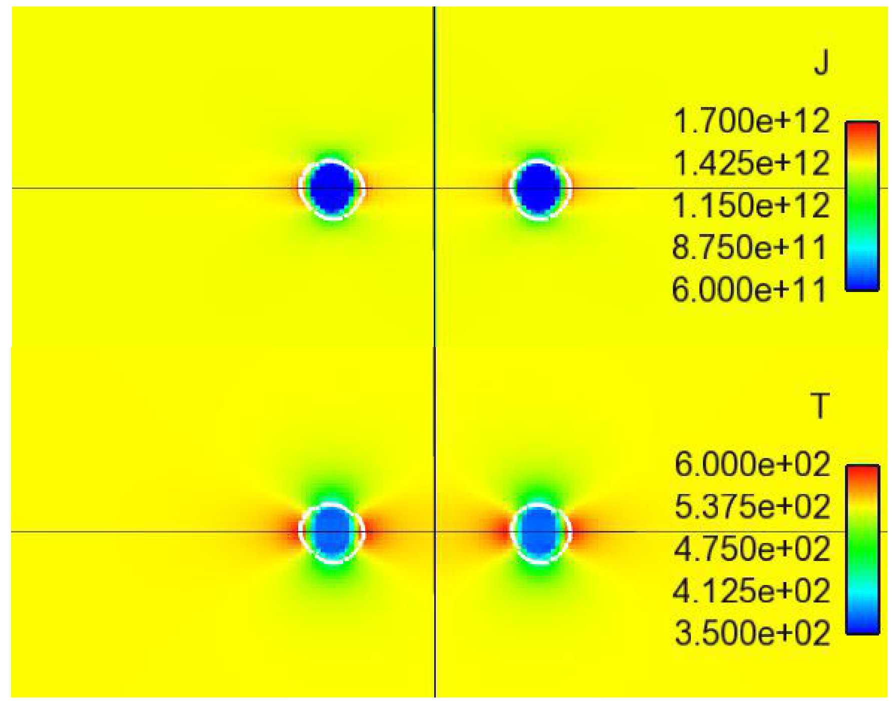
Axes Units: μm

The number of emission (hot) spots is comparable to the number of surface inclusions.

T.J. Awe *et al.*, IEEE Trans. Plasma Sci. 45, 584 (2017)

Experiments At Zebra Also Agree with Computer Simulations Predicting Azimuthal Merging Of Hot Spots

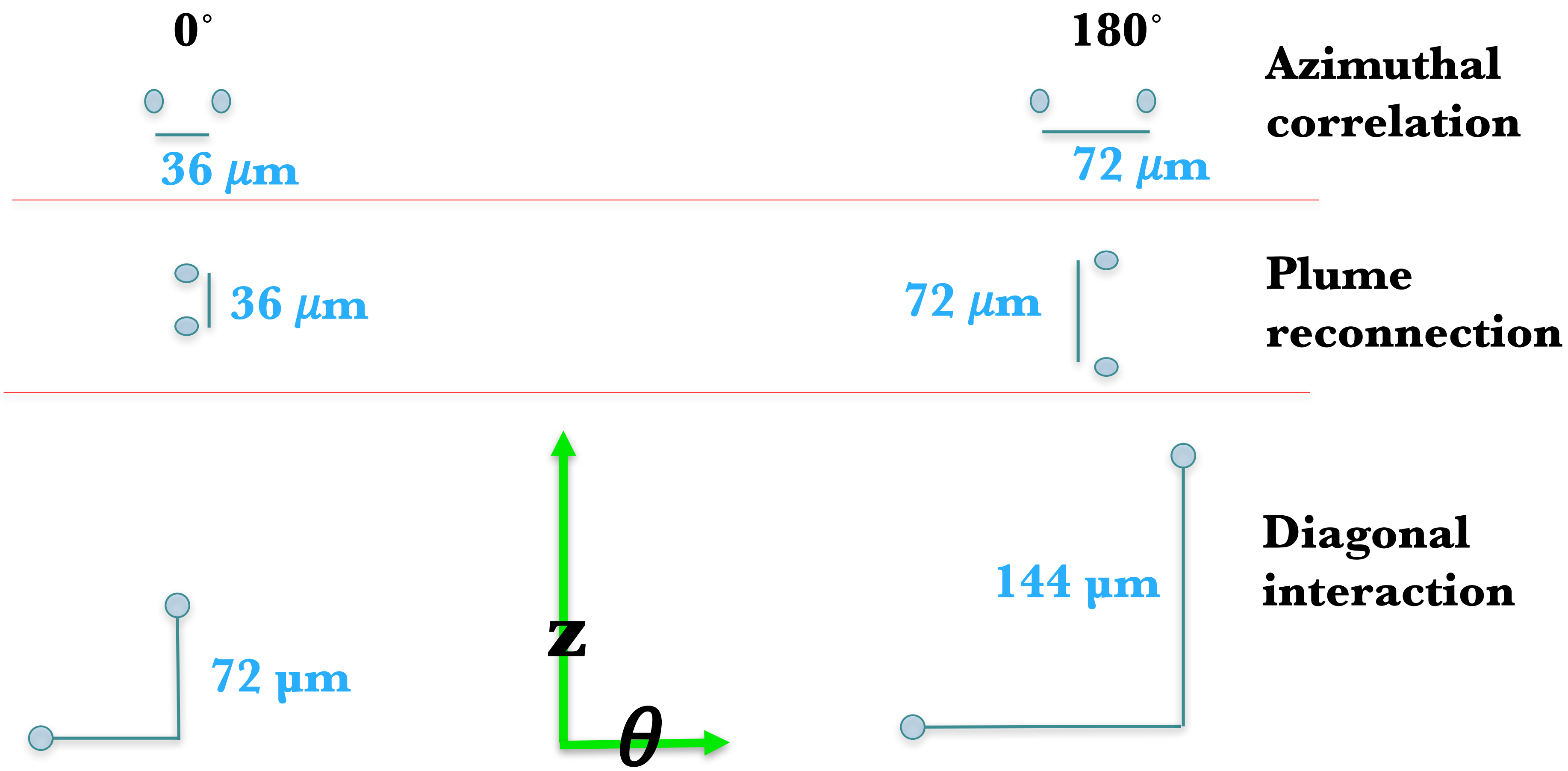




A hotter strip is developing between the inclusions.

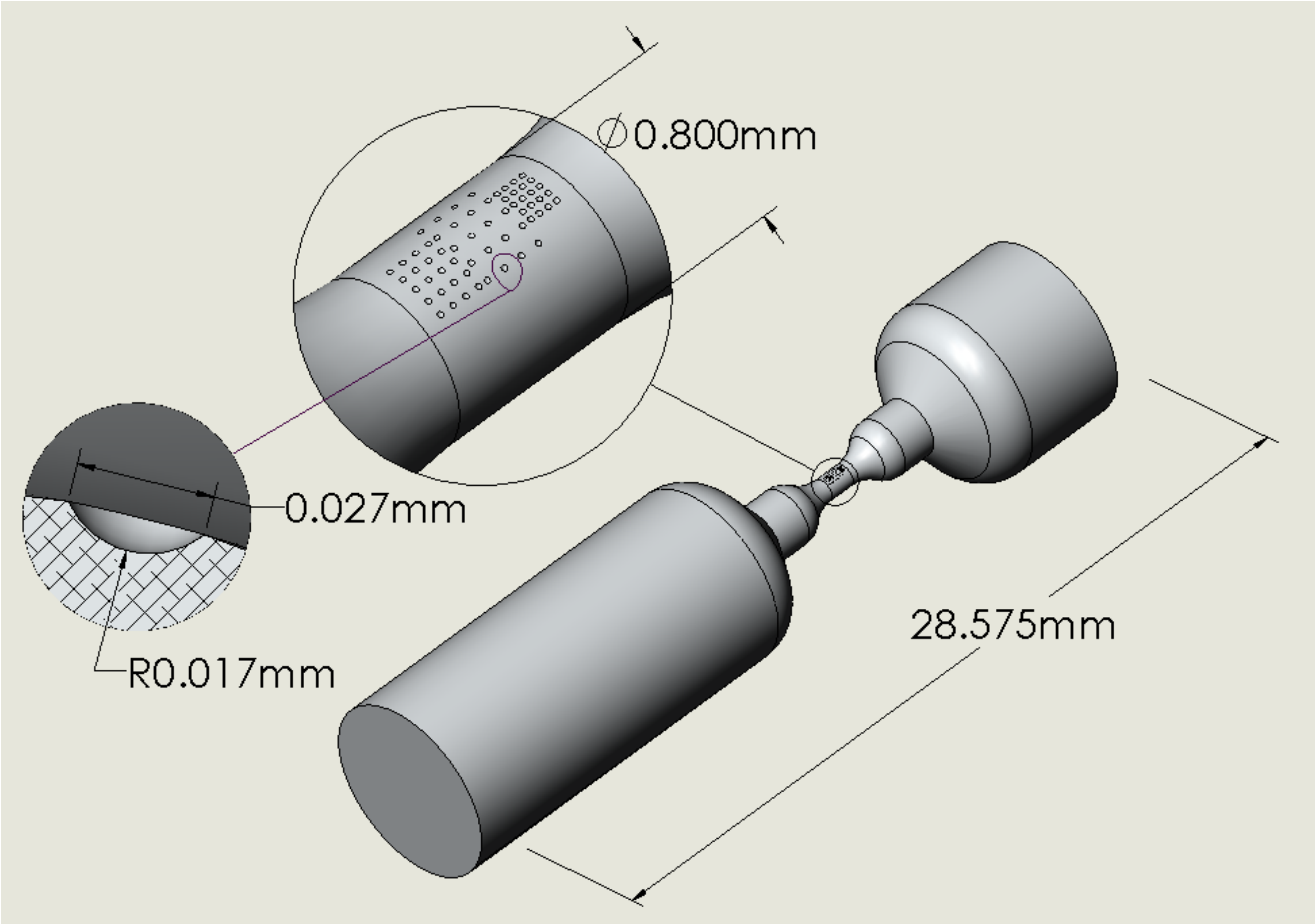
Simulation Graphics Coutesy of Edmund P. Yu
Sandia National Laboratories (2019)

Targets For SNL Mykonos Facility Will Have "Engineered Defects" In Various Patterns To Probe ETI Evolution

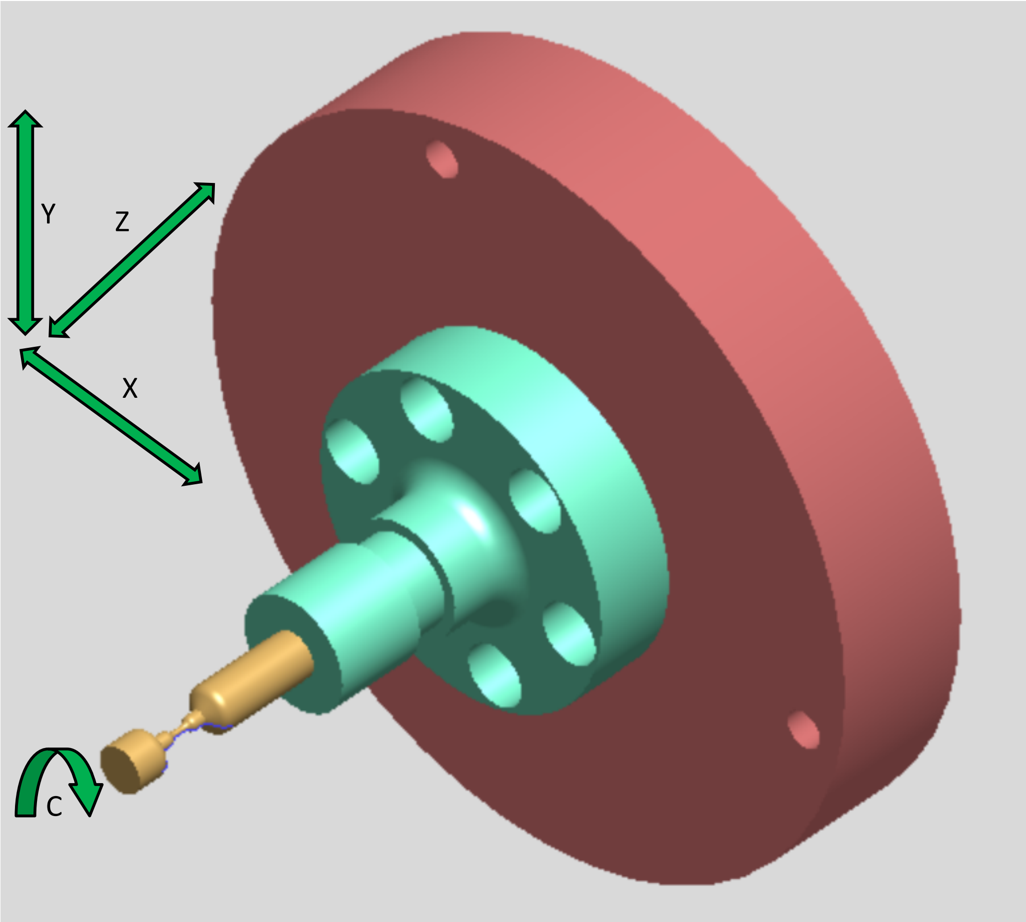


- Targets will use pits because they exhibit qualitatively similar behavior to inclusions and are easier to machine.
- Pit size doesn't significantly affect physics, so they will be larger than common inclusions for ease of machining and diagnosis.

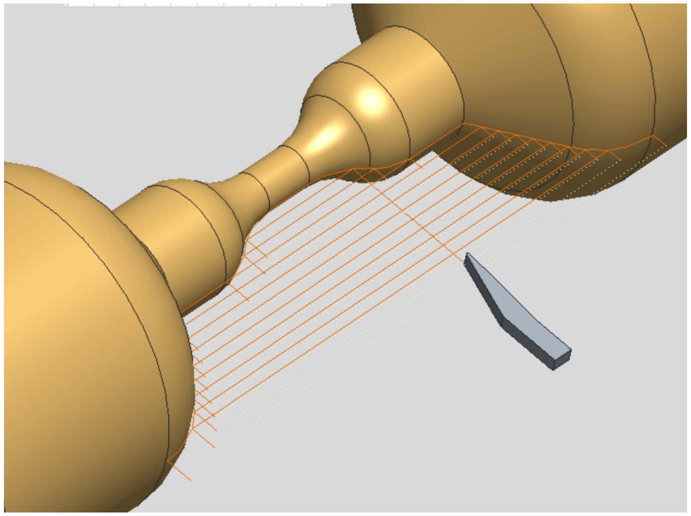
Target With Engineered Defects



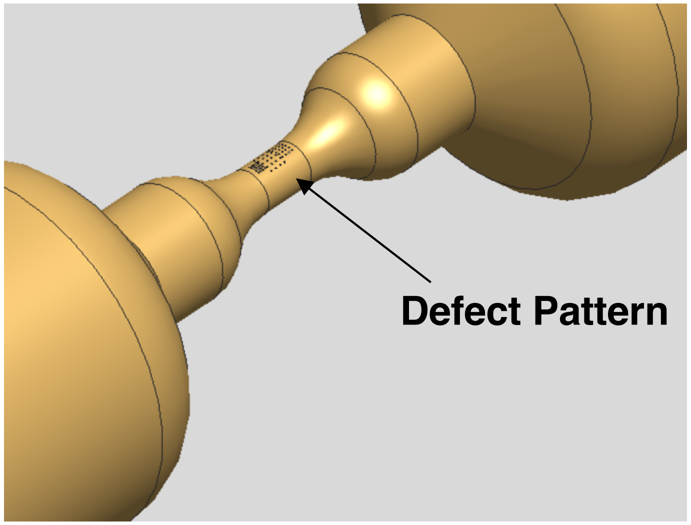
All Machining Is Completed In One Setup



φ¼” x 1-1/8”, 99.999% Pure Aluminum Rod Mounted In Collet In Precitech FF-700 Lathe (4/5-Axis)



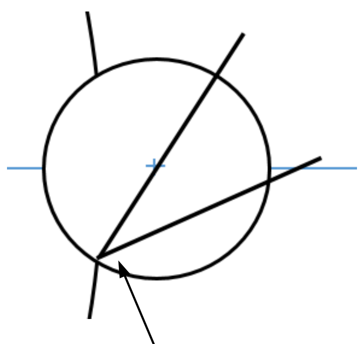
#1 - Turn Profile In Lathe Mode



#2 - Cut Defects in C-Axis (STS) Mode

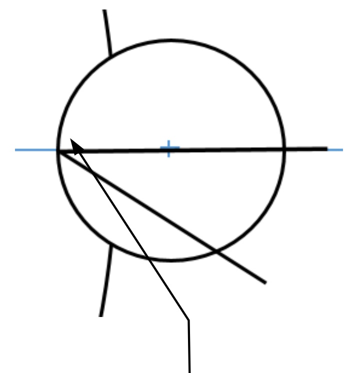
Defect Machining Strategy #1: Tool Rotates Around Defect Center

1



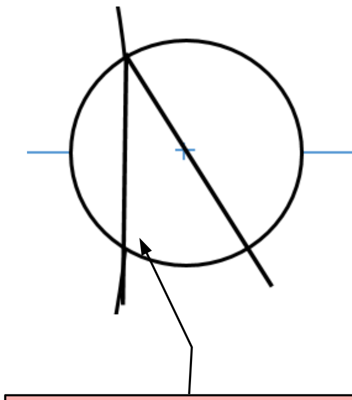
Little Relief Required At Start of Cut

2



Constant 0 Degree Rake Throughout Cut

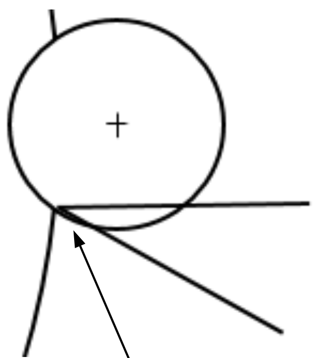
3



Impossible to make diamond with required relief for end of cut. Too fragile.

Defect Machining Strategy #2: No Tool Rotation

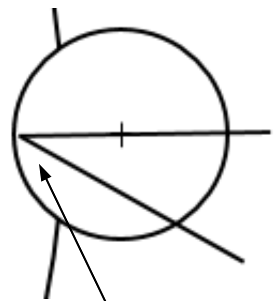
1



Impossible to make diamond with required relief for start of cut.

2

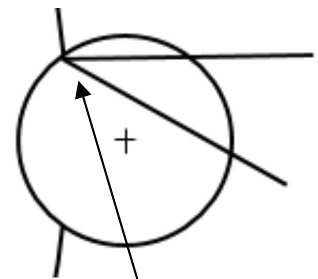
Drive Tool Left & Up.



Good Rake and Relief At Middle Of Cut

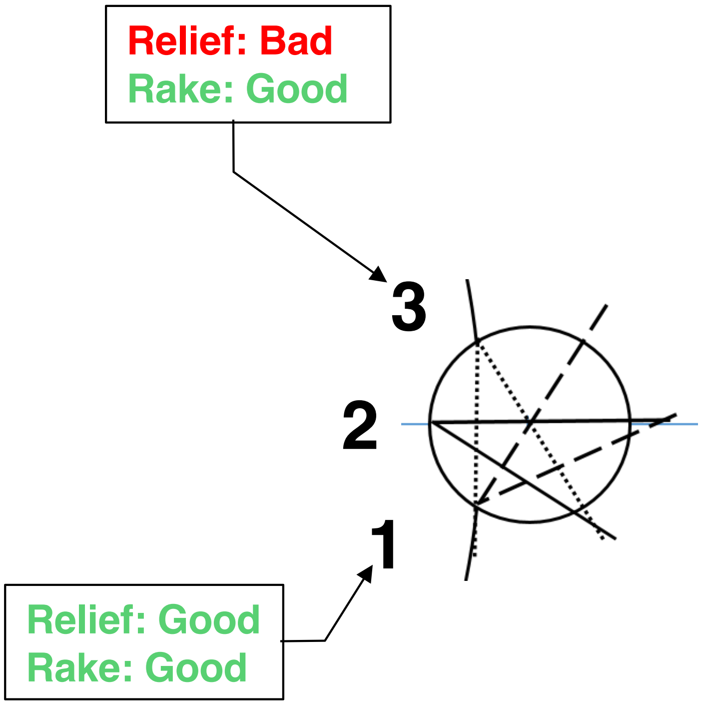
3

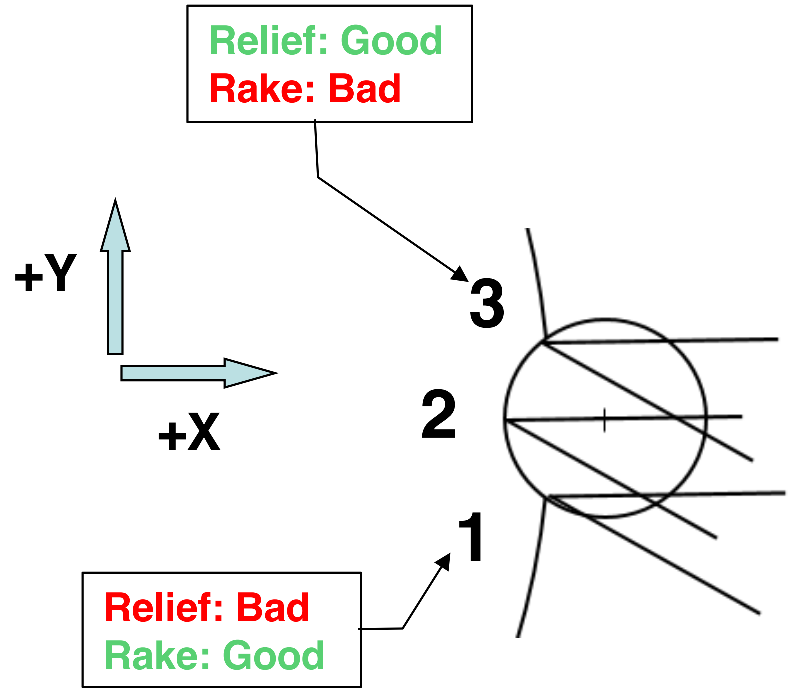
Drive Tool Right & Up



Too Much Negative Rake At End Of Cut

These Strategies Form Two Limiting Cases
How To Choose Optimum Rotation Offset?

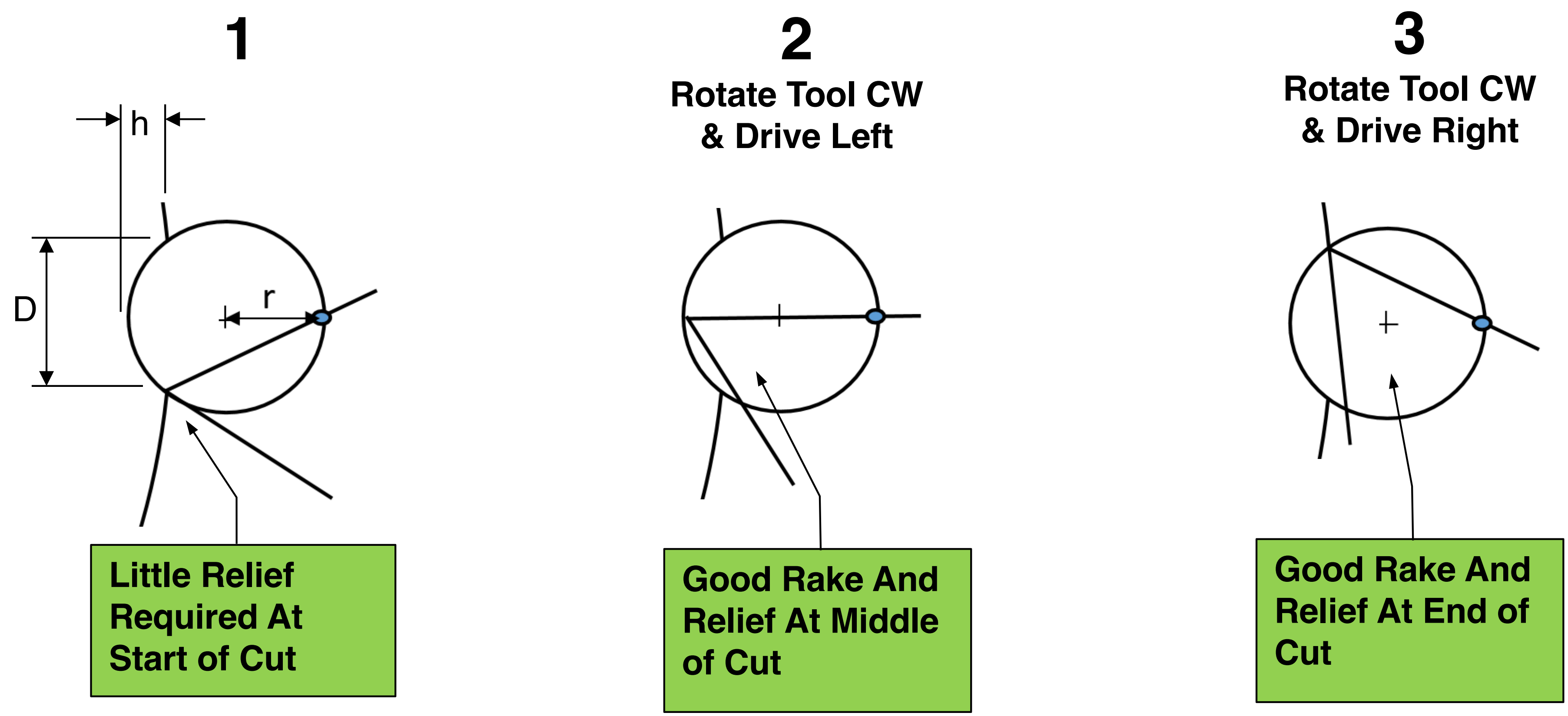




Strategy 1:
Tool Rotates Around Defect Center
(i.e., "Rotation Offset" = 0

Strategy 2:
No Tool Rotation
(i.e., "Rotation Offset" = ∞)

Plugging Governing Equations Into Excel Reveals Satisfactory Defect Geometry and Rotation Offset

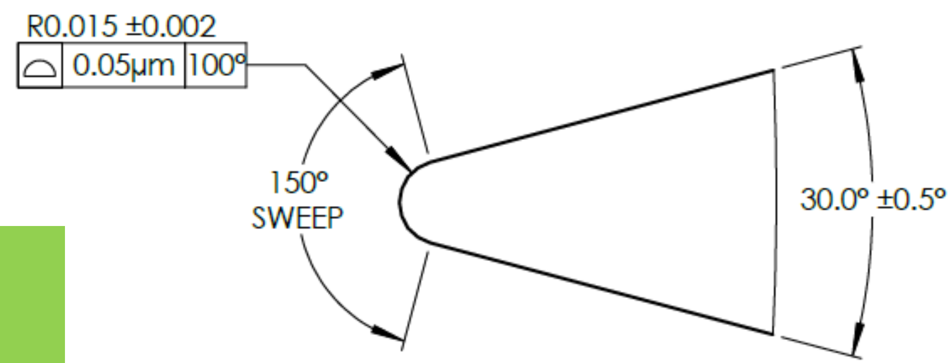


If:
- D/h = 4
- Rotation Offset = r

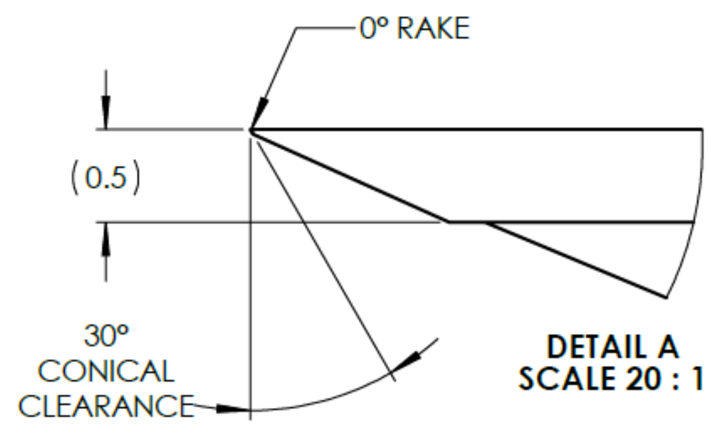
Then:
- Minimum Tool Relief = 26.6 Degrees Throughout Cut

Single Crystal Diamond Tool For Cutting Divots

- **30 degrees diamond relief is greater than minimum requirement of 26.6, resulting in 3.4 degrees clearance.**
- **30 degree relief angle is near the limit of what is possible to produce on a single crystal diamond.**

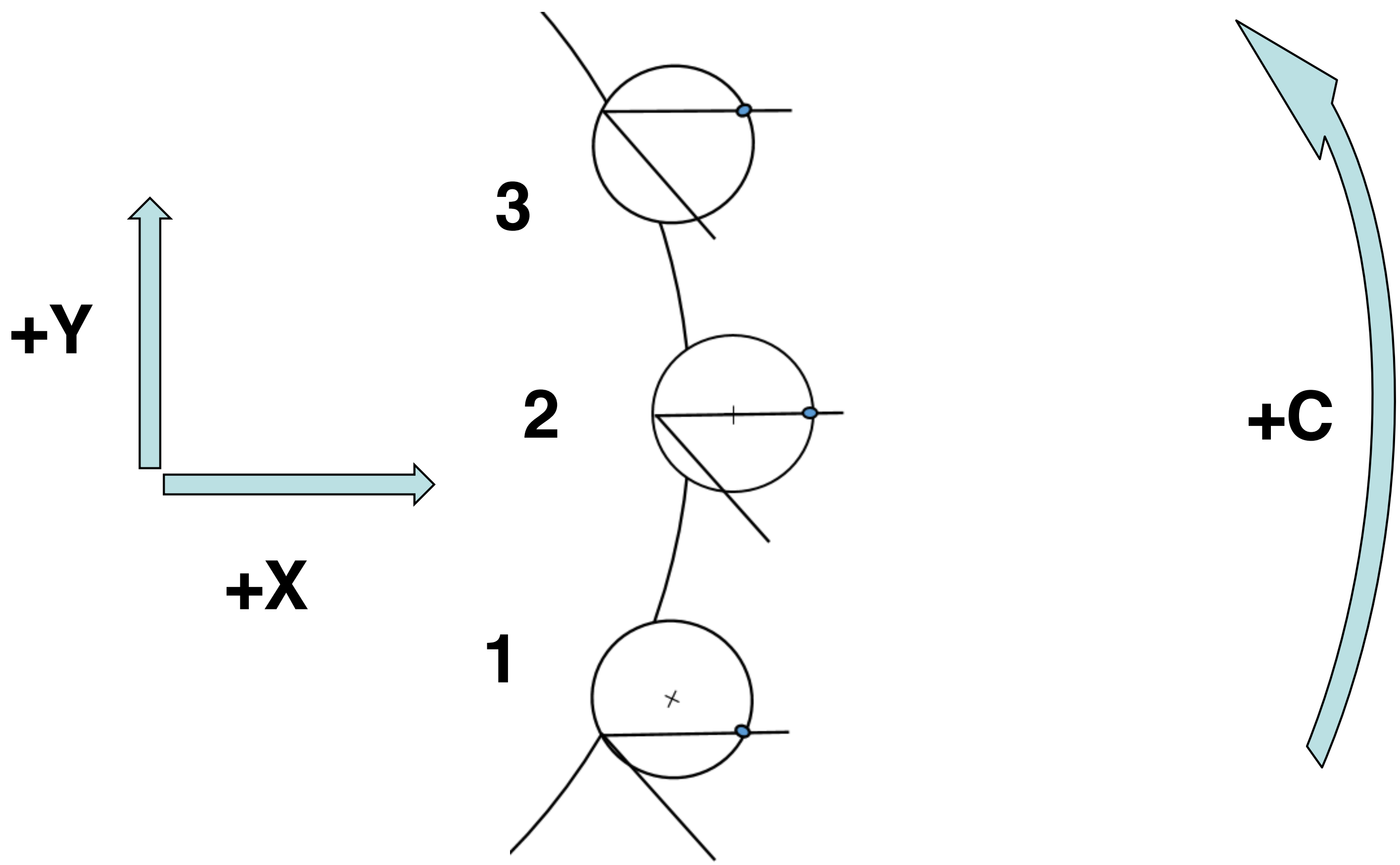


DETAIL B
SCALE 300 : 1



DETAIL A
SCALE 20 : 1

Machine Kinematics To Virtually Rotate Tool

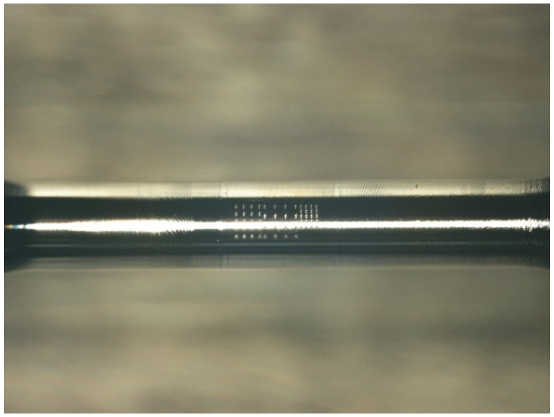


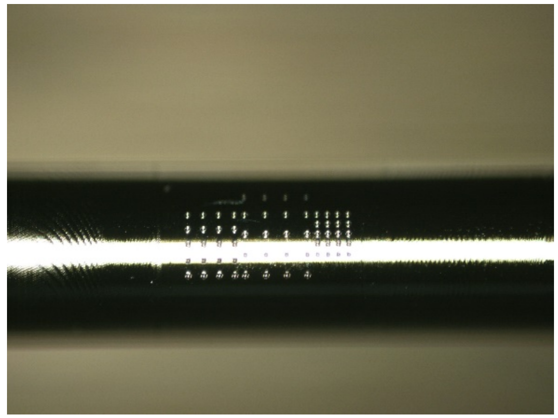
Machine Cannot Rotate Tool So "Virtual Rotation" Is Performed Using Simultaneous Motion of X, Y, and C Axes.

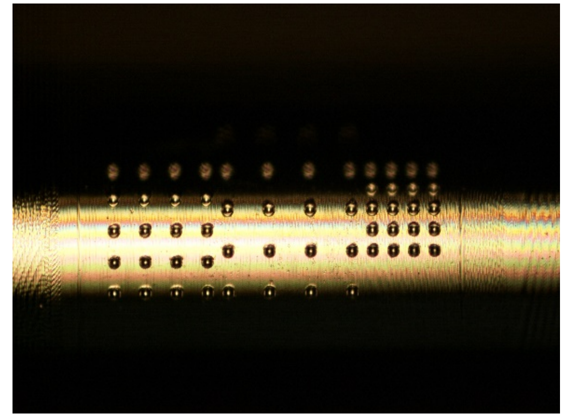
Despite Unusual Motion, NC Program For Machining Defects Is Very Short

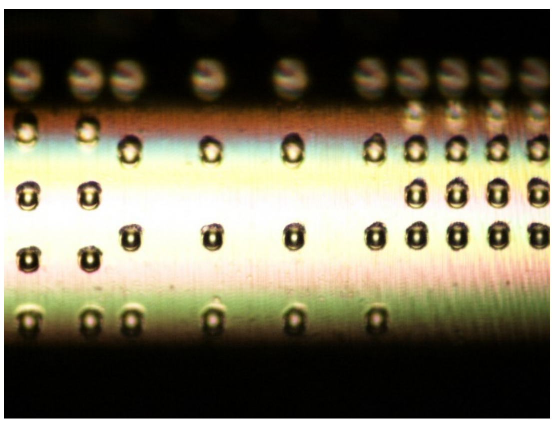
```
;this program machines a hemi-shaped divot
;z-origin is front face
;tool faces operator
;tool must be calibrated at tip
;lathe must be in c-axis mode (m27)

t5                    ;pick up tool offsets

;cutting parameters
p1=.005               ;radial peck depth
p2=.05                ;angular increment (degrees alpha)
p3=.0244              ;tool rotation axis offset (p-L)
p4=.1                 ;retract distance

;part parameters
p11=3.                ;rod radius (R)
p12=.0244             ;divot spherical radius (r)
p13=4                 ;divot dia/depth (B)
p14=0                 ;divot clocking location (degrees)
p15=-.5               ;divot axial location

;calculate divot start coordinates
p20=90.000001         ;starting (alpha) to not divide by zero in p27 calculation
p21=p20               ;set (alpha) to starting (alpha)
p22=atan(p12*sin(p20)/(p3+p12*cos(p20)));starting (theta)
p23=p12*sin(180-p20)/sin(p22);starting (d)
p24=sqrt(p11*p11-p12*sin(p20)*p12*sin(p20))+p12*cos(p20);starting (L)
p25=(p3+p24)*cos(p22)-p23     ;starting (x)
p26=(p3+p24)*sin(p22)         ;starting (y)

;calculate stock removal and set cut counter
p31=p12/p1
p31=fix(p31)
p31=p31+1             ;set rough cut counter
p90=p31*p1            ;set stock level

;set (alpha) counter
p41=180/p2

;watch:p1=cut depth
;watch:p31=cuts to go
;watch:p90=stock level

g1                    ;feed
g14                   ;feed mode all axes
g71                   ;metric
g40                   ;cancel comp
g59                   ;cancel offset
m7.1                  ;tool 1 coolant on
m7.2                  ;tool 2 coolant on
g90                   ;absolute mode

x25y0z25f2000         ;safe start point
z(p15)
while(p31>0)          ;while # cuts remaining > 0...
p31=p31-1             ;decrement cut counter
p90=p90-p1            ;decrement stock level
x(p25+p90)y(p26)c(p14+p22)
gosub 1000
x25
y(p26)c(p14+p22)
p21=p20               ;reset to starting (alpha)
p41=180/p2            ;reset (alpha) counter
endwhile
x25y0z25              ;safe point
g13                   ;feed mode x-y-z only
exit                  ;end of main pgm

n1000
while(p41>0)
p41=p41-1             ;decrement (alpha) counter
p21=p21-p2            ;next (alpha)
p52=atan(p12*sin(p21)/(p3+p12*cos(p21)));next (theta)
p53=p12*sin(180-p21)/sin(p52);next (d)
p54=sqrt(p11*p11-p12*sin(p21)*p12*sin(p21))+p12*cos(p21);next (L)
p55=(p3+p54)*cos(p52)-p53     ;next (x)
p56=(p3+p54)*sin(p52)         ;next (y)
x(p55+p90)y(p56)c(p14+p52);go to next point
endwhile
ret
```

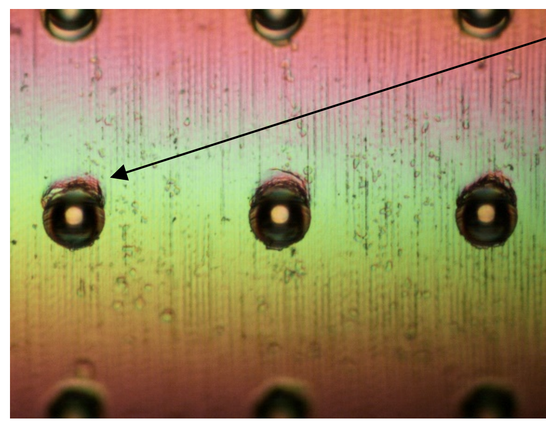
Microscopic Images of Defect Pattern


2.5x


5x


10x


20x



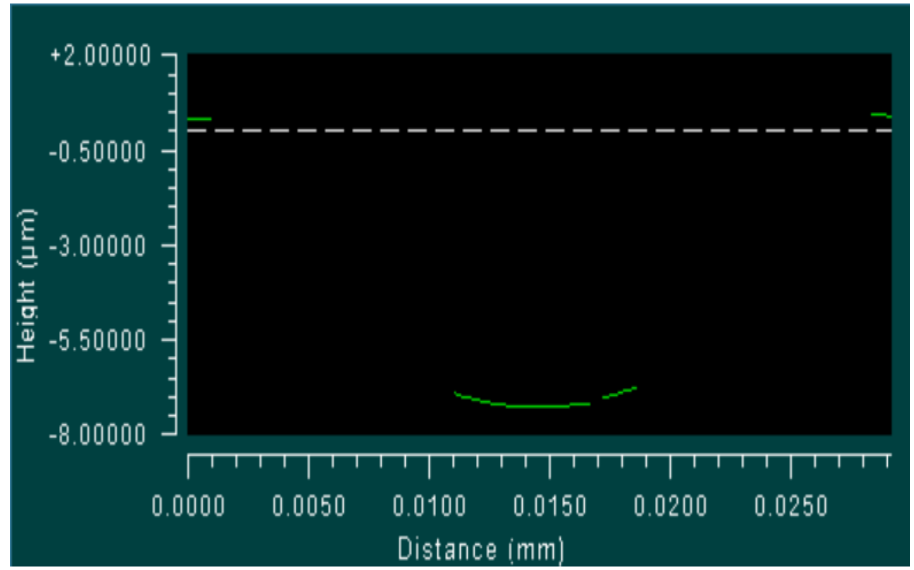
50x

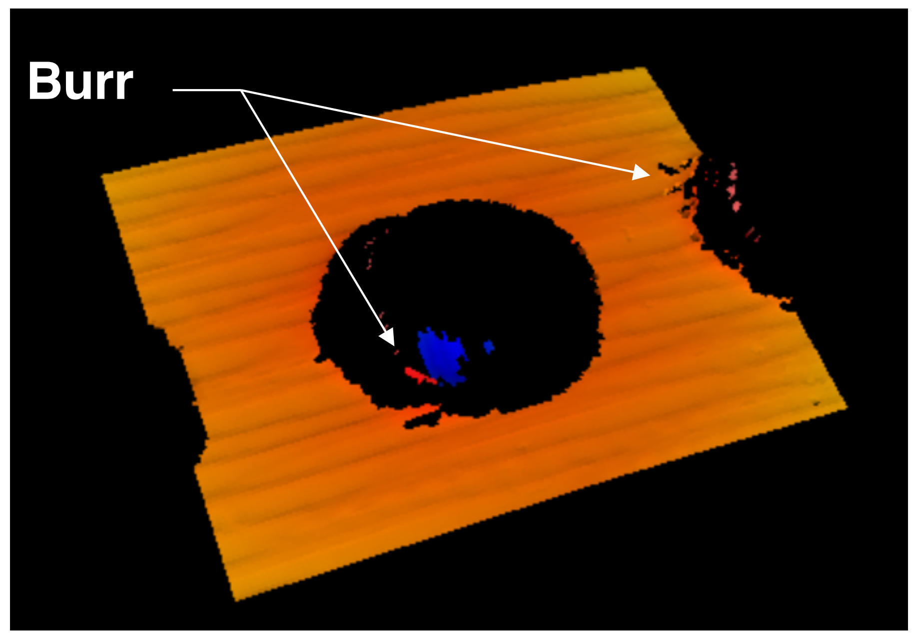
100x Interferometer Scan of Defect

1. Defect is ~28um dia. at surface and is ~7um deep which is about 4:1 as wanted.

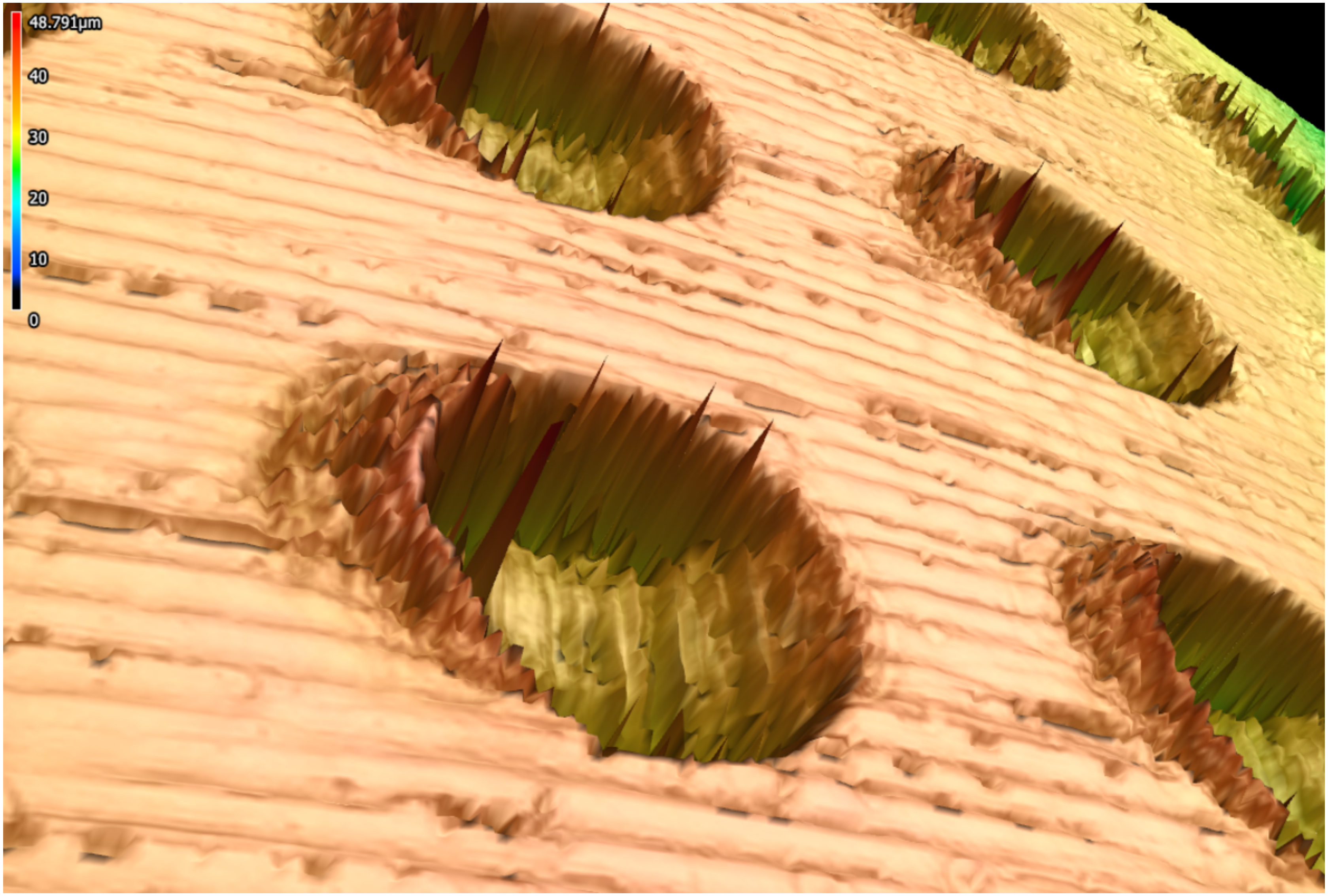
2. Light is not received on divot sides due to angle too steep for objective NA.

3. Burr shown as semi-circles on left side of divots. Will be removed by subsequent turning operation in production run.





Confocal Scan of Defect

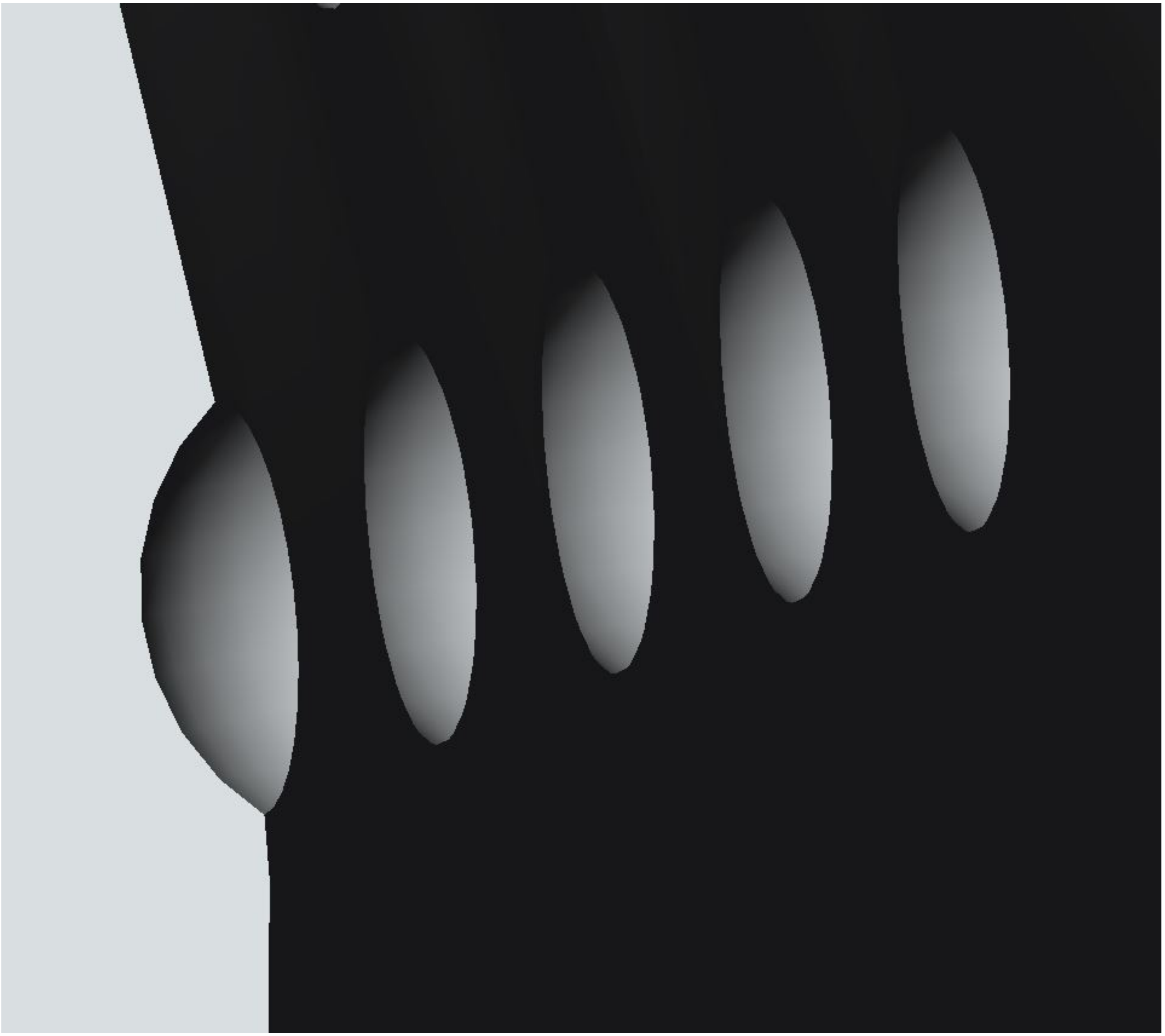


Summary

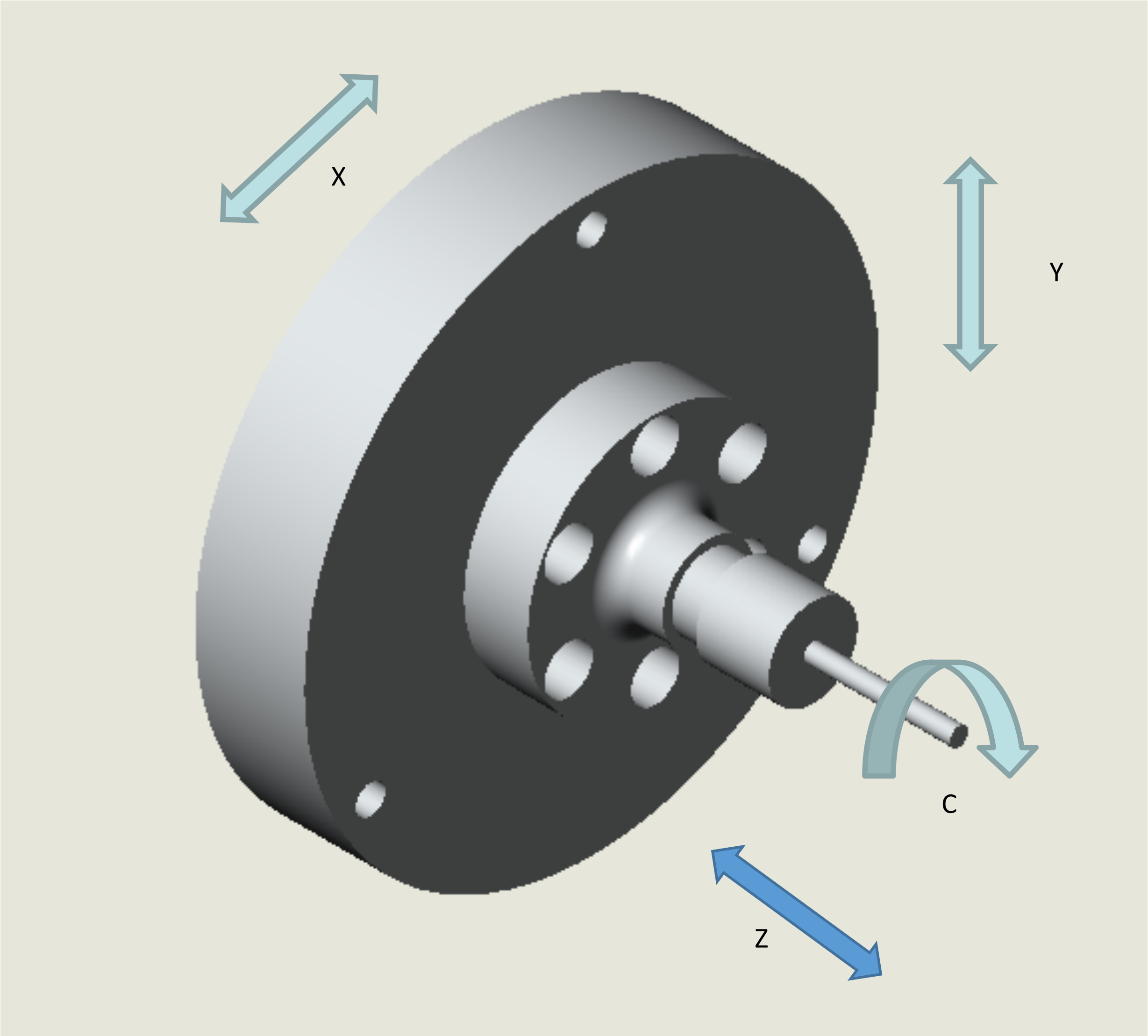
- Using Slow Tool Servo on a diamond lathe with X,Y, Z, and C Axis control, it is possible to create very precise arrays of tiny, semi-hemispherical pits.
- Machine motion and tool geometry are critical to the success of this approach and are interdependent.
- Depth of pits can only be controlled precisely if turning and pit machining are performed in the same setup.
- QUESTIONS???

Extra Slides

Detail of Spherical Defects

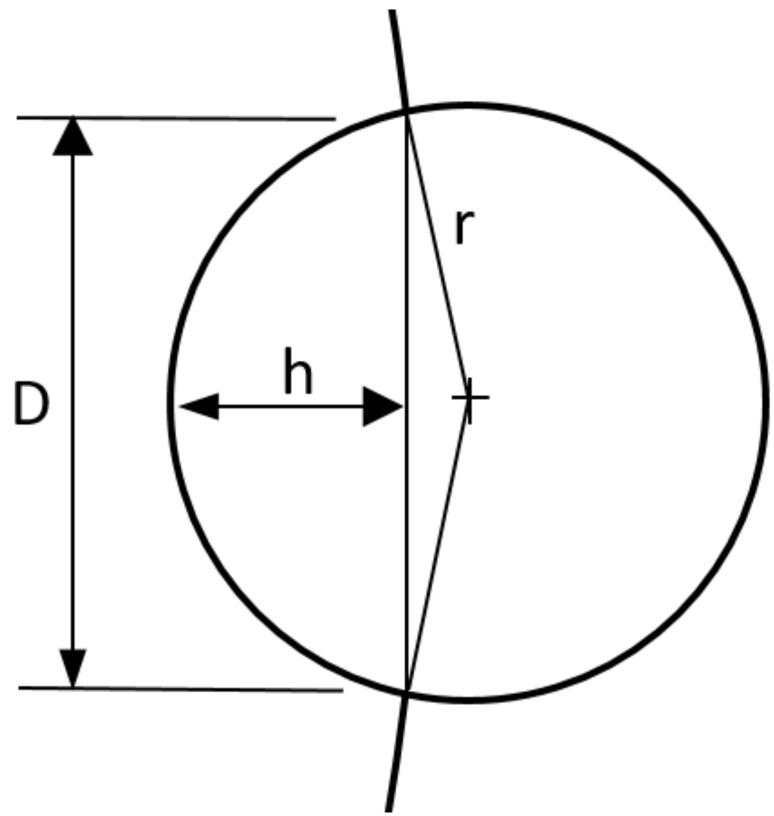


Precitech Lathe Axis Layout



Derive Equation For $h = f(B, r)$

Define Basic Defect Parameters: $B = \frac{D}{h}$; **r = Defect Radius**

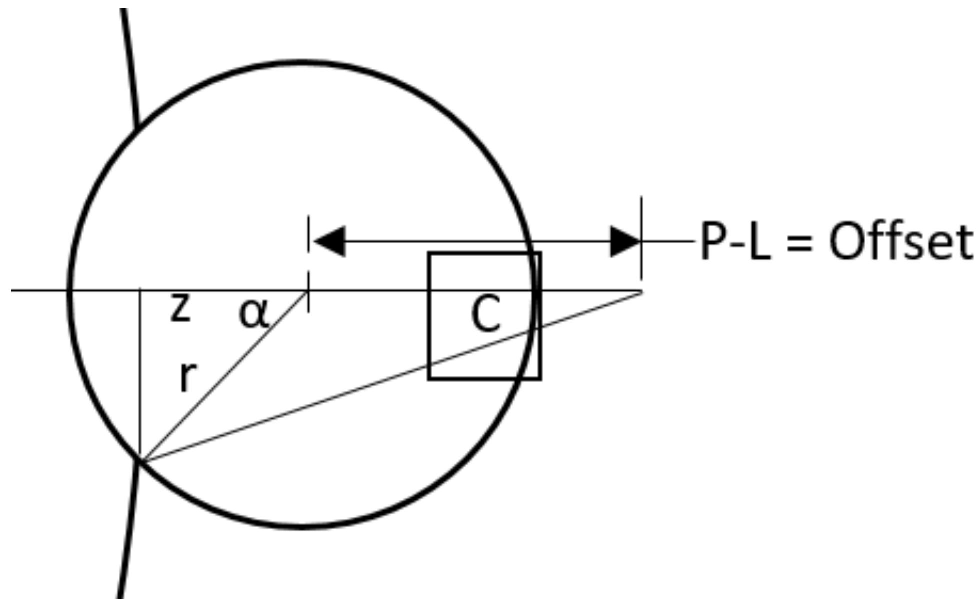


$$h = \frac{8r}{B^2 + 4}$$

Derive Equation For Machine's Rotation Axis

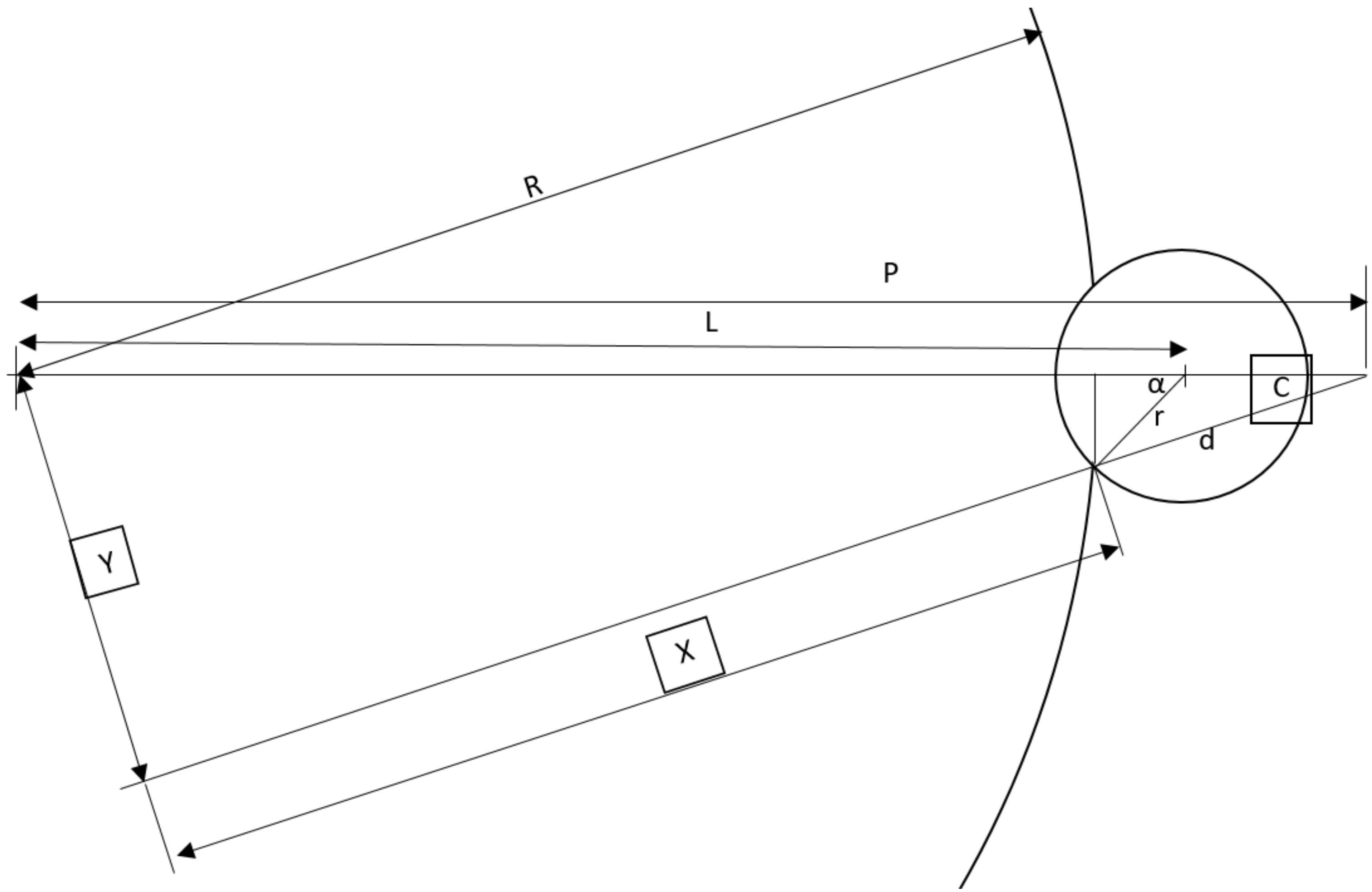
$$C = f(\propto)$$

NC algorithm will calculate machine X, Y, and C for fine increments of α. All machine coordinates must be therefore be based on α.



$$C = arctan\frac{rsin\alpha}{P - L + rcos\alpha}$$

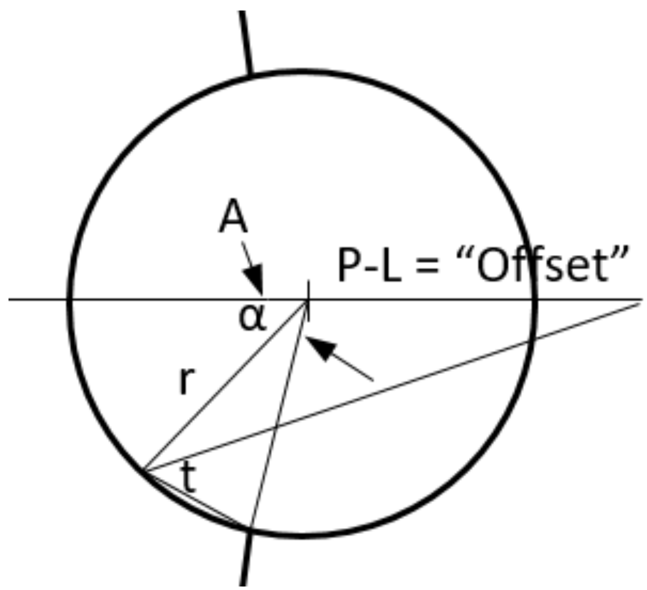
Derive Equation For Machine Translation Axes
X & Y$= f(C)$



$$X = PcosC - d; \quad Y = PsinC; \quad d = r\frac{sin\alpha}{sinC}$$

GENERAL ATOMICS

Derive Equation For Tool Relief Angle $= f(\propto)$

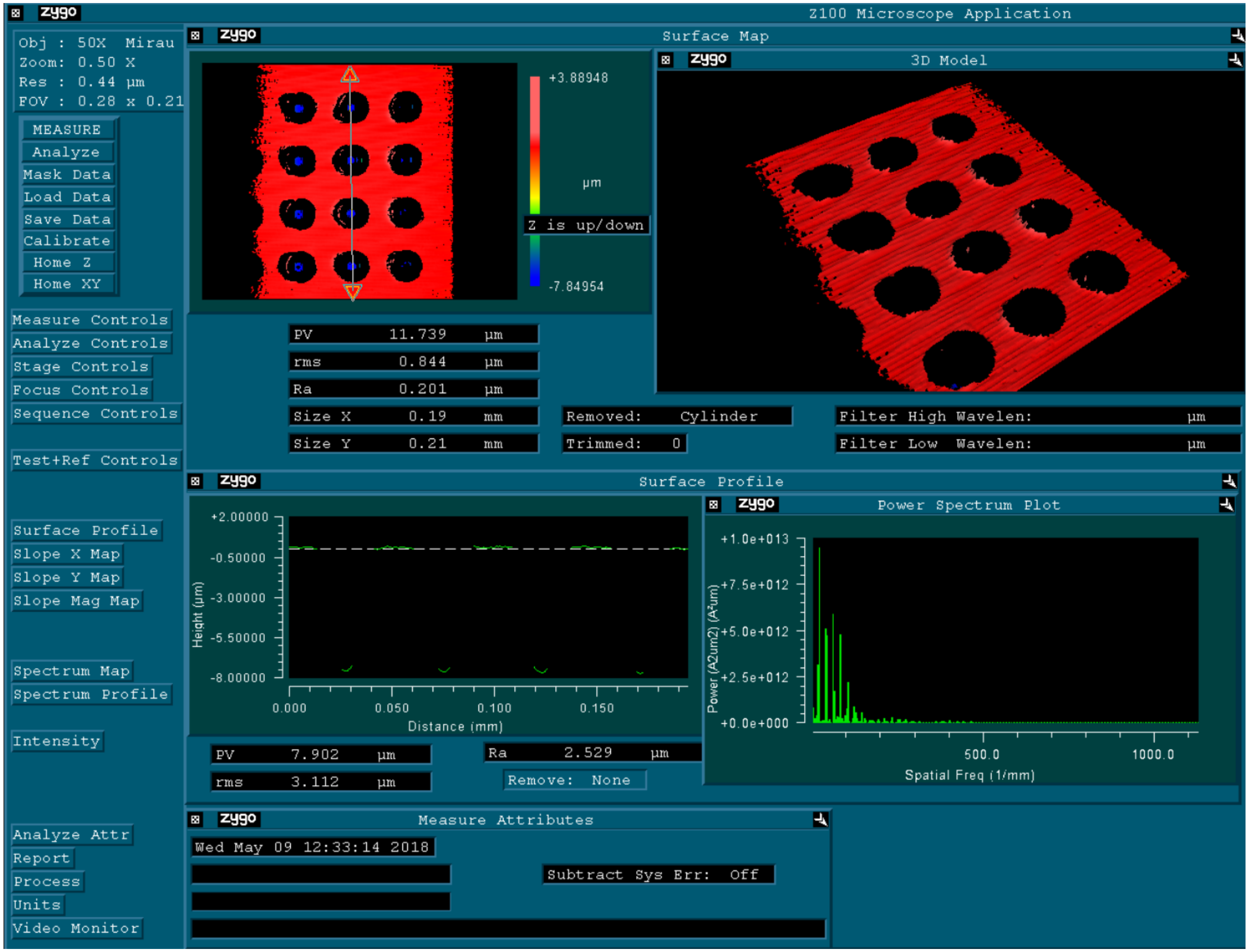


$$t = arcsin\left(cos\frac{A-\alpha}{2}\right) - \alpha + arctan\frac{rsin\alpha}{P-L+rcos\alpha}; \quad Relief = 90 - t$$

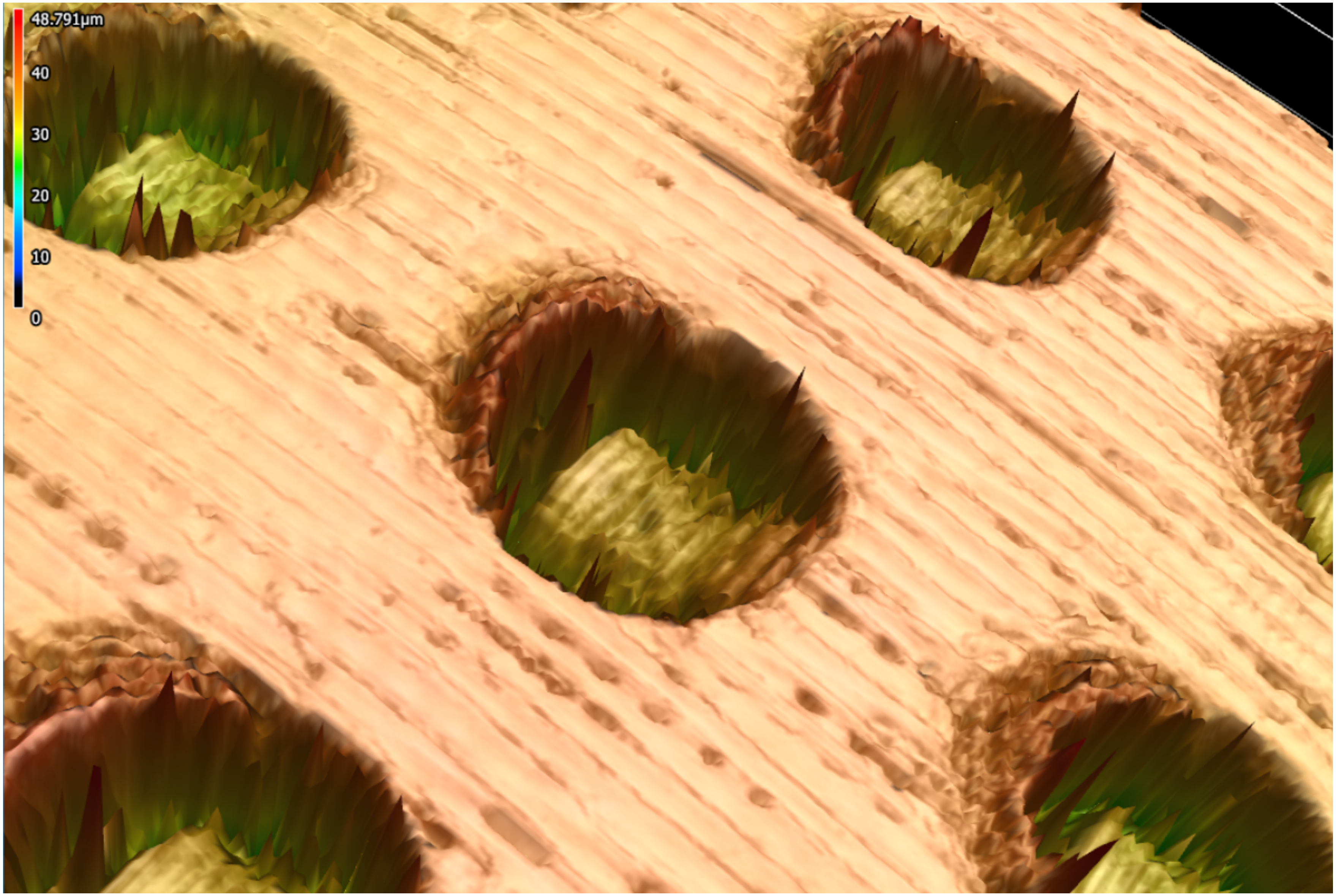
Input Equations Into Excel To Allow Optimization Of Variables

divot radius (r)	divot dia/depth (B=D/h)	divot depth (h)	divot dia (D)	rod radius (R)	divot center (L)	tool rot axis offset (P-L)	tool rot axis (P)	divot angle (alpha)	C-axis angle (theta)	triangle leg (d)	x	y	divot half-angle (max alpha)	tool min relief	tool rake angle
p12	p13	p16	p17	p11	p18	p3	p19	p25	p52	p53	p54	p55			
0.017	4.000	0.0068	0.0272	0.400	0.4102	0.017	0.4272	50.000	25.000	0.0308	0.3564	0.1805	53.130	26.565	25.000
								45.000	22.500	0.0314	0.3633	0.1635		26.565	22.500
								40.000	20.000	0.0319	0.3695	0.1461		26.565	20.000
								35.000	17.500	0.0324	0.3750	0.1285		26.565	17.500
								30.000	15.000	0.0328	0.3798	0.1106		26.565	15.000
								25.000	12.500	0.0332	0.3839	0.0925		26.565	12.500
								20.000	10.000	0.0335	0.3872	0.0742		26.565	10.000
								15.000	7.500	0.0337	0.3898	0.0558		26.565	7.500
								10.000	5.000	0.0339	0.3917	0.0372		26.565	5.000
								5.000	2.500	0.0340	0.3928	0.0186		26.565	2.500
								0.000	0.000	#DIV/0!	#DIV/0!	0.0000		26.565	0.000
								-5.000	-2.500	0.0340	0.3928	-0.0186		26.565	-2.500
								-10.000	-5.000	0.0339	0.3917	-0.0372		26.565	-5.000
								-15.000	-7.500	0.0337	0.3898	-0.0558		26.565	-7.500
								-20.000	-10.000	0.0335	0.3872	-0.0742		26.565	-10.000
								-25.000	-12.500	0.0332	0.3839	-0.0925		26.565	-12.500
								-30.000	-15.000	0.0328	0.3798	-0.1106		26.565	-15.000
								-35.000	-17.500	0.0324	0.3750	-0.1285		26.565	-17.500
								-40.000	-20.000	0.0319	0.3695	-0.1461		26.565	-20.000
								-45.000	-22.500	0.0314	0.3633	-0.1635		26.565	-22.500
								-50.000	-25.000	0.0308	0.3564	-0.1805		26.565	-25.000

25x Interferometer Scan Showing Portion of Defect Pattern



Confocal Scan of Defect



Machining Time Per Target

1. Diamond turn (leaving areas next to defect area oversized): 2.75 hrs
2. Cut defect pattern (60 defects) using C-axis mode: 2.25 hrs

Total: 5 hrs each