Design and Analysis for a Large Two-Lens Cell Mount

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OptoMechanics 523: Final Project
May 15, 2009

Abstract
Presented below is a cell mount for two lenses that are 16" in diameter and made of Fused Silica. They are referred to as the test plate and the illumination lens. Each lens will be held to the cell with six stainless steel flexures. The flexures will be attached to pucks bonded to the lens edge and clamped onto the cell wall. The RMS slope error on the concave side of the test plate is less than 10 nm/cm, and meets all other requirements as requested.

Requirements Review

Table 1: System Requirements

Requirement	Value
RMS Slope Error (Concave side of test plate)	<10 nm/cm
Alignment of Two Lenses	Position: 100 μm Angle: 1 mrad
Separation of Two Lenses	10 mm nominal 100 um tolerance
Interface	3 access points around cell needed for feeler gauge
	Cell will sit within another cell on roller balls in kinematic grooves

This assembly is being used in a lab, so it will operate only at room temperature. Preliminary error budget for the RMS slope error includes 2 nm/cm for the self weight deflection and 9 nm/cm for the error due to mounting. This gives an RSS of 9.21 nm/cm.

Design Concept

The illumination lens and test plate will both be mounted to an aluminum cell in the same manner – both using a hexapod design with six skew flexures (Figure 1). Six evenly spaced, aluminum pucks will be bonded to the side of each lens. One end of the flexures (CRES 17-4) will then be attached to each puck and secured with a nut. The opposite end of the flexure will be held by a clamp which the flexure can slide in and out of. This clamp will be mounted to the inside of the cell wall. A separate picture of the flexure assembly can be seen in Fig 1.

This design allows full constraint of the lenses while keeping the slope error minimized. Looser tolerances on the position requirements allow for simpler mounting of the flexures (using clamps).

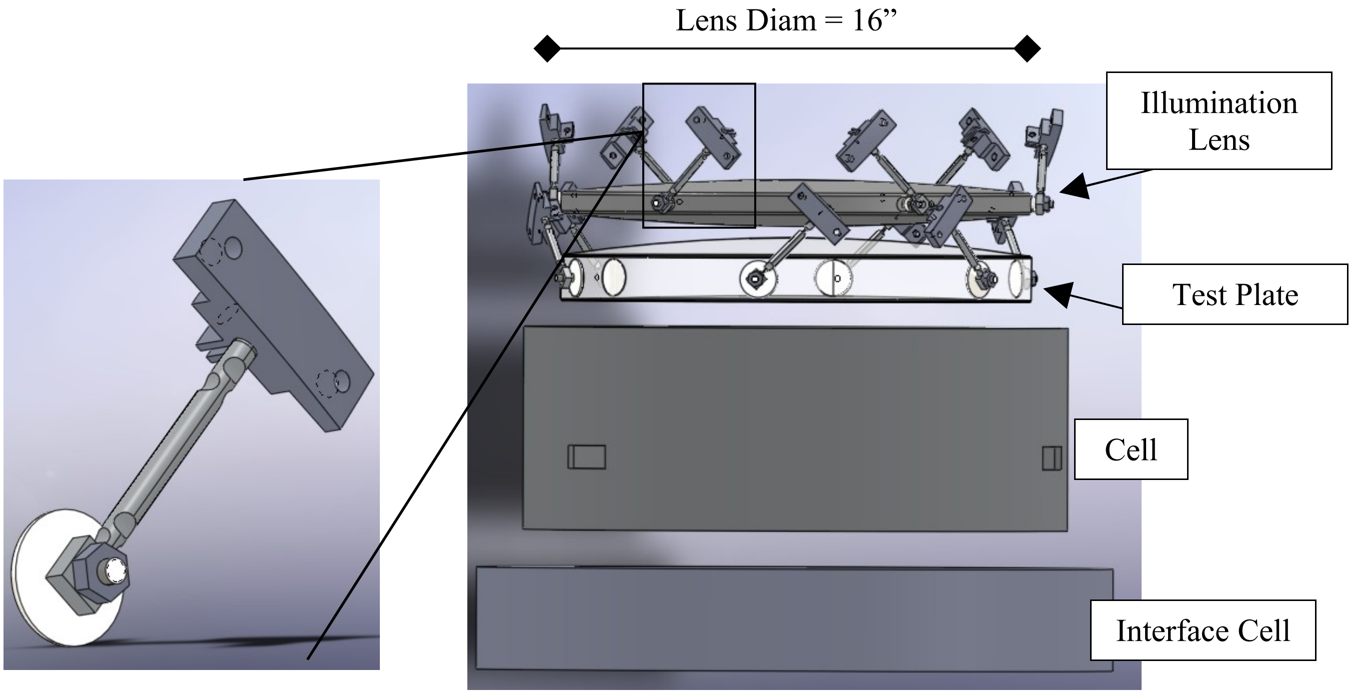
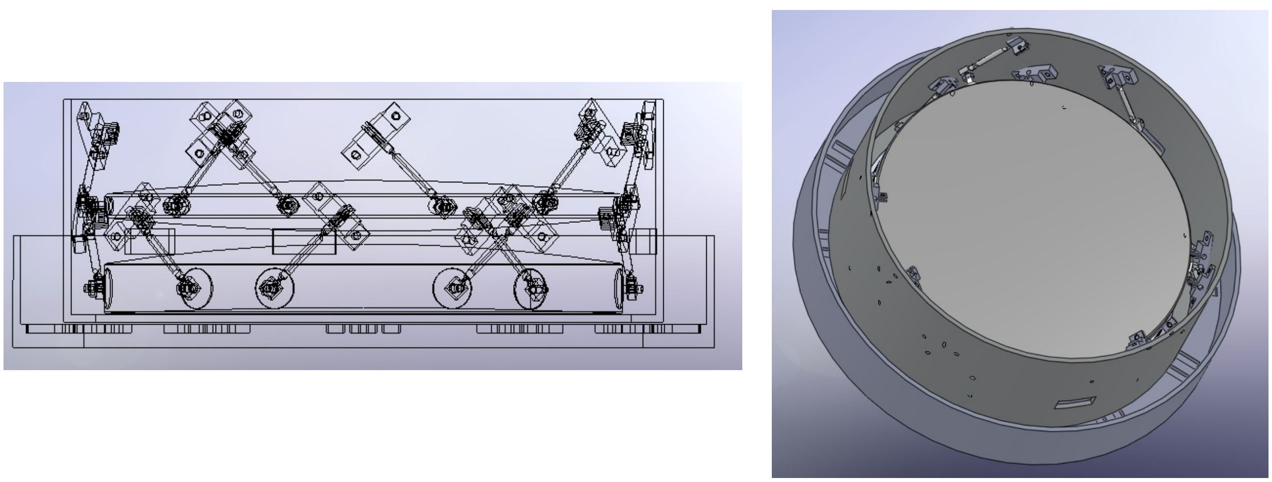


Figure 1: Exploded View of Design Concept (top right) , close up of flexure assembly (top left), fully assembled views (below)



Preliminary Assembly Plan

- The test plate will be held with a jig while mounting it to the cell.
- Bond the 6 pucks to the side of the lens at evenly spaced intervals using ES566 epoxy and allow to cure per instructions.
- Slide one end of the flexure on to each puck and secure with a nut.
- Attach the clamps to the inside wall of the cell at 45°.
- Working with flexures opposite of each other, slide the end of the flexure into the clamp and secure. Do not exceed 15 mm of outward pull from nominal on the flexures.
- Repeat above steps with illumination lens.

Analysis

Flexure Angle

There were two competing factors when determining the angle to mount the flexures at. First, the stability of the mount increases as we move from vertical to horizontal mounting. Second, the slope error increases as the flexures move from vertical to horizontal mounting. Plots can be found in Appendix B which depict the resonant frequency (stability) and slope error that results from flexure mounting angles of 1° – 70°. The ideal condition would be to have low slope error and high stability. For this reason, 45° was chosen as the mounting angle for the flexures to compromise between the two factors.

Self Weight Deflection

The self weight deflection was calculated using CosmosWorks. Restraints were placed on the edge of the lens where the puck/flexure assembly would be holding it. The angles of the restraints were set to 45° and gravity was applied in the –Z direction (Figure 2).

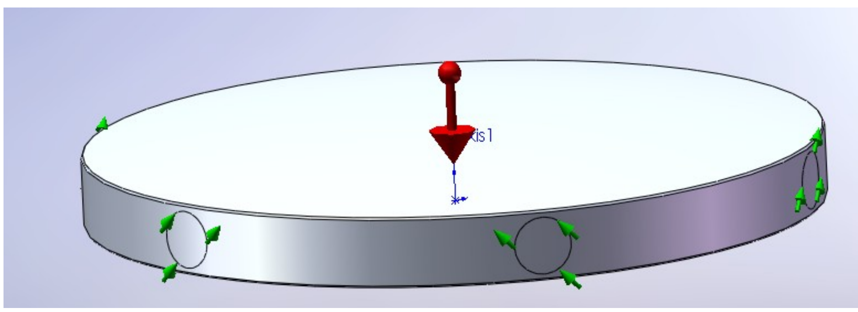


Figure 2: Self Weight Deflection Measurement

The displacement data was post-processed using code developed by Won Hyun Park. The Matlab program takes in a .csv file from Solidworks of the displacement values at each node of the mesh (over the 14" clear aperture). Zernike coefficients are used to weight each node based on the surrounding slopes. From the program, an RMS slope error of **1.9 nm/cm** was found (see Figure 3 for maps of the slope error).

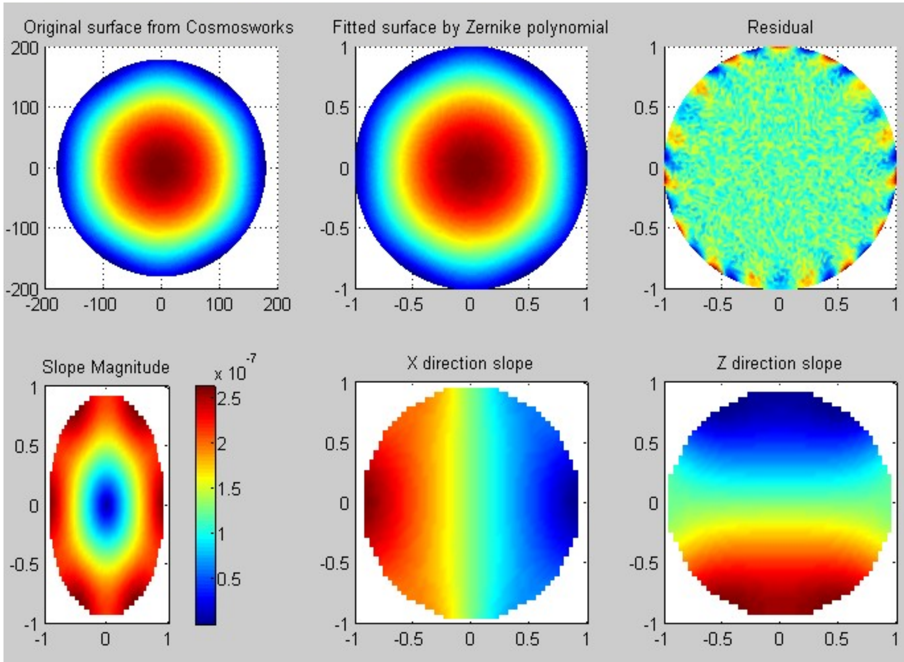


Figure 3: Slope Error Data

Flexure Thickness and Analysis

To choose the flexure thickness, a parametric model was done to determine how thin the flexure could be. The flexure must be thick enough that it can support the lens weight without going beyond yield strength and thin enough that it does not impart too much slope error to the lens. The parametric model included thicknesses from 0.5mm to 3.0mm at 0.5 mm increments

Flexure Yield Strength

The mass of the lens that the flexures support is 12.7 kg. Since one flexure will support one-sixth of this mass, we use 2.118 kg (or 20.78 N of force). A model was set up so the clamped end of the flexure had a fixed constraint and the force was applied at 45° (Figure 4).

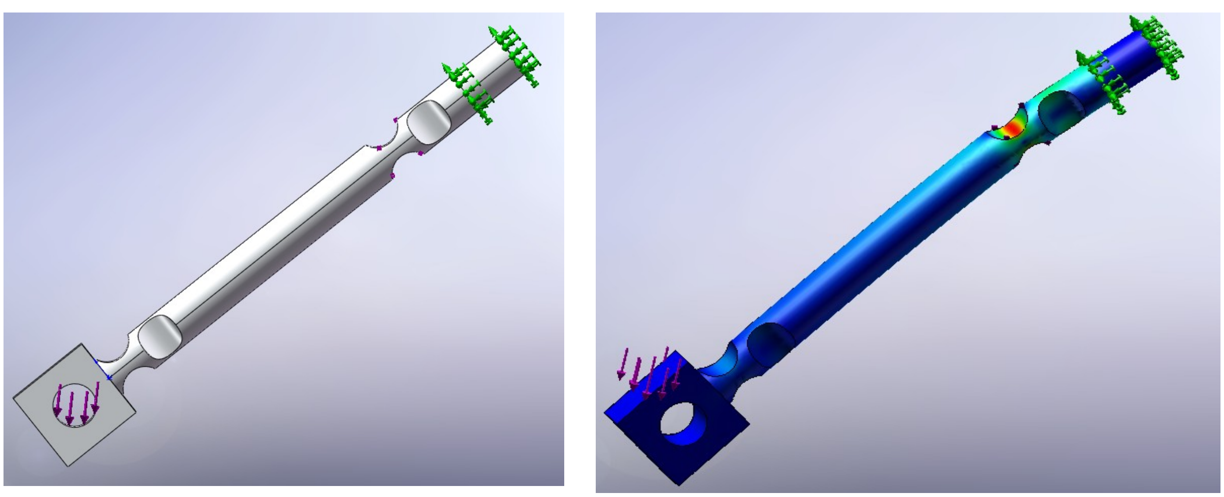


Figure 4: Yield Strength Parametric Model

The stress plot was then looked at to determine the maximum amount of stress that would occur at the thin point of the flexure. This was compared to the yield strength of CRES 17-4 (about 1000MPa) to determine the safety factor of the flexure. Multiple data sheets were compared (see Appendix D for on) to determine the average yield strength.

Table 2: Thickness of Flexure vs Yield Strength Safety Factor

Thickness (mm)	0.5 mm	1.0 mm	1.5 mm	2.0 mm	2.5 mm	3.0 mm
Safety Factor	0.3	1.9	2.6	4.4	6.5	8.75

So, from this data, the thickness should remain above 1.5 mm to have a reasonable safety factor built into the system.

Slope Error due to Flexure Thickness

Using the same parametric model, the maximum thickness was determined by seeing how much slope error would be imparted to the lens. First, the axial stiffness of the flexure was calculated using $k = \frac{F}{\delta x}$. The flexure was held on the bottom (where the nut would connect it to the puck) and a 1N force was applied across the top of the flexure (Figure 5). The displacement was calculated and results for axial stiffness can be found in Appendix E.

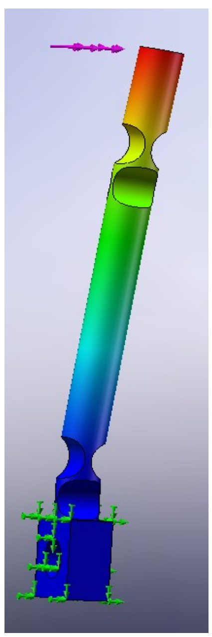


Figure 5: Axial Stiffness Measurement

Knowing the axial stiffness, the force that the lens will experience due to misalignment/ tolerances in the assembly can be calculated. By applying forces to the SolidWorks model, we find that if the force exceeds 1100N, the slope error exceeds the error budget of 9 nm/cm. The force felt by the lens will be based on two factors- the inherent design, and the assembly tolerances.

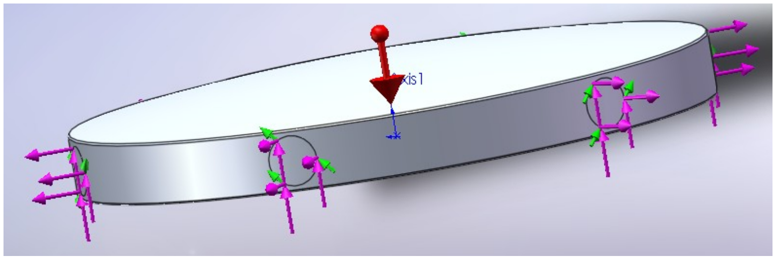


Figure 6: Moment/Force imparted on lens by flexure

First, there is an inherent force/moment that will be applied since the flexures must be pulled out slightly to slide into the clamps on the side wall. The distance that the flexures will have to be pulled based on the inherent design is 5 mm (resulting in 1.53 nm/cm of error).

Second, tolerances are needed for assembly, since it will not be a perfect fit. Using the calculated axial stiffness, different tolerances were applied and the resulting forces were calculated (see Appendix E for the multiple calculations). A tolerance of 10mm is reasonable and still allows for a safety factor greater than 2.

Thickness	k (N/m)	tolerance (dx)	F (calculated)	Slope Error*
(mm)				
0.5	2.01166767	0.01	0.020116677	0.000164591
1	9596.92898	0.01	95.96928983	0.78520328
1.5	22138.5876	0.01	221.3858756	1.811338982
2	37495.3131	0.01	374.9531309	3.067798343
2.5	53447.3544	0.01	534.4735436	4.372965356
3	68212.824	0.01	682.1282401	5.581049237

*A parametric model was done with specific forces, so these slope errors are extrapolated between points

Comparing this table to our previous thicknesses chart, 2.0mm thick flexures would provide for a safety factor of 4.4 in regards to yield strength and 3 with regards to slope error. Therefore, 2 mm thick flexures were chosen with a total error of 4.6 nm/cm. (1.53 nm/cm due to the design + 3.07 nm/cm due to assembly).

Combined with the error due to self weight deflection, the RSS slope error is just under **5 nm/cm**, well within the requirement of 10 nm/cm.

Shear strength of Epoxy and Puck

Appendix C gives the data sheet for ES566 epoxy, which will be used to bond the pucks to the lenses. The shear strength of the epoxy is 11 MPa (if cured at 80°C). The mass of the lens that the flexures support is 12.7 kg. Since one flexure will support one-sixth of this mass, we use 2.118 kg (or 20.78 N of force). Shear stress is given by:

$$\tau = \frac{V}{A}$$

where V = shear force (20.78N) and A = bond area. The smaller of the two pucks is on the illumination lens and has a radius of 6.35mm, or an area of 127 mm^2. The shear stress, τ, is then found to be 0.164 MPa. This is much less than the shear strength of the epoxy (with a safety factor of greater than 65), so the epoxy will hold.

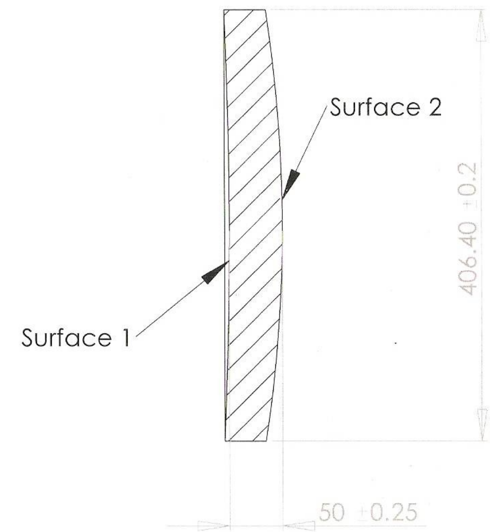
The same analysis can be done for the puck, to ensure the weight of the lenses do not shear the puck. The diameter of the cylindrical part of the puck is 6.096 mm, giving an area of 29 mm^2. The shear stress is then found to be 0.71 MPa. This is much less than the shear strength of 6061 aluminum (207 MPa).

Appendix A

Preliminary

NOTES:

1. All dimensions in millimeters
2. Material: Ohara SK1300 fused silica n= 1.4685
3. Radius of curvature
    a. Surface 1: 4543.54 mm CC
    b. Surface 2: 1336.55 mm CX
4. Surface spec
    a. Surface 1: RMS slope error less than 10 nm/cm
    b. With a 100 mm diameter test plate, there should be less than 5 fringes of power and 1 fringe of irregularity anywhere in the clear aperture
5. Scratch/dig: 60/40
6. Clear aperture: 355.6 mm
7. total indicated runout: 0.2 mm
8. Bevels: <2 mm at 45 deg or equivalent rounded edge
9. Provide as built center thickness and radii
    a. 0.05 mm uncertainty on thickness
    b. 4 mm uncertainty on surface 1
    c. 1.5 mm uncertainty on surface 2
10. Test Wavelength 632.8 nm



UNLESS OTHERWISE SPECIFIED:

NAME DATE

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ENG APPR.

MFG APPR.

Q.A.

COMMENTS:

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

NEXT ASSY USED ON

APPLICATION

DO NOT SCALE DRAWING

TITLE:

SIZE DWG. NO. REV

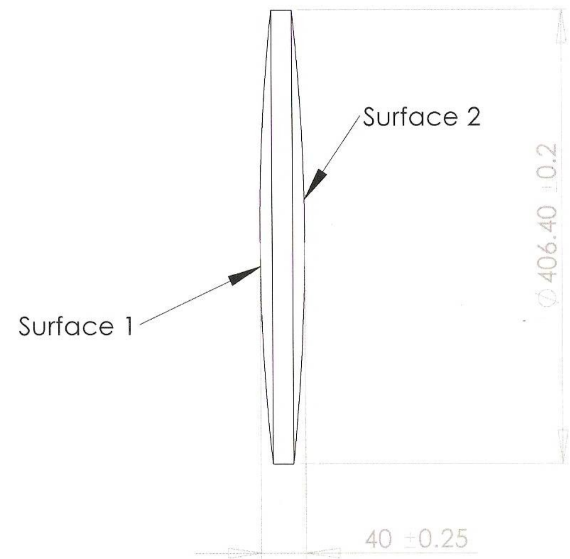
A prelim test plate

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

Preliminary

NOTES:

1. All dimensions in millimeters
2. Material: Ohara SK1300 fused silica
3. Radius of curvature
    a. Surface 1: 1919 mm CX
    b. Surface 2: 1919 mm CX
4. Surface spec (both surfaces): With a 100 mm diameter test plate, there should be less than 5 fringes of power and 1 fringe of irregularity anywhere in the clear aperture
5. Scratch/dig: 60/40
6. Clear aperture: 355.6 mm
7. total indicated runout: 0.2 mm
8. Bevels: <2 mm at 45 deg or equivalent rounded edge
9. Provide as built center thickness and radii
    a. 2 mm uncertainty on radius
    b. 0.05 mm uncertainty on thickness
10. Test wavelength 632.8 nm



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A prelim illumination lens

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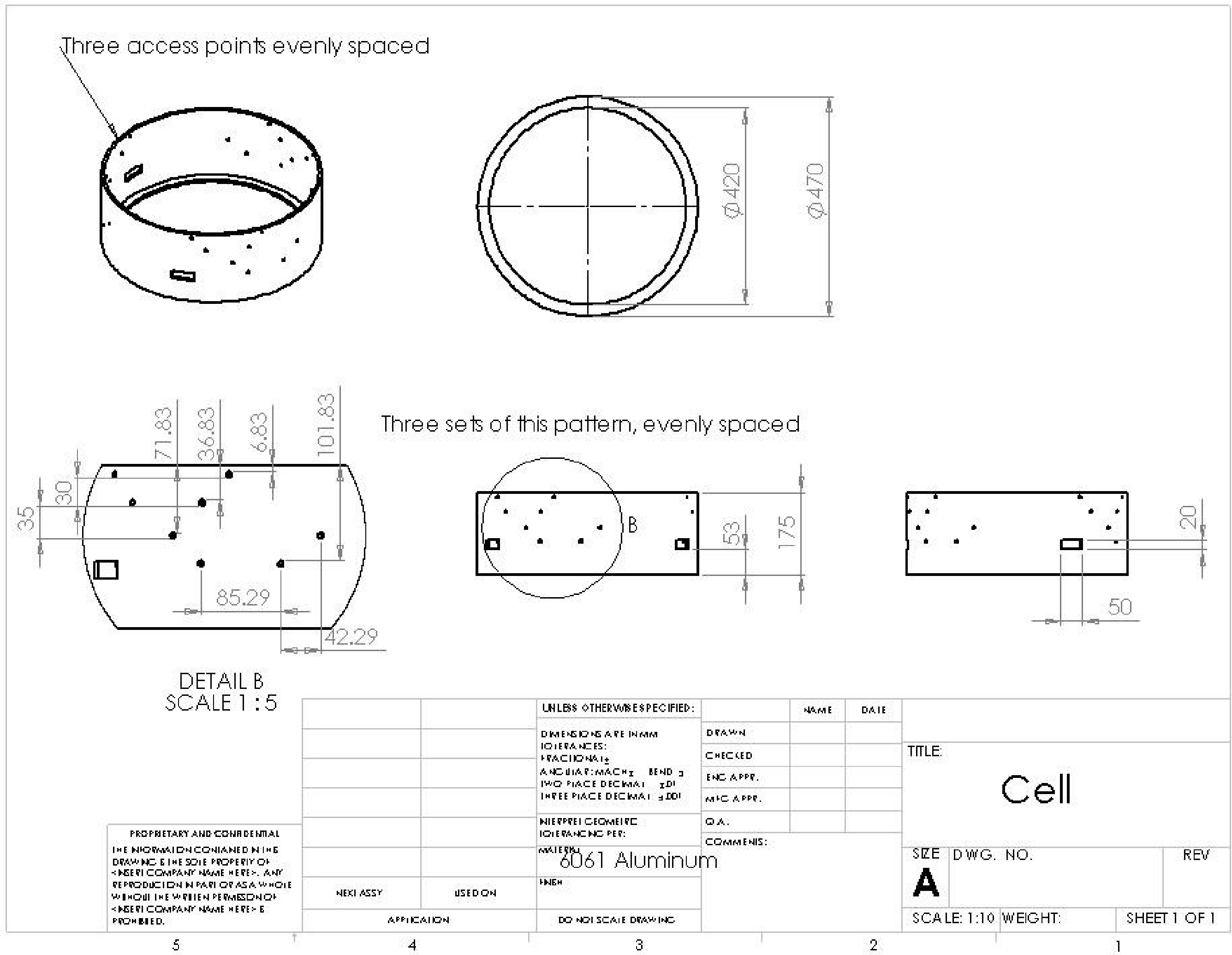
Three access points evenly spaced
Ø420
Ø470
71.83
36.83
6.83
101.83
Three sets of this pattern, evenly spaced
35
30
85.29
42.29
B
53
175
20
50
DETAIL B
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COMMENTS:
TITLE:
Cell
MATERIAL
6061 Aluminum
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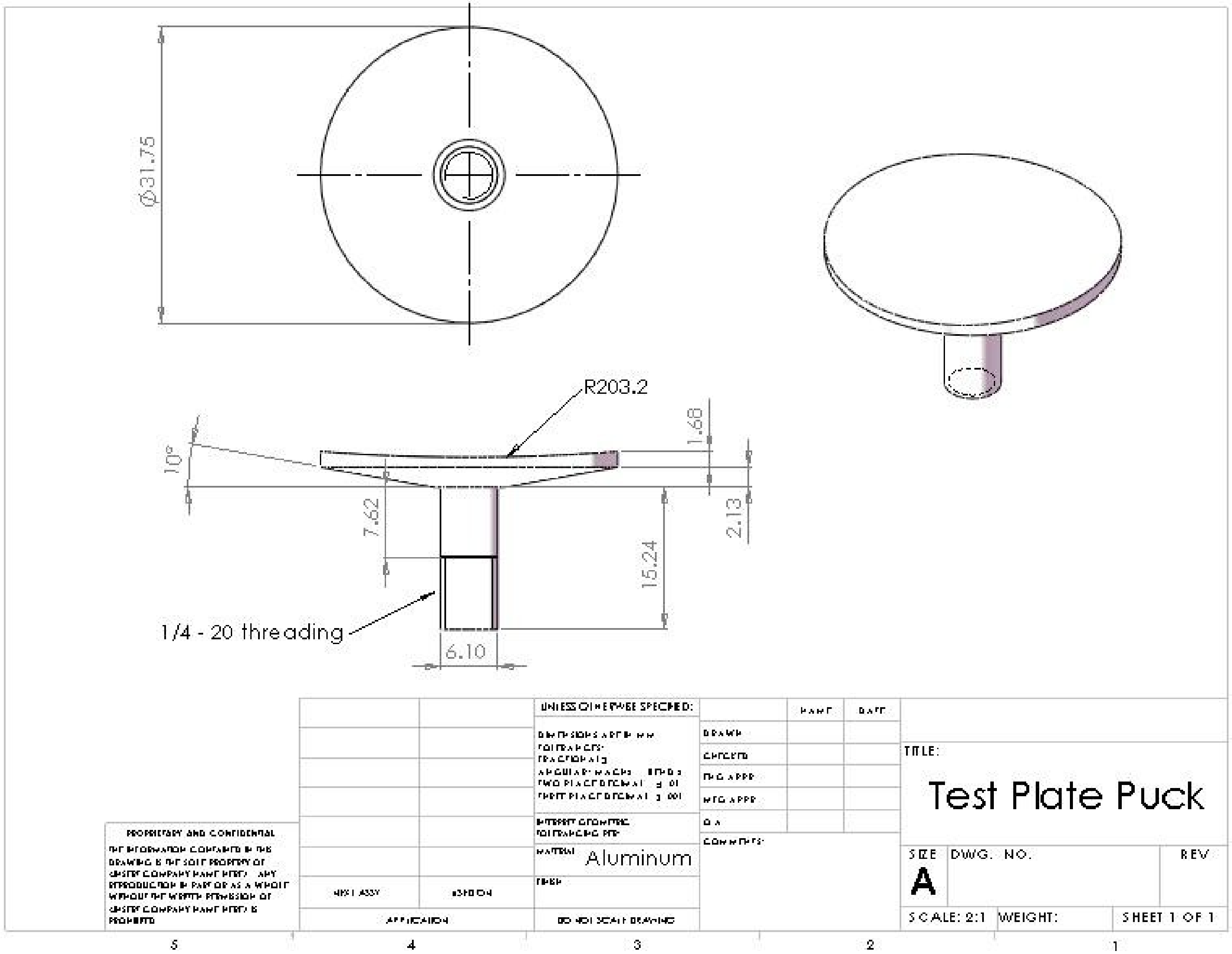
Ø31.75
R203.2
1.68
10°
7.62
2.13
15.24
1/4 - 20 threading
6.10
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MFG APPR.
Q.A.
COMMENTS:
TITLE:
Test Plate Puck
MATERIAL
Aluminum
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WEIGHT:
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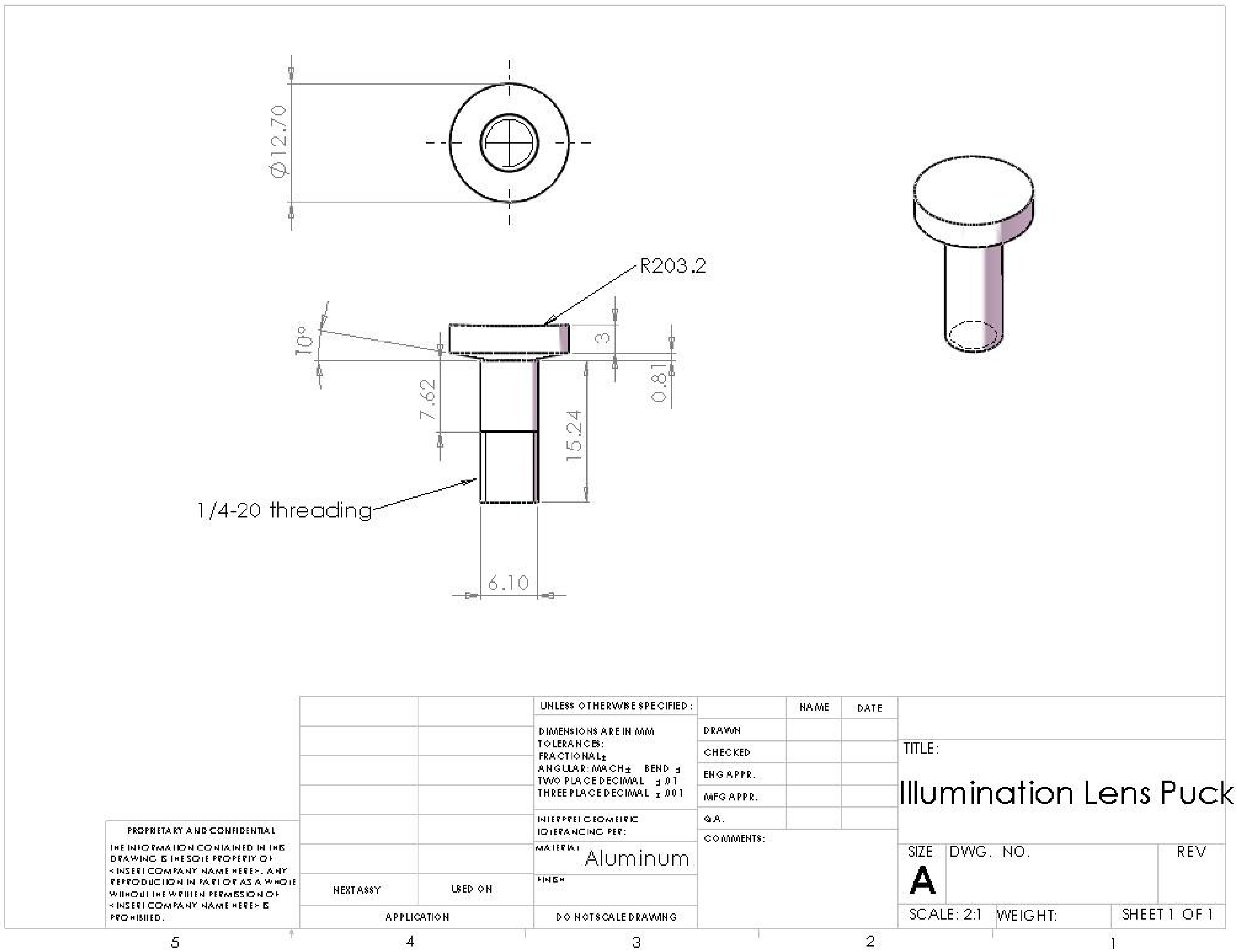
Ø12.70
R203.2
10°
3
0.81
7.62
15.24
1/4-20 threading
6.10
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DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Aluminum
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ENG APPR.
MFG APPR.
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COMMENTS:
TITLE:
Illumination Lens Puck
SIZE A
DWG. NO.
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
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APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
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4
3
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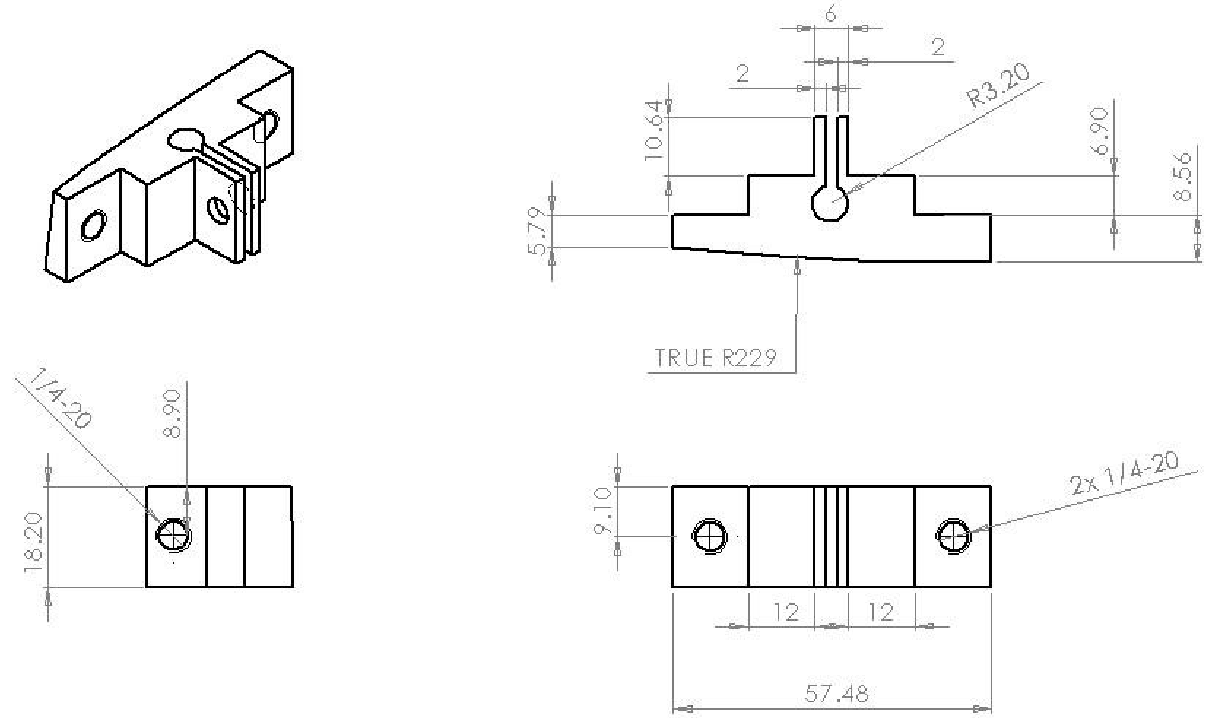

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TOLERANCES:
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ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL Aluminum

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Clamp

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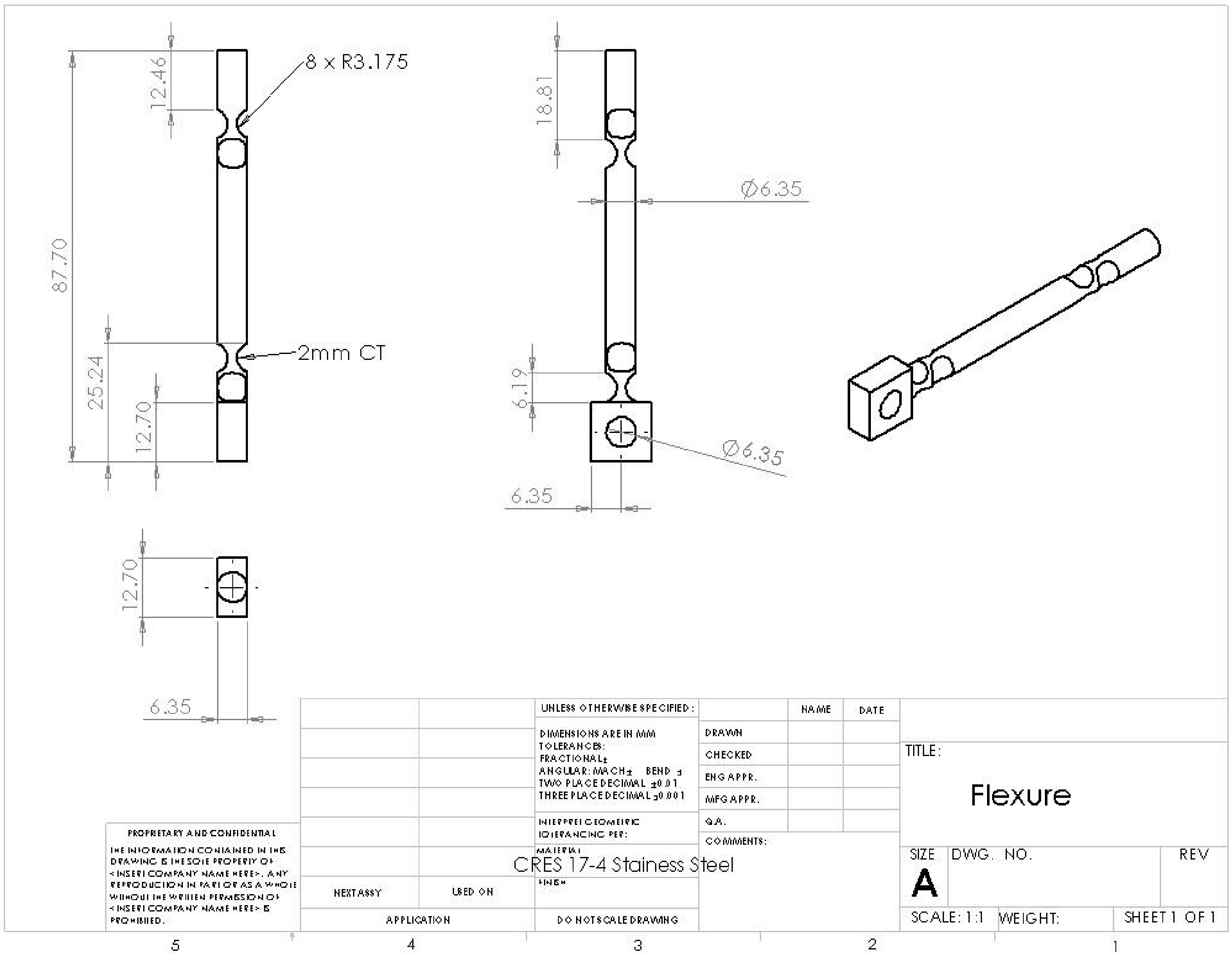
5 4 3 2 1


8 x R3.175
2mm CT
12.46
87.70
25.24
12.70
18.81
Ø6.35
6.19
Ø6.35
6.35
12.70
6.35
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MM
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±0.01
THREE PLACE DECIMAL ±0.001
MATERIAL
CRES 17-4 Stainess Steel
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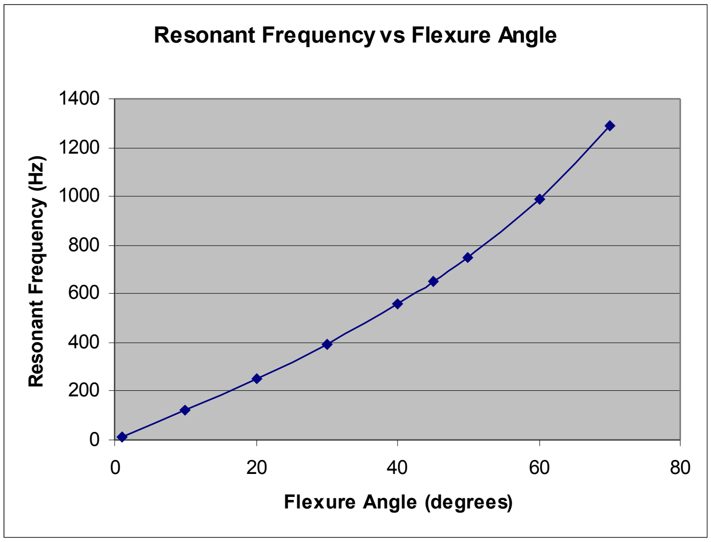
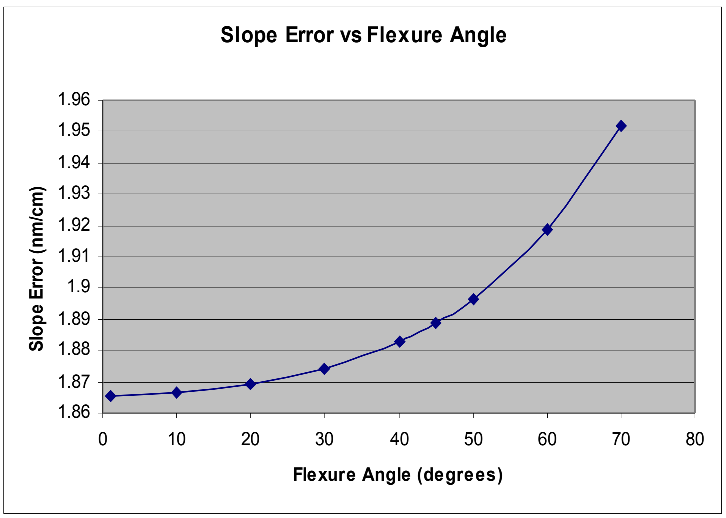
WEIGHT:
SHEET 1 OF 1

Appendix B



Resonant Frequency vs Flexure Angle
Resonant Frequency (Hz)
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
Flexure Angle (degrees)



Slope Error vs Flexure Angle
Slope Error (nm/cm)
1.96
1.95
1.94
1.93
1.92
1.91
1.9
1.89
1.88
1.87
1.86
0
10
20
30
40
50
60
70
80
Flexure Angle (degrees)

Appendix C

Permabond
Engineering Adhesives

ES566

Single Part, Heat-Cure Epoxy
Provisional Technical Information Sheet

Permabond ES566 is a single-part epoxy adhesive with controlled flow when heated during curing. The adhesive has excellent adhesion to metal surfaces and composites. The high bond strength of this adhesive allows it to replace mechanical fastening, soldering or brazing. It has a rapid cure - 15 minutes at 100°C and can be cured at temperatures as low as 80°C

Physical Properties

Chemical Type	Epoxy
Colour	Grey
Viscosity	Thixotropic 150,000 mPa.s
Maximum Gap Fill	0.3mm
Density	1.25
Cure Time*	80°C: 20 minutes 100°C: 15 minutes 120°C: 12 minutes

**Actual cure times will depend on the time it takes for the adhesive to reach this temperature - for example, large assemblies or a crowded oven will require longer to reach full cure. Alternative, quicker methods of curing include induction, hotplates, infrared lamps and hot-air guns .*

Typical Performance

Shear Strength	ASTM D-1002	11 MPa cured at 80°C 14 MPa cured at >100°C
Coefficient of Thermal Expansion		45 x 10^{-6} mm/mm/°C
Shore D Hardness		80
Service Temperature*		-40 to +180°C

**Higher temperatures may be endured for short periods providing the parts are not unduly stressed.*

Surface Preparation

Surfaces should be clean, dry and grease-free before applying the adhesive. Permabond Cleaner A is recommended for the degreasing of most surfaces. Some metals such as aluminium, copper and its alloys will benefit from light abrasion with emery cloth (or similar), to remove the oxide layer.

Adhesive Application

- The adhesive should be dispensed from the cartridge via the nozzle supplied (this can be cut to give the appropriate sized bead to cover the bond area).
- Apply the adhesive to one surface and avoid entrapping air.
- Assemble parts applying sufficient pressure to ensure the adhesive spreads to cover the entire bond area.
- Use a jig / clamp to prevent parts moving during cure.
- It is advisable not to disturb the joint until the adhesive is fully cured.

Storage and Handling

Storage Temperature	2 to 7°C
Shelf Life Stored in original unopened containers	3 months

Users are reminded that all materials, whether innocuous or not, should be handled in accordance with the principles of good industrial hygiene. Full information can be obtained from the Material Safety Data Sheet.

Contact Permabond:
Europe: Tel. +44 (0)1962 711661
UK Helpline: 0800 975 9800
Deutschland: 0800 10 13 177
France: 0805 11 13 88
info.europe@permabond.com
US: Tel. 00 1 732-868-1372
Helpline: 800-640-7599
info.americas@permabond.com
Asia: Tel. 00 886 939 49 3310
info.asia@permabond.com
www.permabond.com

Appendix D

Metal Type 17-4

- Chromium-nickel grade of Stainless Steel
- Hardened by a single low-temperature precipitation-hardening treatment which provides excellent mechanical properties at a high strength level
- Should not be used in the solution treated condition

Available Forms

Type 17-4 stainless steel is available in:

- Bar
- Wire

Specifications

Type 17-4 is covered by the following specifications:

- AMS 5643
- ASTM A 564 Type 630

Composition

Property	**Type 17-4 %**
Carbon	.07 max
Manganese	1.00 max
Phosphorus	.04 max
Sulfur	.03 max
Silicon	1.00 max
Chromium	15.50 - 17.50
Nickel	3.0 - 5.0
Copper	3.0 - 5.0
Columbium plus Tantalum	.15 - .45

Mechanical Properties

Property	**Annealed**	**H900**	**H1150**
Tensile strength, psi	150,000	200,000	145,000
Yield strength, psi	110,000	185,000	125,000
Elongation in 2?	10%	14%	19%
Reduction of area	40%	50%	60%

Rockwell ?C? hardness 34 44 33

Appendix E

Table 3: Calculated Axial Stiffness

Thickness (mm)	F(N)	dx(m)	k (N/m)
0.5	1	4.97E-01	2.01166767
1	1	1.04E-04	9596.92898
1.5	1	4.52E-05	22138.5876
2	1	2.67E-05	37495.3131
2.5	1	1.87E-05	53447.3544
3	1	1.47E-05	68212.824

Table 4: Calculated Slope Errors due to various tolerances

10 mm tolerance

Thickness (mm)	F(N)	dx(m)	k (N/m)	tolerance (dx)	F (calculated)	Slope Error (approximate)
0.5	1	4.97E-01	2.01166767	0.01	0.020116677	0.000164591
1	1	1.04E-04	9596.92898	0.01	95.96928983	0.78520328
1.5	1	4.52E-05	22138.5876	0.01	221.3858756	1.811338982
2	1	2.67E-05	37495.3131	0.01	374.9531309	3.067798343
2.5	1	1.87E-05	53447.3544	0.01	534.4735436	4.372965356
3	1	1.47E-05	68212.824	0.01	682.1282401	5.581049237

15 mm tolerance

k (N/m)	tolerance (dx)	F (calculated)	Slope Error (approximate)
2.01E+00	0.015	0.030175015	0.000246886
9.60E+03	0.015	143.9539347	1.177804921
2.21E+04	0.015	332.0788134	2.717008473
3.75E+04	0.015	562.4296963	4.601697515
5.34E+04	0.015	801.7103153	6.559448035
6.82E+04	0.015	1023.19236	8.371573856

20 mm tolerance

k (N/m)	Tolerance (m) (dx)	F (calculated)	Slope Error (approximate)
2.01E+00	0.02	0.040233353	0.000329182
9.60E+03	0.02	191.9385797	1.570406561
2.21E+04	0.02	442.7717512	3.622677964
3.75E+04	0.02	749.9062617	6.135596687
5.34E+04	0.02	1068.947087	8.745930713
6.82E+04	0.02	1364.25648	11.16209847