Supplementary Information for:

Towards Automated Manufacturing Process Chains for Freeform Optics with Effective Reference Structures

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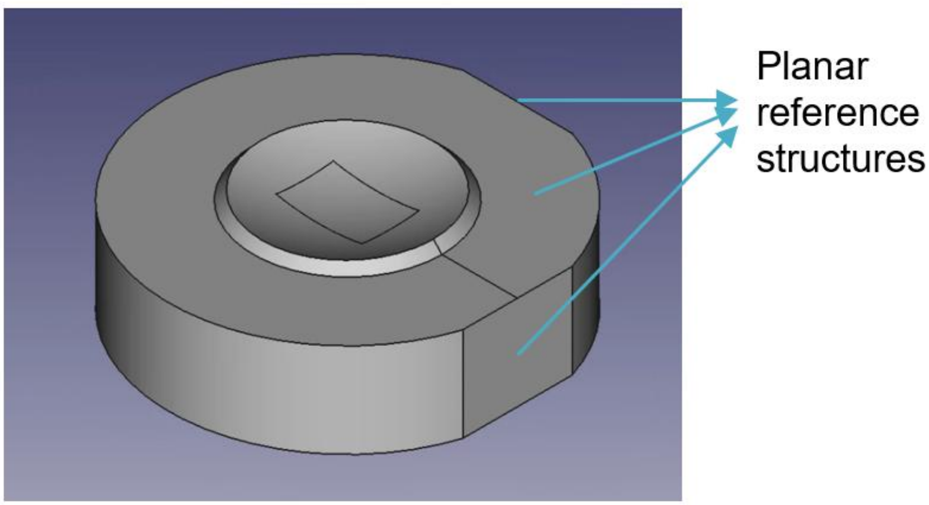
Questionnaire for the industry survey on reference structures

The full questionnaire is provided as follows. There are four sections with nine questions that cover the design, fabrication, and registration of reference structures in the process chain.

Section 1: Introduction
What is this survey about? Reference structures are physical features precision fabricated in addition to the optical surface to help establish an absolute coordinate system for the part. Such reference structures are often referred to by many names including datums, fiducials, alignment features, etc.    Reference structures, along with registration methods, can be used to properly align a part onto machines, to recreate the position and orientation of a part in metrology software, and to make assembly easier and more accurate. This repeatable alignment is particularly important for the manufacturing of freeform systems where the lack of symmetry necessitates more robust alignment procedures. **Why we are doing this survey and why it is useful:** We want to investigate the application of reference structures in the freeform optics industry. Through this survey, we would like to learn more about the standard process chains and machine-related practices involving any kind of reference structures and registration methods in the fabrication, metrology, and assembly of freeform optical systems. The application of reference structures along with repeatable and reproducible registration methods in the manufacturing process chain could bring huge improvement in time- and cost-efficiency, yet there is a lack of deeper understanding and standardization of such reference structures. The results of this survey will help us identify requirements, develop standards, guidelines,

and software for reference structures, which could benefit the freeform optics industry by promoting better concurrent engineering.

This survey is divided into several sections. Each section covers a part of the process chain in the production of freeform optical systems. ***Please try to answer the questions to the best of your knowledge. If you find overlapping between questions, there is no need to repeat. Just make a simple statement about what has already been covered and include any supplementary information if needed. Thank you!***

Number of questions: 9

Definitions of the terms that will appear in this survey.

Reference structures: physical features that are precision fabricated in addition to the optical surface to help establish absolute coordinate systems for the part.

Registration: the action of aligning the optical part on the fabrication and metrology machines, as well as during assembly.

Alignment errors: 3 translational and 3 rotational deviations from the intended location and orientation of the part.

Section 2: Design of reference structures

This section of the survey contains questions that relate to the design process of reference structures.

This section also addresses how tolerances of the reference structures contribute to the alignment errors of the part.

1. How do you choose the geometries and locations of the reference structures?

The following are some examples of additional ideas you can further address in this question.

- Who usually designs/modifies the reference structures and when are the reference structures usually designed/modified in the entire process chain?
- What are the main functions of the reference structures? In which production stages (fabrication, metrology, assembly) do they play a role?
- What are the criteria that you evaluate when choosing the geometries/locations of the reference structures?
  - How do different methods/machines of fabrication, metrology, and assembly influence these criteria?
  - Are there any public guidelines or standards that you follow and how fitting are they to your needs?

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2. How do you specify the tolerances for the reference structures?

The following are some examples of additional ideas you can further address in this question.

- How are the alignment error tolerances for optical components translated to the tolerances of reference structures, or vice versa?
- How do the tolerances differ for reference structures with different geometries (flat, curved, cylindrical, other)?

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3. Based on your experience, how does each of these possible fabrication errors of the reference structures contribute to the alignment errors of the optical part?
    - Position/Centration error
    - Surface form error
    - Surface roughness error

Section 3: Fabrication of reference structures

This section of the survey contains questions that relate to the fabrication process of reference structures.

1. How is the **fabrication procedure** of the reference structures determined?

The following are some examples of additional ideas you can further address in this question.

- When are the reference structures usually fabricated in your processes?
- How do you choose the fabrication method(s) for the reference structures?

2. How are the reference structures **tested**?

The following are some examples of additional ideas you can further address in this question.

- What metrology methods do you usually use for different reference structure geometries (e.g., flat, cylinder, spheres, etc.)?
- What parameters do you usually measure?

3. In the case of having multiple sets of reference structures for a single part, how do you usually control the relative position errors between each set of them during the fabrication of reference structures?

Section 4: Registration with reference structures

This section of the survey contains questions about the methods of registration.

1. What is the general procedure of registering a part with reference structures?

The following are some examples of additional ideas you can further address in this question.

- How many degrees of freedom are constrained by the reference structures?
- What registration methods and apparatuses are commonly used?
- How does the use of standard or custom coupling fixtures influence the registration process?
- How are the registration processes different in different production stages (e.g., fabrication, metrology, assembly)?

2. How do you evaluate the **alignment accuracy** (in respect to a global coordinate system) and **alignment repeatability** (precision) of your registration methods in each production stage? What metrics do you measure to evaluate them?

3. In the case of having multiple sets of reference structures for a single part, how do you relate different sets of them (coordinate systems) together?

Visualization of the varying tilt between individual measurements

Figure S1 shows the form error of the three individual measurements of the toroid test piece used to validate the CAD tool. Additionally, Figure S1d shows the coefficients when fitting each form error using Fringe Zernike coefficients. The main difference is in the coefficients for Z2 and Z3 corresponding to tilt.

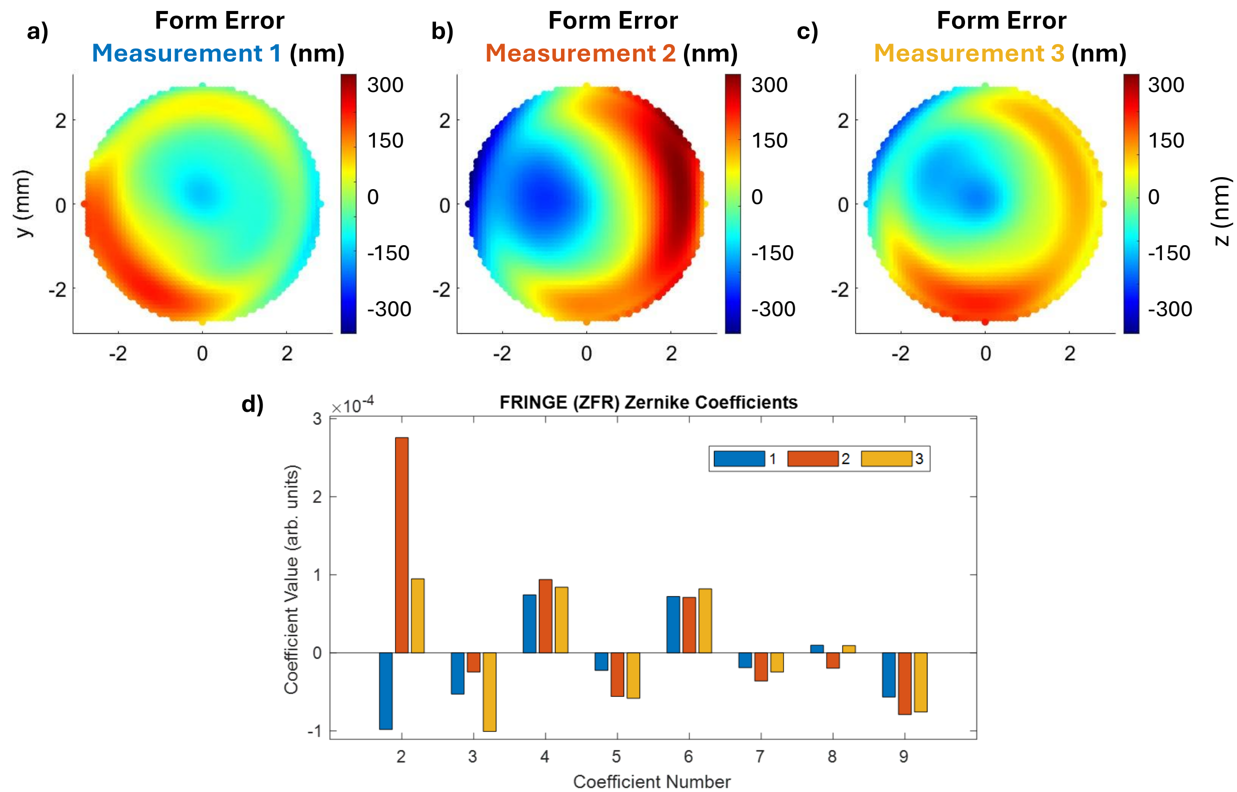
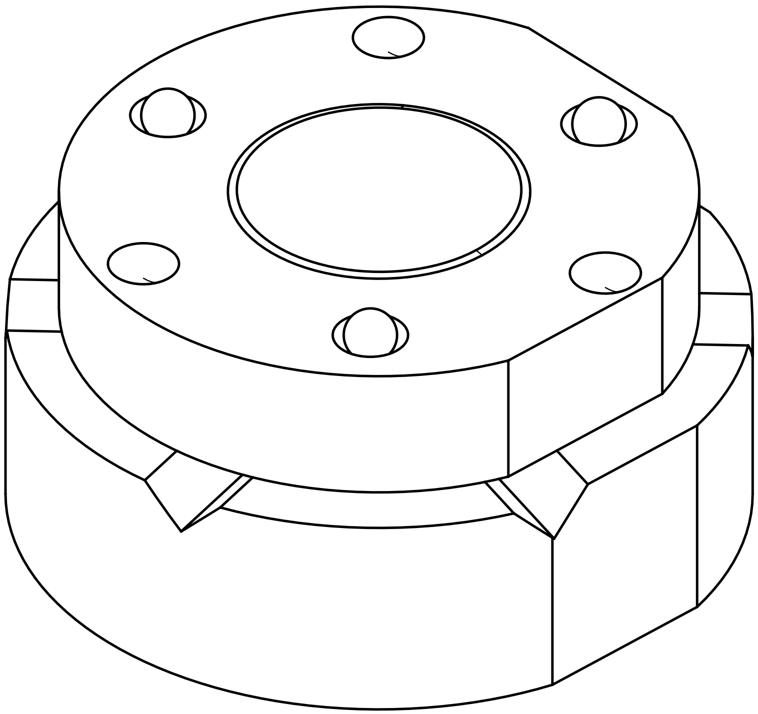
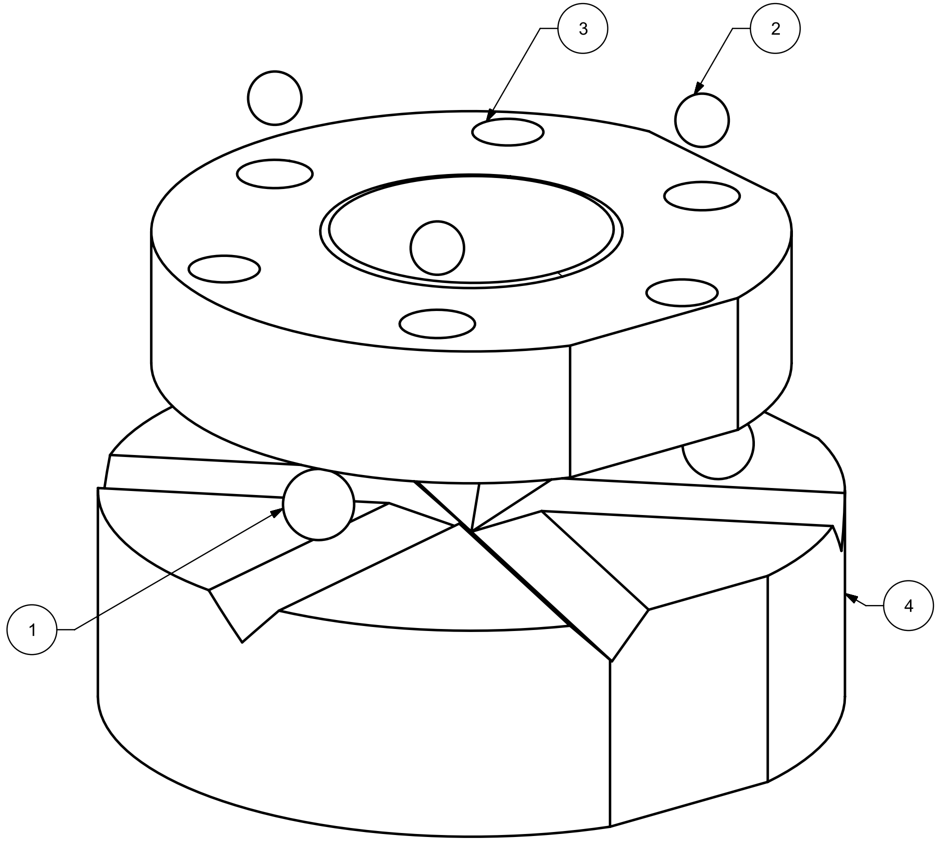


Figure S1. Visualization of the variation in form error between individual measurements. a, b, c. Three individual measurements of the as-built surface form error in respect to the reference structure (RS) coordinate system (CS). **d.** Coefficients for the Fringe Zernike Fitting of each of the three form errors up to Z9.

GD&T technical drawing for the anamorphic asphere test component

The technical drawing shown below contains key dimensions and GD&T compliant tolerances for all reference structures on the test components and the freeform optical surface. Detailed surface description is attached after the drawing.





PC NO	PART NAME	QTY
4	TOROIDMOUNT	1
3	[Toroid Part]	1
2	1.5MMSPHERE	3
1	2MMSPHERE	3

NOTES:
1. THE BALLS ARE GRADE 10 SILICON CARBIDE BALLS
2. THE BALLS SHOULD BE ADHERED TO THE CONIC POCKETS

ALL DIMENSIONS IN MM

FIRST ISSUED	02/16/2025	UNIVERSITY OF ROCHESTER	
DRAWN BY	ANJELI ESTRADA	TITLE: ASSEMBLY	
MATERIAL			
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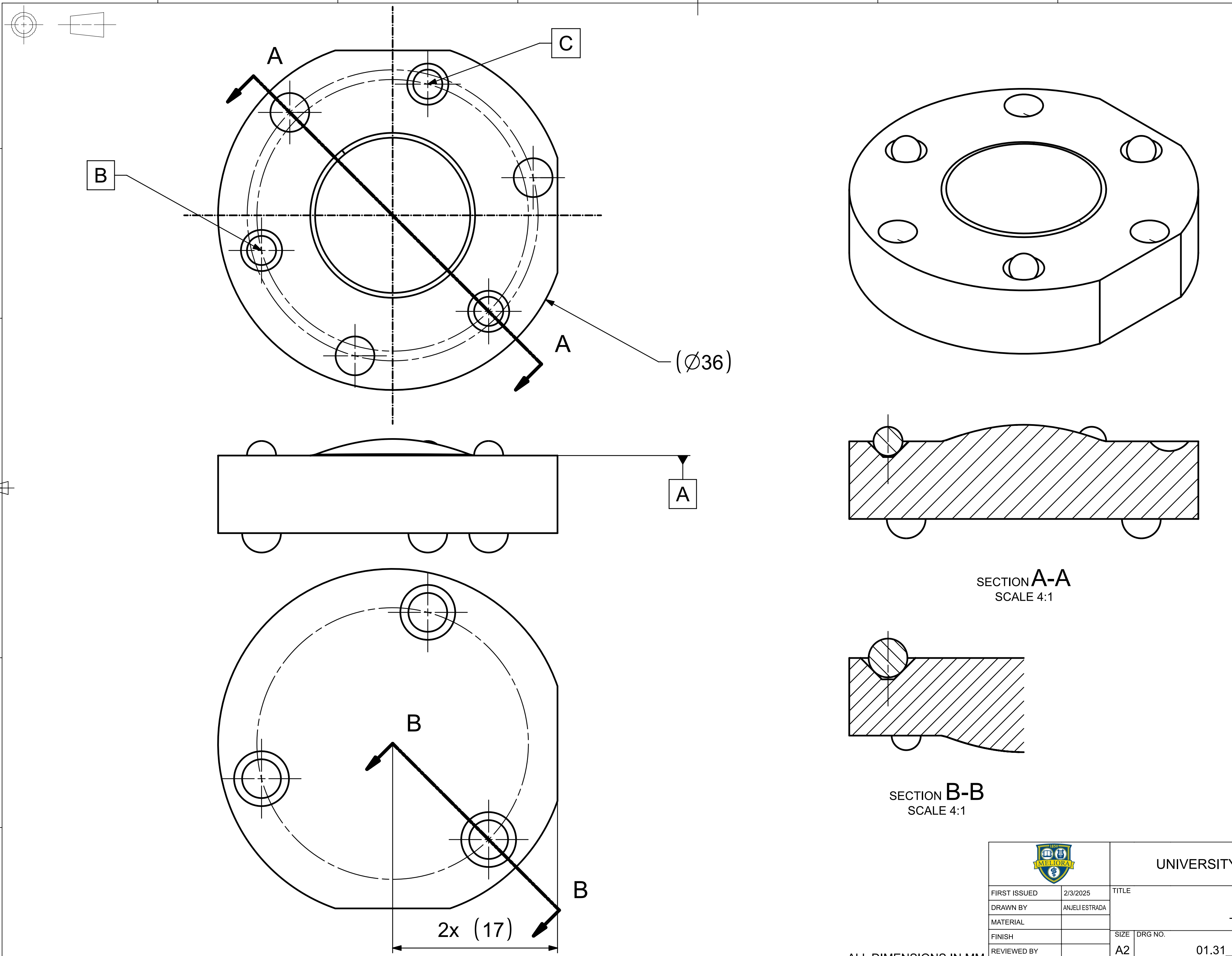
REVIEWED BY		SCALE 5:1	SHEET 1 OF 1



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REVIEWED BY		
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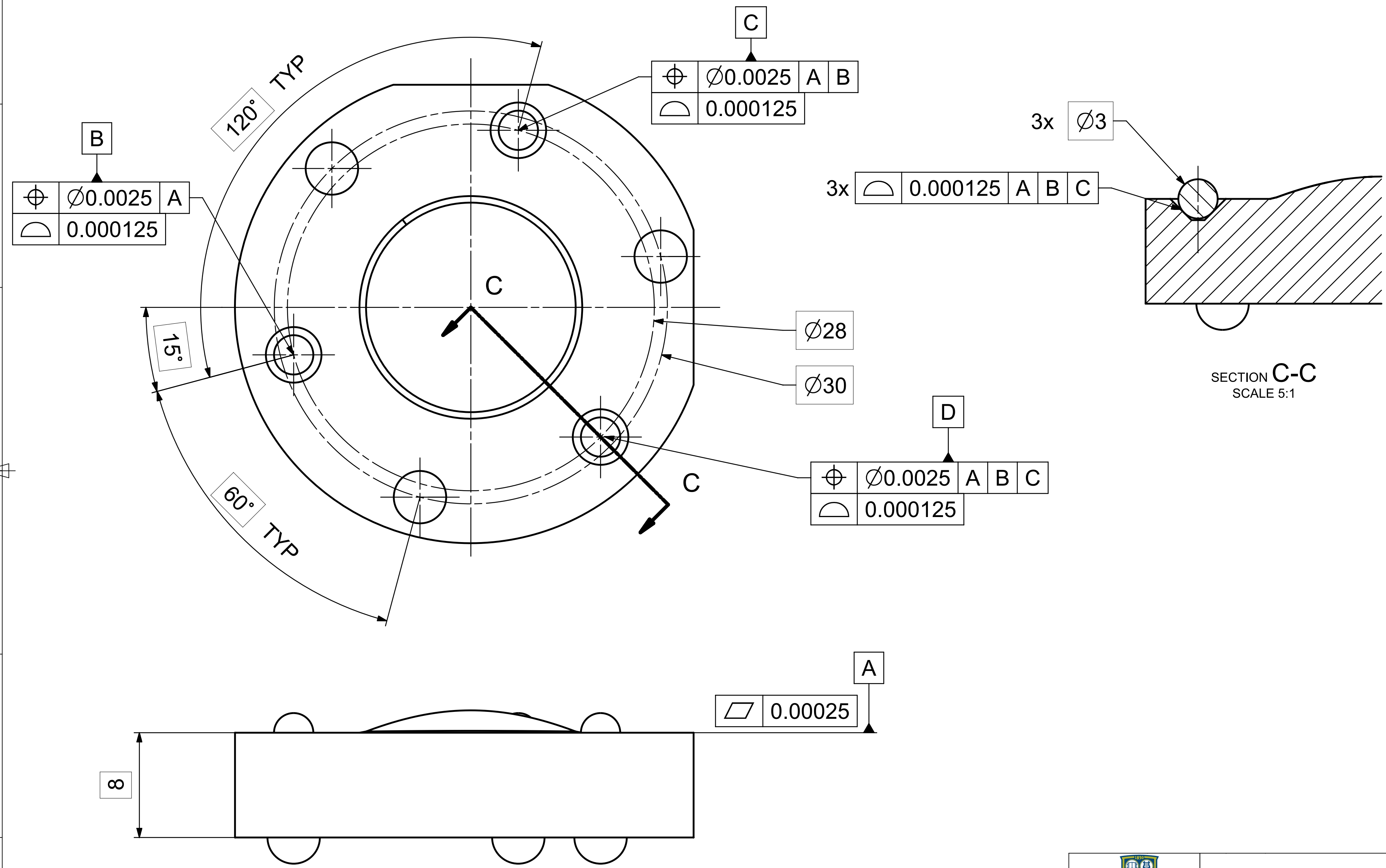

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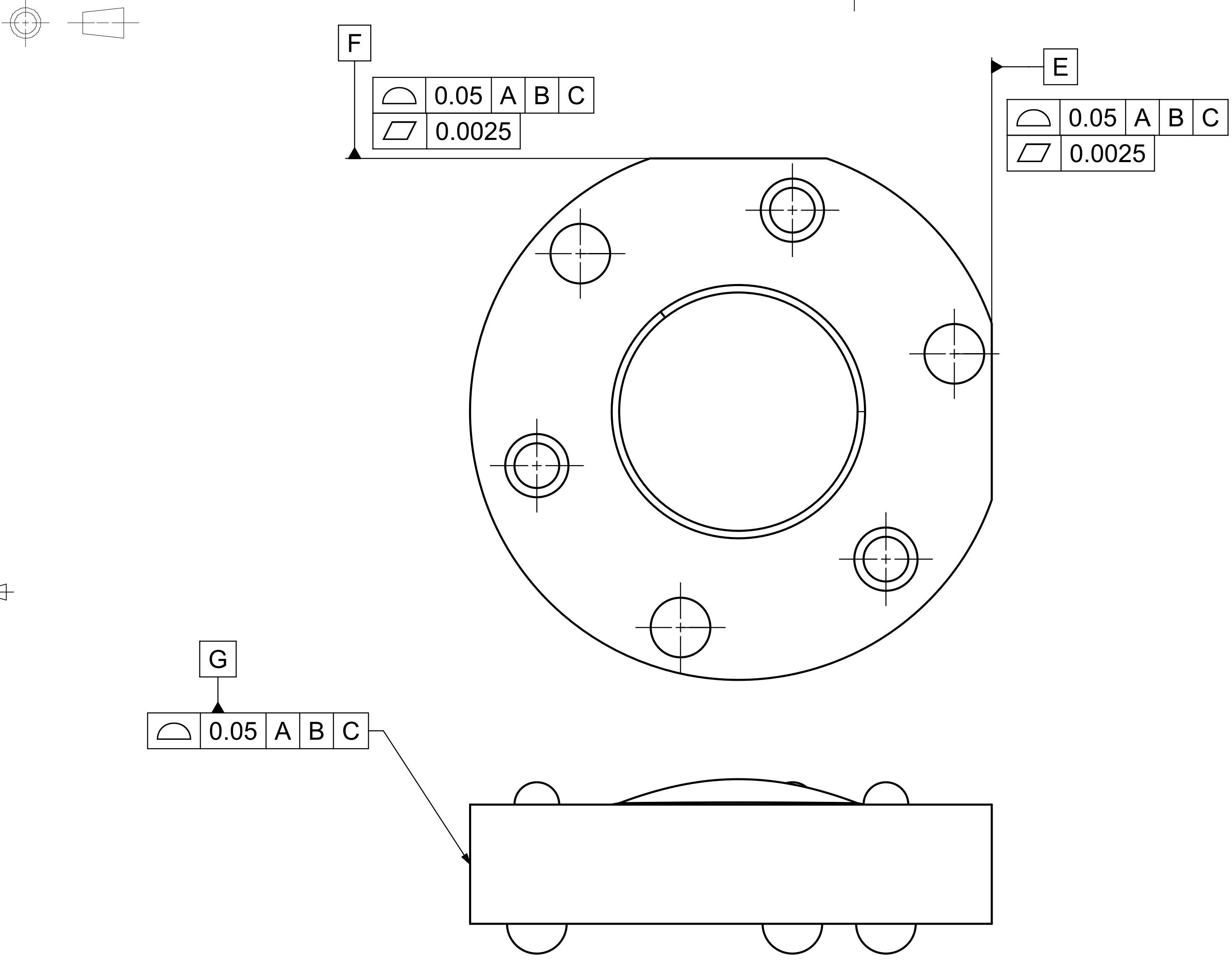

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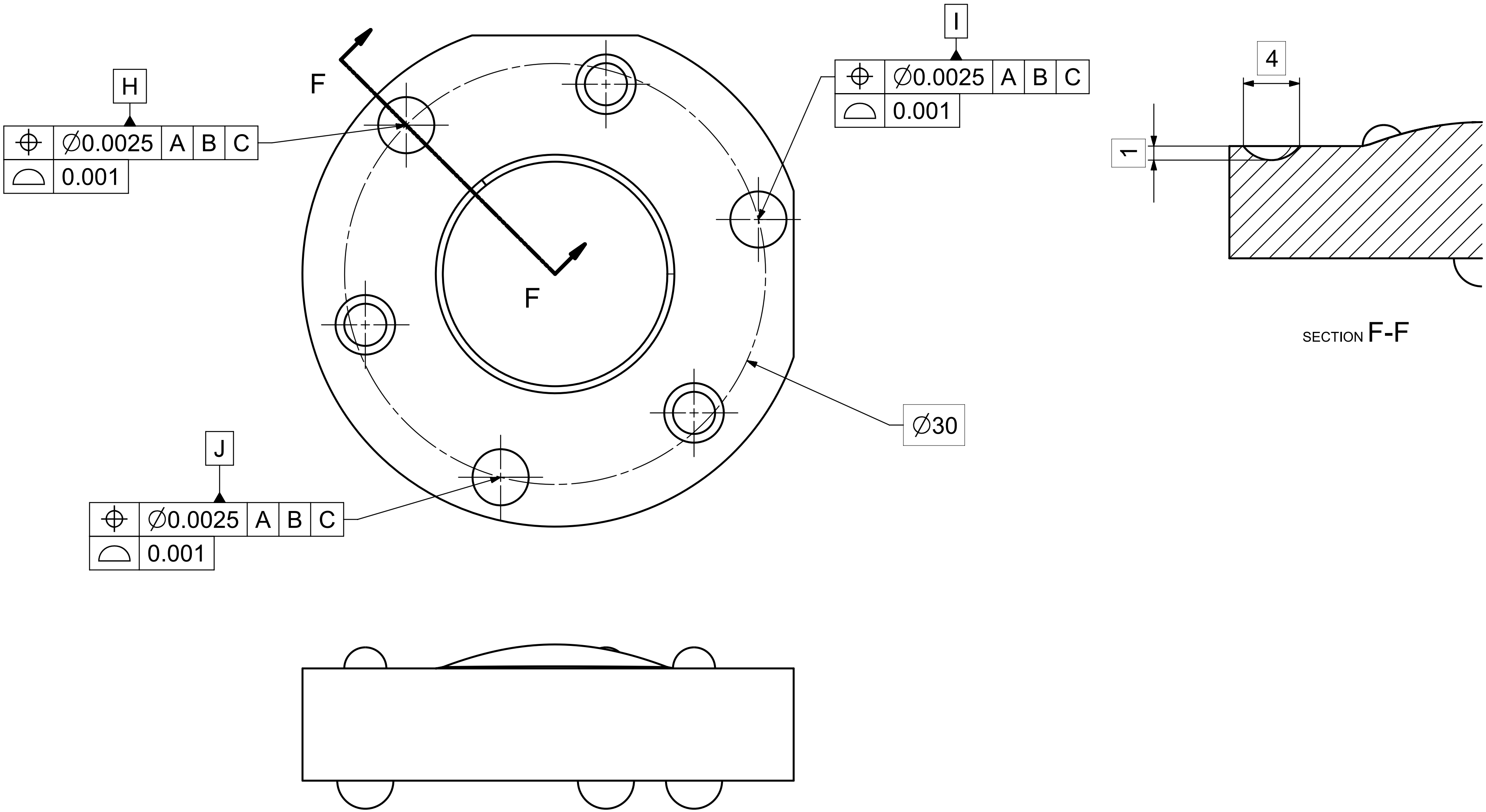

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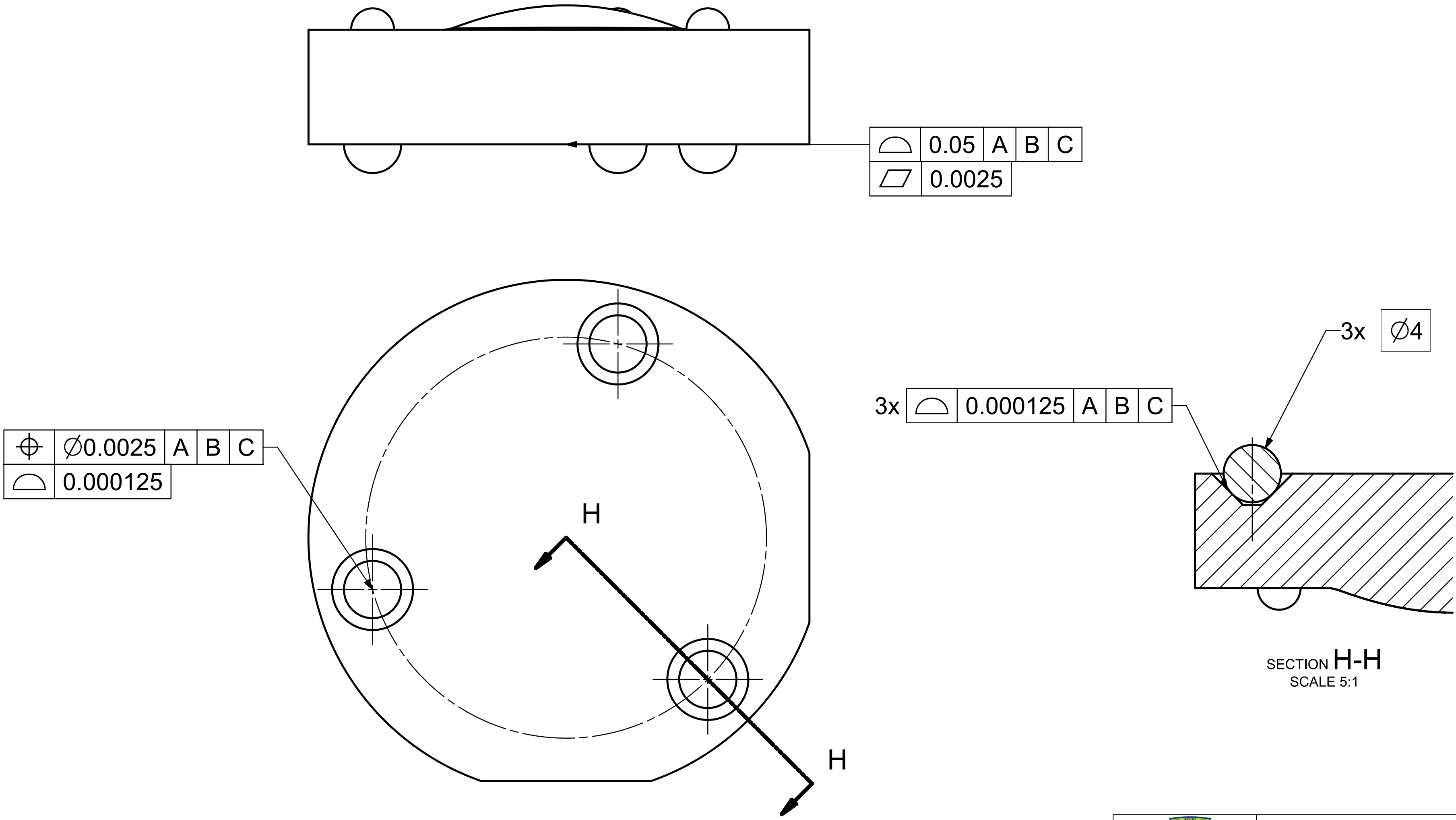

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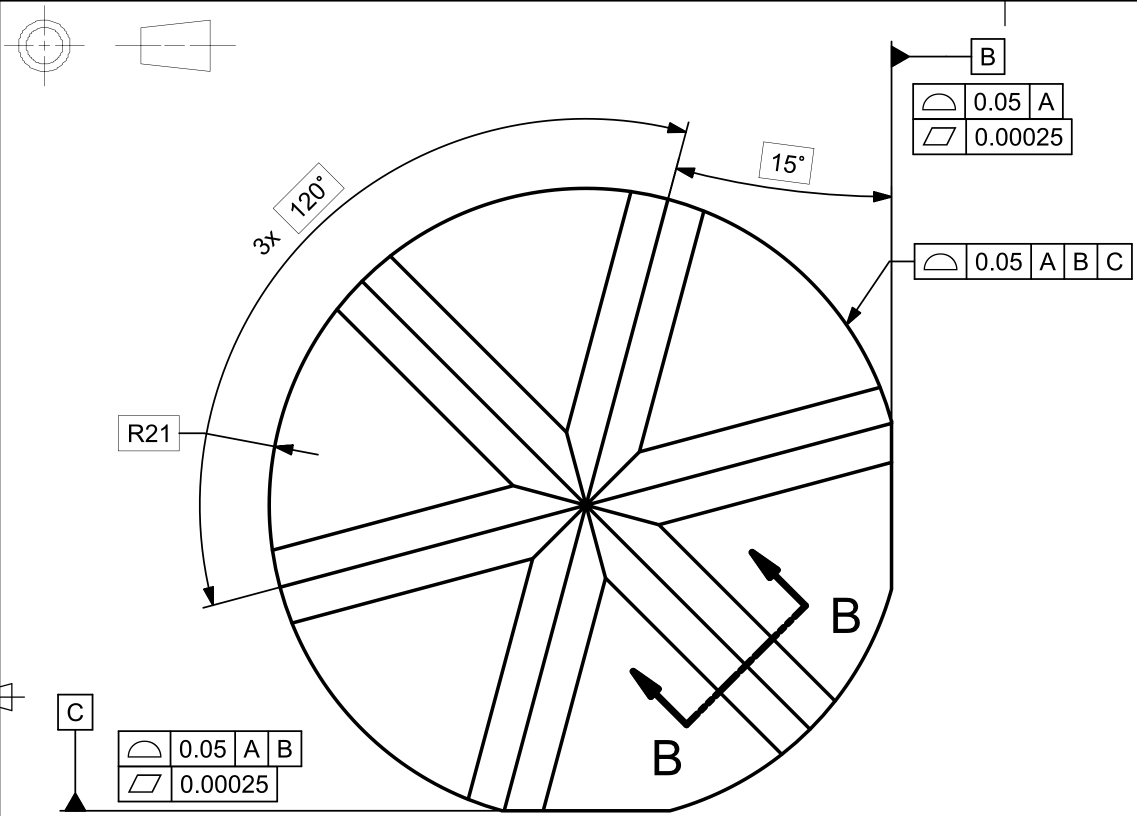

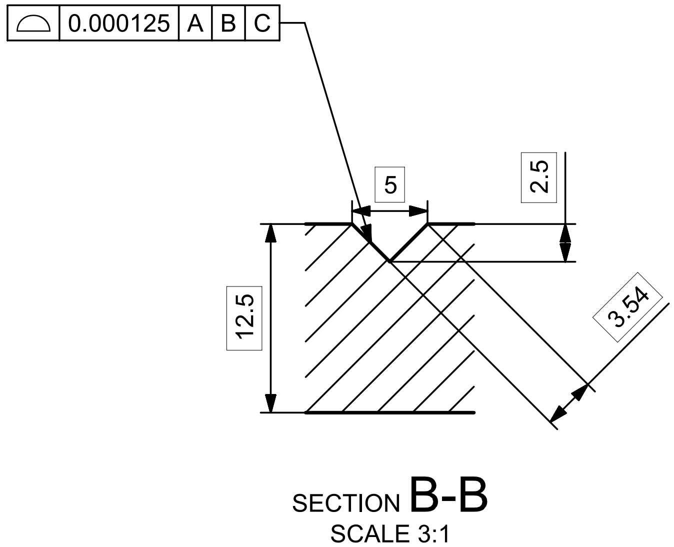

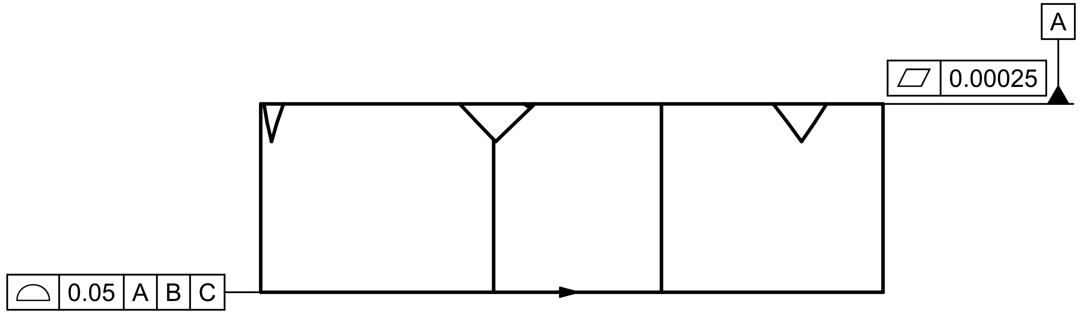

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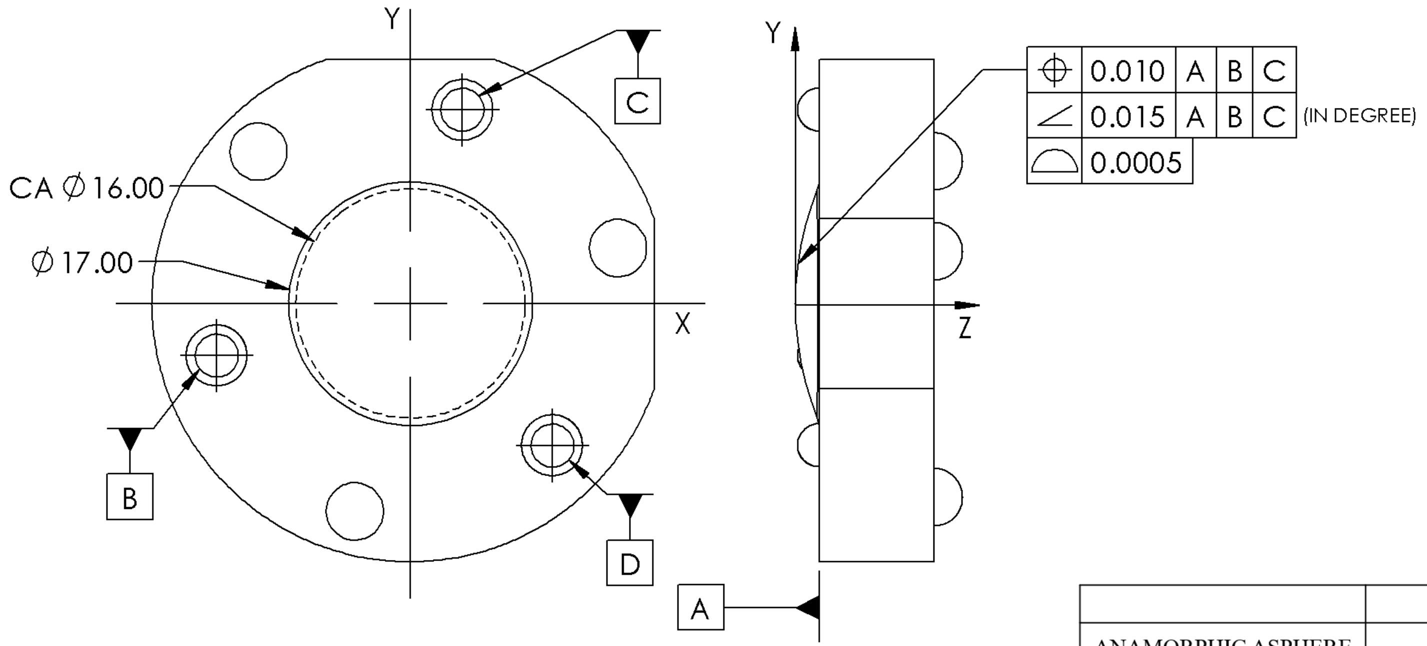
FINISH		SIZE	DRG NO.	SHEET REV
REVIEWED BY		A3	toroidMount	A
		SCALE 3:1		SHEET 1 OF 1



ANAMORPHIC ASPHERE COEF		SAG TABLE			
		X	Y	Z	S
		-8.000	0.000	1.614373	20.66610°
R_x	18.5	-4.000	4.000	0.822656	15.66022°
R_y	19.0	-4.000	0.000	0.424808	11.78593°
KX	0.0	-4.000	-4.000	0.822656	15.66022°
KY	0.0	0.000	8.000	1.561512	19.89048°
AR	-5.0e-5	0.000	4.000	0.413024	11.45050°
BR	0.0	0.000	0.000	0.000000	0.00000°
CR	0.0	0.000	-4.000	0.413024	11.45050°
DR	0.0	0.000	-8.000	1.561512	19.89048°
AP	0.0	4.000	4.000	0.822656	15.66022°
BP	0.0	4.000	0.000	0.424808	11.78593°
CP	0.0	4.000	-4.000	0.822656	15.66022°
DP	0.0	8.000	0.000	1.614373	20.66610°

NOTES:

1. MATERIAL: METAL ALLOY
   TYPE: NICKEL-PHOSPHORUS, HIGH-P
2. SCRATCH DIG (ISO 10110-7:2017) 60-40
3. NO COATING ON SURFACE
4. RMS SURFACE ROUGHNESS ON S1 < 10 Å
5. THE OPTICAL SURFACE IS DEFINED BY ANAMORPHIC ASPHERE IN CODE V. PLEASE SEE THE APPENDIX FOR DETAILED SURFACE DESCRIPTION
6. THE CLEAR APERTURE IS MARKED WITH THE DASHED LINE AND HAS A DIAMETER OF 16 MILLIMETERS
7. THE 17 MM DIAMETER APERTURE SHOULD BE COPLANER WITH DATUM B. THE FORM OF THE TRANSITION AREA BETWEEN THIS APERTURE AND THE CA DOES NOT NEED TO BE CONTROLLED

ALL DIMENSIONS IN MM

UNIVERSITY OF ROCHESTER

FIRST ISSUED	2/3/2025
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MATERIAL	
FINISH	
REVIEWED BY	

TITLE: TOROID

SIZE: A2 | DRG NO.: 01.31_toroid_asm | SHEET REV: A

SCALE 5:1 | SHEET 7 OF 7

AA_Toroid Surface Description Report

March 21, 2025

1. AA_Toroid Surface Definition

This surface is an **Anamorphic Asphere**

$$z = \frac{(CUX)x^2 + (CUY)y^2}{1 + \sqrt{1 - (1 + KX)(CUX)^2x^2 - (1 + KY)(CUY)^2y^2}}$$

$$+AR[(1 - AP)x^2 + (1 + AP)y^2]^2 + BR[(1 - BP)x^2 + (1 + BP)y^2]^3$$
$$+ CR[(1 - CP)x^2 + (1 + CP)y^2]^4 + DR[(1 - DP)x^2 + (1 + DP)y^2]^5$$

z	The sag of the surface along the z-axis as measured from the plane of the vertex
CUX, CUY	The curvature of the surface in x and y, where CUX = $1/R_x$, CUY = $1/R_y$
KX, KY	The conic constant in x and y
AR, BR, CR, DR	The 4^{th}, 6^{th}, 8^{th}, 10^{th} Order Symmetric Coefficient
AP, BP, CP, DP	The 4^{th}, 6^{th}, 8^{th}, 10^{th} Order Asymmetric Coefficient

2. AA_Toroid Surface Parameters

Parameters	Value
X Radius (R_x) [*1]	18.5 mm
Y Radius (R_y) [*1]	19 mm
X Conic Constant (KX)	0
Y Conic Constant (KY)	0
Clear aperture radius	8 mm
4th Order Symmetric Coefficient (AR)	-5.000e-05

[*1] Sign is based on the coordinate aligned with the surface normal at the vertex.

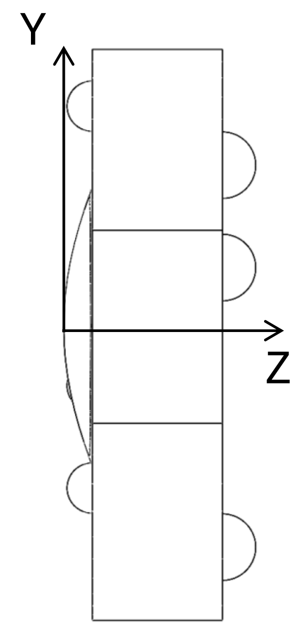

Figure 1. Coordinate axis orientation at the vertex.

4. AA_Toroid Surface Profile

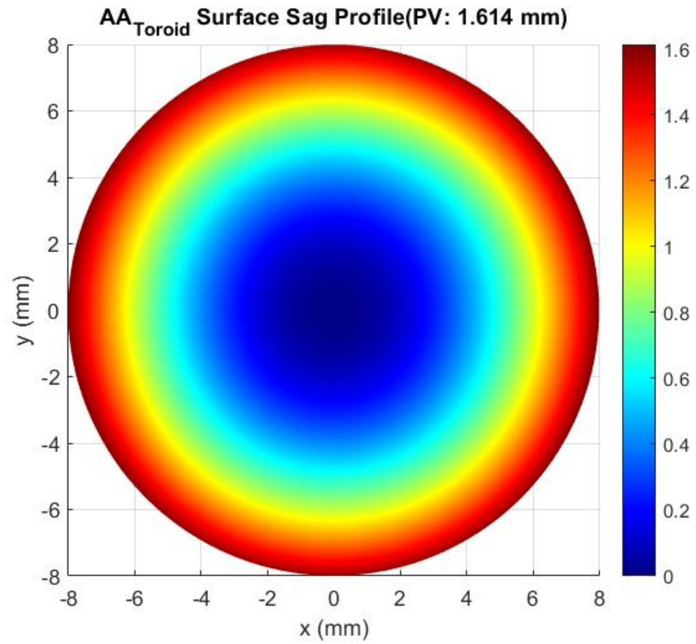

Figure 2. Total surface sag with Z axis aligned with the surface normal at the vertex.

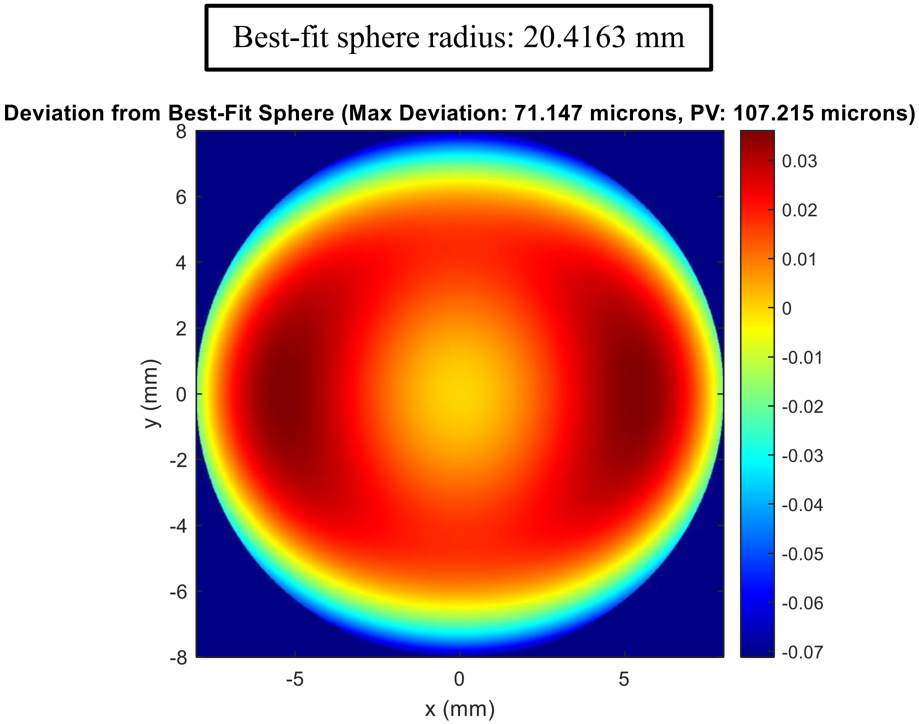

Figure 3. Surface sag departure to the best fit sphere R=20.4163mm. The Max Deviation is absolute value of the maximum departure.