

SIMPLE TECHNIQUE FOR FABRICATION OF TOROIDAL SURFACE WITH A BENDER AND CYLINDRICAL POLISHING MACHINE

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ABSTRACT

Toroidal surfaces are required as optical elements for the mirrors which are used as grazing incidence for focusing x-ray beams in synchrotron- radiation beam lines. Toroidal surface has two radii of curvature in perpendicular planes. We present a simple technique to fabricate a toroidal surface by designing a bender and using conventional cylindrical grinding/polishing machine. A bender is designed to hold a glass strip in a stressed condition to form a curved surface. Long radius is generated by the bender and short radius of curvature is generated by grinding using cast iron tools. Jigs and fixtures are designed to hold the bender and fix the tool on the cylindrical polishing machine (CPM). After generating the toroidal surface, it is polished by using pitch polishing tool. The profile was measured using a coordinate measuring machine.

KEYWORDS: Design of Bender, Fabrication of Synchrotron Mirror, Grinding, Overhanging Beam and Polishing

INTRODUCTION

Toroidal mirrors are focusing devices having two different radii whose axes are oriented perpendicular plane as shown Figure 1. They are used for controlling the propagation and imaging of x ray beams in synchrotron-radiation beam lines [1], and at instances where optics at grazing incidence are required. Toroidal mirrors also correct the astigmatism that result when a spherical mirror is used off axis.

Different types of machining processes are used to fabricate the toroidal mirror. Plasma chemical vaporization machining is done by using numerically controlled plasma machine [2]. Another method is to generate a toroidal surface with bonded cup wheel which is numerically controlled using a programmable controller [3]. Another method involves using a bender to maintain the long radius of curvature during the experimental period. The bender is designed to provide bending moment on both sides independently [4]. We present a simple technique to fabricate toroidal surface by designing mechanical bender and machining using a conventional cylindrical polishing machine. To generate the long radius of curvature, the bender is used to bend the glass strip convex shape and hold it in a stressed condition within elastic zone. Overhanging beam with symmetrical loads configuration is applied to the bend of the glass strip. Between two reactive support bending moment is constant and shear force is zero. So, the Actual cylindrical shape of the work piece is generated between two reactive support. The bender with strip in stress condition is fixed to the conventional cylindrical polishing machine. Conventional cylindrical grinding/polishing machine is used for generating short radius of curvature. After grinding and polishing the strip is released from the bender. The Long radius surface is generated reverse direction in a concave shape

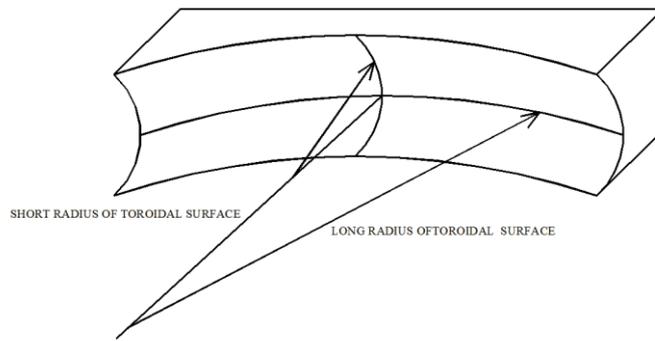


Figure 1: Diagram of Toroidal Mirror

WORKING PRINCIPLE OF BENDER

Bender is a device which contains a number of links to provide constant bending moment over the required length of work piece. A typical bender is shown in Figure 2. It consists of a main block with rollers, two arms of applying load on the work piece and nut and screw arrangement for generating the force for bending. The screw is fixed to the main block and supporting plate by using ball bearings at both ends. The nut is fixed on the supporting bar. The supporting bars moves linearly by rotating the screw in the nut and using the slide pairs which restricts the rotational motion. When the links (arms) are moved downwards, the ends of the glass blank strip are pulled by both the arms. The two rollers resist the linear motion of the strip resulting in bending on the rollers points. The arms are joined to the supporting bar with hinges to accommodate angular tilting. Fixtures for locking the work piece in the required stressed condition are attached with bender and glass strip arm as shown in Figure 3.

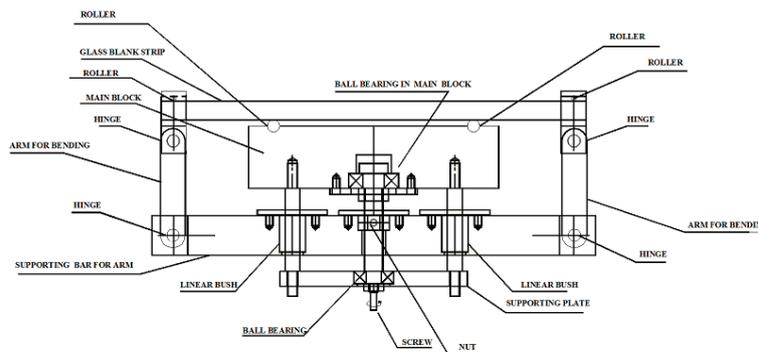


Figure 2: Schematic Diagram of Bender



Figure 3: Bender with Glass Strip in Stress Condition

DESIGN PROCEDURES AND MATERIAL SELECTION OF BENDER'S COMPONENTS

Calculation of Minimum Radius of Curvature of Glass Strip

A float glass strip of size 320 mm x 25 mm x 12 mm was taken. As the bender bends the strip in a circular shape, we calculated the minimum radius of curvature of the strip at which the strip would fracture. The bender's components were designed to consider overhanging symmetrical loads as shown in Figure 4

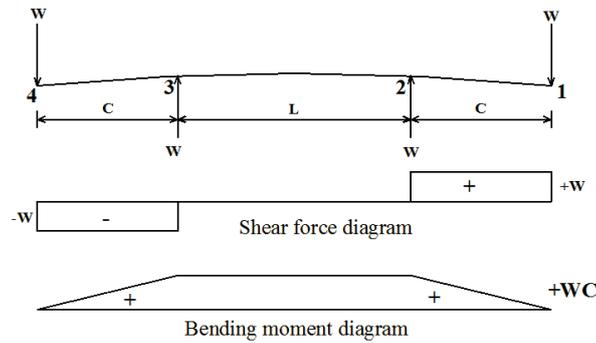


Figure 4: Overhanging Beam Configuration with Symmetrical Load, Shear Force and Bending Moment Diagram

Table 1: Float Glass (Sic 600) Properties

Modulus of elasticity (E)	64 GPa
Bending stress (σ_b)	81 MPa

Using bending equation, Bending stress (σ_b) = M / Z (1)

Section modulus (Z) = I / y (2)

Bending moment (M) = $W.C$ (3)

Where W denotes applied load, C is the distance between support and applied load, I the moment of inertia and y the distance between neutral axis and the top of the strip.

The glass strip is considered as an overhanging beam with a symmetrical load as shown Figure 4 above. Bending moment will be constant over the length L.

From Eq. (1), Bending stress between the two supports is given by, $\sigma_b = M / Z$

The Deflection (δ) in the center of the strip will be:

$\delta = ML^2 / (8EI)$ (4)

Calculation for radius of curvature and deflection at the center of the glass strip:

The size of the strip = 320 mm x 25 mm x 12 mm.

Moment of inertia (I) of rectangular section

$I = bh^3 / 12$ (5)

Moment of inertia of glass strip

$$I = 3600 \text{ mm}^4$$

$$y = 6 \text{ mm}$$

From Table 1, Bending stress of float glass is $(\sigma_b) = 81 \text{ MPa} = 81 \text{ N-mm}$

Bending moment of the strip was calculated using eq. (1) and eq. (2)

$$M = \sigma_b I/y \quad (6)$$

$$M = 48400 \text{ N-mm}$$

Applied load (W) on the strip by bender

$$W = M/C$$

$$C = 80 \text{ mm}$$

$$W = M/C = 48400/80 = 607.5 \text{ N}$$

Deflection (δ) at midpoint of the glass strip

$$\delta = ML^2 / (8EI) \quad (7)$$

L= distance between two reactive support

$$L = 160 \text{ mm}$$

Deflection of the strip in the center, using the values from eq. (7)

$$\delta = 0.672 \text{ mm}$$

Radius of curvature (R) is obtained using the bending equation:

$$R = L^2 / (8 \delta) \quad (8)$$

The minimum radius of curvature of the glass strip for 12 mm thickness of the strip using eq. (8)

$$R = 4761.90 \text{ mm}$$

So, we cannot bend the glass strip below the radius of curvature 4761.90 mm.

For designing the mechanical components of a bender, it is required to know the applied load on the bender. So, applied load was calculated for maximum size of glass strip 320 mm x 40 mm x 20 mm (thickness).

A similar procedure was used to determine the applied load on the glass strip.

Calculation for bender components''

Moment of inertia of thick glass of thickness 20 mm and 40 mm width using eq. (5):

$$I = 26666.66 \text{ mm}^4$$

$$y = 10 \text{ mm}$$

Bending moment of the strip is determined by using bending stress.

$$M = \sigma_b I / y$$

$$M = 216000 \text{ N-mm}$$

Therefore, the applied load W is:

$$W = M/C = 216000/80 = 2700 \text{ N}$$

Deflection (δ) of the strip in the center is given by, $\delta = 0.405 \text{ mm}$

So the minimum radius of curvature of glass strip is, $(R) = L^2 / (8 \delta) = 7903.18 \text{ mm}$

So, we cannot bend the strip below the radius of curvature of 7903.18mm.

Bending moment for the strip = $216 \times 10^3 \text{ N-mm}$

Applied load $W = 216 \times 10^3 / 80$

$$W = 2700 \text{ N}$$

The deflection at the center = $405 \mu\text{m}$, radius of curvature = 7.90 m

Design and Selection of Main Block

The size of the main block was selected to be 200 mm x 50 mm x 50 mm with supporting screw pair and rollers at 160 mm to provide bending of a 320 mm x 40 mm x 12 mm glass strip over 160 mm. The material of the main block was selected as aluminium grade 6061-T6. Aluminium is chosen as it has low density and therefore will not disturb the polishing parameters

Selection of Bearings for Fitting the Screw

According to the size of the block, a ball bearing SKF 6203-2Z was chosen to support the screw its size is outer diameter 40 mm and inner diameter 17 mm and other SKF ball bearing 6201-2Z/C3 its size outer diameter 32 mm and inner diameter 12 mm. M15 x 1 screw was chosen to movement of the arm. The material of screw was selected medium carbon steel EN8 grade.

Tensile stress in screw was calculated;

carbon steel grade EN8 yield stress (δ_{yt})

$$\delta_{yt} = 245 \text{ MPa}$$

Tensile stress = P/A

Where P is applied load on the screw and A is section area at root diameter

$$P = 2W = 2 \times 2700 = 5400 \text{ N}$$

Section area of the screw at root diameter (A) = $151.45 \text{ mm}^2 = 0.000151 \text{ m}^2$

Stress induced in screw = $5400/0.000151 = 35.76 \text{ MPa}$

Yield stress of EN 8 grade carbon steel = 245 MPa

Factor of safety (FS) = yield stress/induced stress (working stress)

$$FS \text{ for screw} = 245 / 35.76 = 6.8$$

It means the screw is safe. Factor of safety is more sufficient up to 3. We consider here that the elongation should be minimum so that the desired long radius can be generated accurately.

Load (W) is applied on both sides of the block in which a screw is rotated to move a bar to linear motion. After bending process, the screw bears the loads (2W) then induced stress is 35.76. Its stress is applied to the aluminium main block which size is 200 mm x 50 mm x 50 mm. The main block is used to fix the screw with sliding support using linear bush THK LM12UU

Supporting Bar for Bending Arm

A bar which size was 320 mm x 35 mm x 32 mm. The function of the bar is to bear the load (W) on both ends. The load was applied to the bar in overhanging symmetrical loads configuration. The material selected was aluminium grade 6061-T6 due to lower density. The induced stress in the bar was also evaluated and verified to be less than the yield stress of the bar.

From eq. (1), Bending stress (σ_b) = M/Z

$$M = 2700 \times 95 = 256500 \text{ N-mm} = 256.5 \text{ N-m}$$

$$\text{Moment of inertia of the bar (I)} = 95573.33 \text{ mm}^4$$

$$Y = 16.00 \text{ mm}$$

$$Z = I / y$$

$$Z = 95573.33 \text{ mm}^3 = 0.0001 \text{ m}^3$$

$$\text{Bending stress} = 2.56 \text{ MPa.}$$

The value of bending stress of the aluminium bar is very less compared to the yield stress 386 MPa and therefore the bar is safe functioning.

Calculation for deflection of the bar at the end:

Applied load on the bar

$$W = 2700.0 \text{ N,}$$

$$C = 95 \text{ mm, } L = 130 \text{ mm, } I = 95573.33 \text{ mm}^4, y = 16 \text{ mm.}$$

$$E = 69.0 \text{ GPa}$$

Deflection at load (δ_1) of the bar

$$\delta_1 = W \cdot C^2 (2C + 3L) / 6EI \quad (9)$$

$$\delta_1 = 0.355\text{-mm}$$

Design and Material Selection for Arms for Bending

Two arms for bending were used to pull the glass strip. The material of the bar was selected to be stainless steel grade 304. Tensile load is applied to the bar. Tensile stress in the bar is evaluated as follows:

Size of arms was 76 mm x 20 mm x 6.5 mm.

Tensile Stress = Tensile load / Area

Tensile load = 2700 N

Area of the bar = 130 mm² = 0.00013 m²

Tensile stress = 2700/ 0.00013 = 20.77MPa

Its value is very less compared to the value of yield stress 185.0 MPa. So, the components are safe in function.

Young modulus (E) of the stainless-steel grade 304

E = 180.0 GPa

Stress in the bar = 20.77 MPa

E = Stress / Strain

Strain = Change in length / Original length

Strain = stress/ E = 20.77 / (180 x 1000) = 0.00012

Change in length = strain x original length

Change in length = 0.00012 x 76 = 0.00912 mm

Elongation in Stainless steel bar (link) is 0.0912mm

After attaching the glass strip with bender, under loading the arm of bending may be deflected. To resist the deflection, two locking plates were fixed to the bender.

FABRICATION OF GRINDING TOOLS AND POLISHER

Grinding tool was fabricated having a radius of curvature of 150 mm in a convex shape for grinding. The material selected was grey cast iron FG 300 whose tensile strength is 300 N/mm² and hardness between 180 HB to 230 HB. Pitch polisher was fabricated to polish the glass strip. The radius of curvature of polisher surface is formed by using the similar radius of curvature in a concave shape of the cast iron grinding tool.

METHOD FOR FABRICATION OF THE TOROIDAL SURFACE

A strip of float glass size 300 mm x 25 mm x 12 mm was mounted in a bender. Bender holds the strip in convex form by symmetrical loading in overhanging configuration within the elastic zone as shown in Figure 3. After grinding and polishing to form short radius of surface, relieving the stressed condition by unloading from the bender leads to the generation of concave surface with long radius. The radius of the surface is then evaluated by measuring the sag between the two supporting pins of the cylindrical meter as shown Figure 5. To generate circular shape of the part, bending moment should be maintained constant between the entire strip section or shear force should be zero. So, the pure circular shape can be generated between two reactive supports (rollers) of the bender. To generate the short radius surface in a perpendicular direction, bender along with the stressed strip was attached to the cylindrical grinding/polishing machine as shown in Figure 6. The glass surface was ground on the cylindrical grinding / polishing machine using coarse abrasives in three stages with a convex tool. The tool and dovetail guide are shown in Figure 7. Next the grinding tool and the work piece

along with the bender was detached from the machine. The machine and the workpiece were then cleaned using water to clear the rough abrasives.



Figure 5: Cylindrical Meter



Figure 6: Cylindrical Polishing Machine with Bender



Figure 7: Dovetail Guide and Tool for Grinding

The polishing tool was prepared with pitch and the convex shape was formed using concave master tool of the required radius. The workpiece and the polishing tool were then reloaded on the cylindrical polishing machine using dovetail guides to relocate the original positions during grinding. Relocation of the position is very important to maintain the surfaces generated during grinding. Next fine grinding and polishing was done by using fine grain size ($15\ \mu\text{m} - 1\ \mu\text{m}$) alumina abrasive. Finally, polishing was done using $0.5\ \mu\text{m}$ grain size polishing compound of cerium oxide. The polished surface is continuously inspected for scratches, digs and pits and polishing is continued till the surface is scratch free. The workpiece is then removed from the machine and cleaned. Next, the mirror strip is released from the bender. The strip settles into a concave surface of long radius and the concave surface of short radius in the perpendicular planes. The glass strip between the reactive supports is the desired toroid.

RESULTS AND DISCUSSIONS

A fabricated toroidal surface of a glass strip shown in Figure 8 was generated and coordinates of the surface were determined by coordination measuring machine (CMM) Model No. G90C LK, UK. A grey cast iron tool was fabricated which surface radius of curvature was 150 mm and 14000 mm of long radius of curvature surface was formed in convex shape by the bender. Surface profile of the short radius surface and the long radius was plotted as shown in Figure 9 and Figure 10 respectively. The radius was evaluated by curve fitting and was found to be 150.21 mm and 13.47 m for the short and long radius respectively.



Figure 8: Fabricated Toroidal Mirror

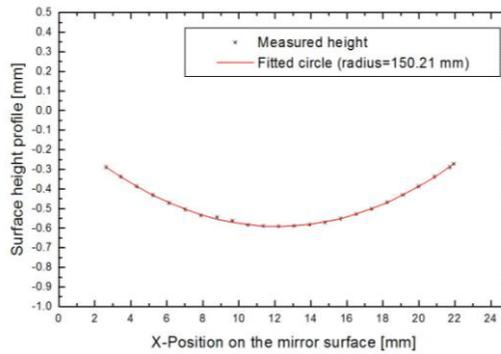


Figure 9: Generated Short Radius of Curvature Profile

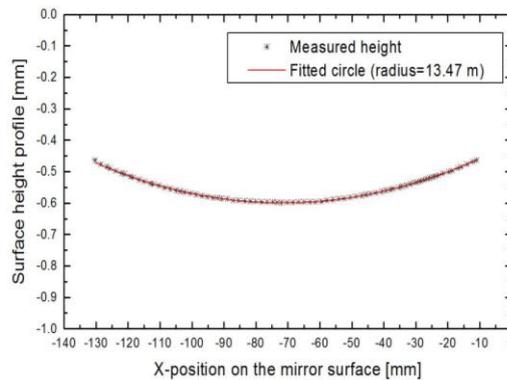


Figure 10: Long Radius of Curvature Profile

Short radius of the toroidal surface depends upon the radius of grinding tool and the stroke of the tool. Long radius of the surface depends upon the setting of sag of the glass strip in the bender and mounting of the components.

Results show the sag of the strip was increased during mounting the components. Due to material removal from the surface, the strength of strip decreases and hence the sag of the strip is increased.

CONCLUSIONS

Pure bending theory was applied in the overhanging configuration on the glass strip and designing of the bender's components. This technique was used to generate long radius and short radius together in grinding and polishing operations. We have fabricated toroidal surface on the float glass strip by using a bender and conventional cylindrical polishing machine.

ACKNOWLEDGEMENTS

We thank Y. Pavan Kumar, Sarvendra Singh for providing profile figures and Swapan Kumar Dey, D. Raghunathan for supporting fabrication of the toroidal surface. We also thank D.K. Jain for fabrication of bender's components and D.K. Ram for providing measuring data of surface with coordinate measuring machine at Raja Ramanna Centre for Advanced Technology, Indore.

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