ULE Mirror Edging

Opti523 – Independent Project

Prepared by: Amanda Smith

1. Overview

During the polishing of aspheric mirrors, a computer controlled polisher (CCP) is often used to figure the surface. This process typically causes an “up-edge” to occur near the OD of the mirror, since the polishing tool cannot overhang on the edge while running. A solution to this problem is to polish an oversized mirror and grind the edge down to final size once polishing is nearly complete; however for large mirrors this can be a messy and time consuming project. This design project suggests a new method for edging large aspheric mirrors in which the edge is cut off as a solid piece, specifically for the case of aØ100 inch ULE mirror. To do so, a mechanical method is needed to secure the residual glass and protect the final mirror.

2. Requirements

2.1. Top Level Requirements

- All modeling and analysis shall be completed in Pro-E/ Mechanica
- The overall stress in the residual shall stay less than 1000psi until the last millimeter of the cut (stress due to the weight of the residual, ignoring any stresses due to the saw)
- Safety factor (SF) of 5 incorporated into 1000psi value
- Stress defined as Principal stresses
- Optic safety shall be maintained with no risk of damage to the final diameter or the polished surface (damage defined as anything outside the expected fractures inherent to the sawing operation)

2.2. Derived Requirements

- Design a bridging mechanism to hold the residual glass during the cut
- Can be an adhesive or mechanical device, or combination of both

2.3. Interfaces

- ULE glass shall interface with a saw, whose imparted stress on the glass is not considered for this project
- Polished surface of the glass shall interface with a bridging tool
- Surface condition of the mirror – cannot use primers, cannot achieve a perfectly clean R1 surface in shop environment (which may be necessary for adhesives)

2.4. Environment

- Edging of the ULE mirror will occur on a shop floor
- Working temperature ranges between 65 and 75°F

2.5. Schedule and Cost

- No specified cost constraints
- Mirror edging shall complete in less than 40 hours

2.6. Design Preferences

- Prefer to complete the edge cut in larger, rather than smaller pieces
- Bridging component shall avoid or minimize the use of metal
- Bridging component shall bridge the gap on the polished surface

3. Design Concept

During the edging process, the ULE mirror will be fixed to a turn table that is raised at an angle to bring the edge of the mirror perpendicular to the saw. The mirror is specified as having a 0.5-inch thick lip that overhangs the edge by 2-inches. During edging, a 1-inch radius of the lip is removed. This arrangement is shown in Figure 1.

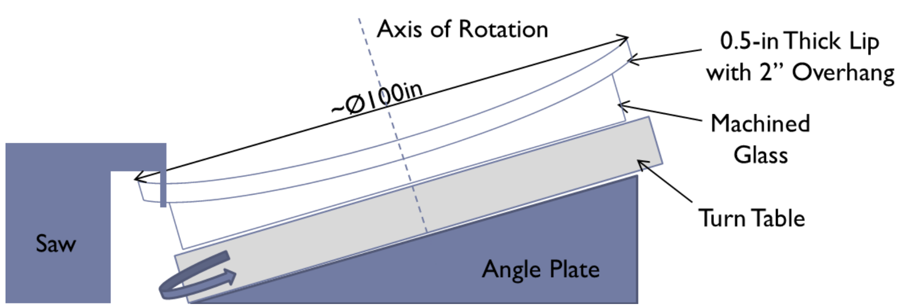


Figure 1: ULE Mirror Edging Setup

As the mirror is cut, the 1-inch wide residual creates a cantilever around the edge of the mirror. The optimal method for creating this cut is defined in terms of the size of each cut (in degrees) and the bridging method. For this project, two bridging methods were chosen. The first method utilizes a tab of ULE bonded over the kerf of the glass. The second method uses a clamp to secure the residual glass to the final optic. The final parameter for the mirror edging project is to determine the number of bridging components necessary.

4. Design Details

The following section reviews the four parameters of the mirror edging trade study: the size of the cut, the bridging mechanism, the adhesive type (for the case where a ULE tab is used as a bridge), and the number of bridges required.

4.1. Size of the Cut

The optimal size of the cut can first be approximated using the cantilever beam bending equations. These equations describe the self-weight deflection and maximum stress of a beam given its weight, dimensions, second moment of inertia, and the modulus of the beam material. Since any forces due to the saw are ignored in this problem, the residual glass that remains after a cut has been started can be described as shown in Figure 2 with a distributed force representing the weight of the beam.

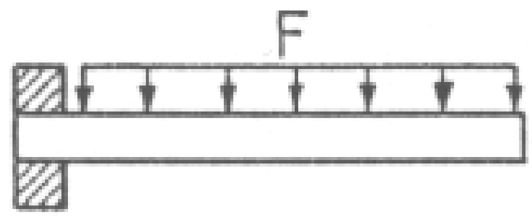


Figure 2: Self Weight Deflection Cantilever Model

The deflection and max stress for the geometry described are given in Equations 1 and 2. In these equations, the *F* is the force given the weight of the beam, *L* is the length of the beam, *E* is the elastic modulus of ULE, *I* is the second moment of inertia given the cross section of the beam (1" wide by 0.5" tall), and y_{max} is the y extent of the beam (half the height, or 0.25"). Table 1 describes the deflection and max stress given a 10, 20, and 30 degree cut.

$$Deflection = \frac{FL^3}{8EI}$$ Equation 1

$$Max\ Stress = \frac{FLy_{max}}{I}$$ Equation 2

Table 1: Deflection and Stress Given Size of Cut

Cut Angle *degrees*	Length *inches*	Weight *lbs*	Deflection *Inches*	Max Stress *psi*
10	8.73	0.34	0.0003	72
20	17.45	0.69	0.0045	289
30	26.18	1.03	0.0227	650

Since the ULE mirror is circular, the deflections and stresses shown in Table 1 are not exact; therefore, a model of the mirror was designed in Pro-E. Instead of modeling the mirror as a spherical surface, however, the mirror was designed with a flat surface. This provides a conservative estimate in regards to the stress and facilitates the model.

Figure 3 and Figure 4show the tensile and compressive stress given the residual ULE glass cantilevered over 10, 20, and 30 degrees. Table 2 documents the maximum and minimum principal stresses for each geometry. As evident, once the cantilever reaches 30 degrees the maximum permissible stress is reached. As such, a bridging device is needed for any cuts extending 30 degrees or more.

Figure 3: Max Principal Stress (Tensile) for a Cantilever of Residual ULE

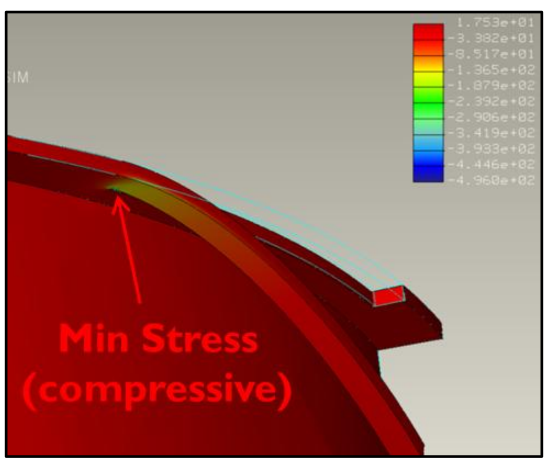


Figure 4: Min Principal Stress (Compressive) for a Cantilever of Residual ULE

In order to respect the design preferences, specifically the preference to work with larger rather than smaller cuts, a cut of 180° using multiple bridges was chosen for analysis. This cut was applied on the

Pro-E model of the mirror and extended out to the last 1mm of the edge, after which each bridging mechanism was added to the model for a comparison of principal stresses.

4.2. Bridging Mechanism

The following section defines the two types of bridging mechanisms chosen for analysis: a ULE tab and a pivot clamp.

4.2.1. ULE Tabs

To implement the ULE tab, the geometry must be such that it mates with the mirror. Figure 5 shows the geometry for the ULE tab, in which the length of the tab (2.5-inches) is bridged across the kerf of the cut during edging. The tab would be adhered to the R1 surface using a thermoplastic adhesive. Though the actual geometry of the tab contains a slight spherical surface to match the mirror, all analysis will assume the ULE mirror is planar and that the ULE tab is also planar to match the surface. In addition, the connection between the ULE tab and ULE mirror is assumed in Pro-E as a bonded interface for all meshing. This method was chosen since the wax only creates about a 0.005" bond line and Mechanica cannot accurately model thin layers of adhesive.

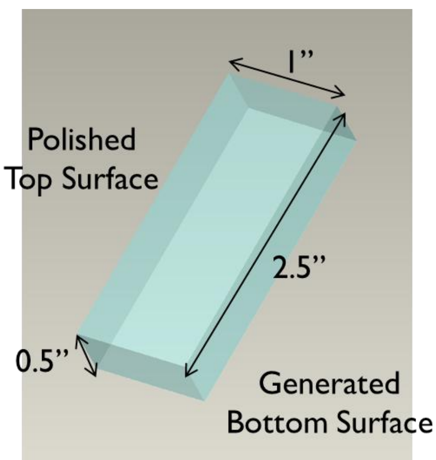


Figure 5: ULE Tab Geometry

Adding the ULE tabs into the ULE mirror model (including the 180° cut) creates a series of tensile and compressive stresses, described in terms of the max and min principal stresses (see Figure 7).Figure 6 shows the configuration with ULE tabs spaced around a 180° cut, with the first tab applied 2.5° into the cut. Also shown is the movement constraint applied to the bottom surface of the mirror and the gravity load. Figure 7 shows the resulting stresses due to the gravity, which concentrate at the last millimeter of the cut.

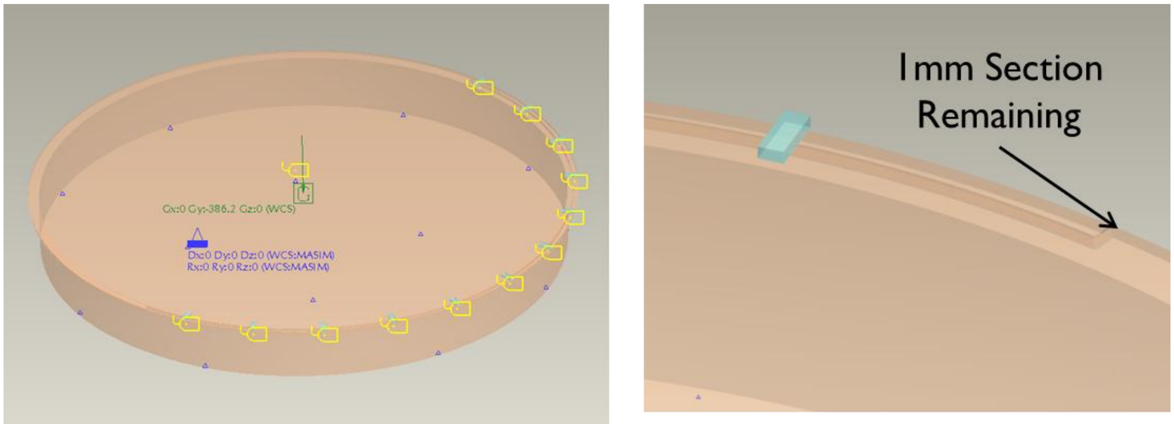


Figure 6: ULE Tabs Spaced around 180° Cut

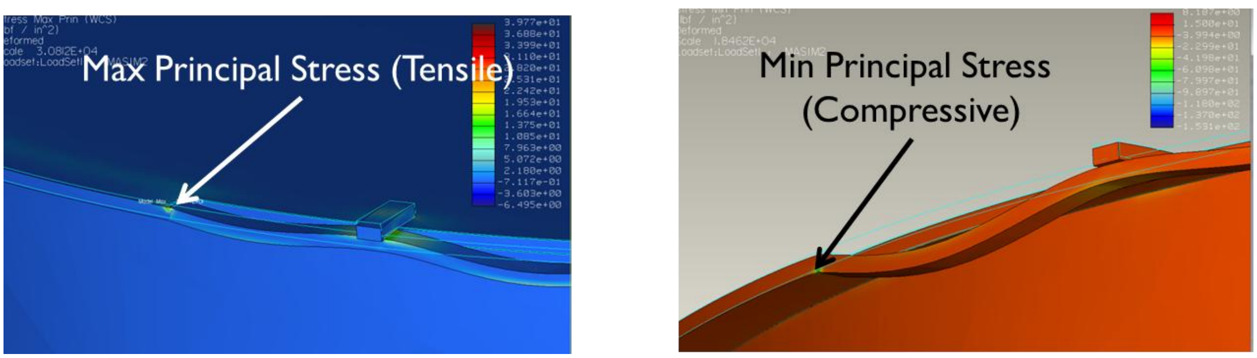


Figure 7: ULE Tabs Bonded Over 180° - Max and Min Principal Stresses

Table 2 shows the resulting principal stresses for the ULE tabs spaced at increments of 10, 15, and 20°. As mentioned earlier during the analysis of the cantilever effect, the tabs cannot exceed an extent of 30°, therefore only a tab spacing less than 30° was considered. All scenarios pass well within the stress requirement of 1000psi. As expected the maximum tensile stress is roughly equal and opposite the minimum compressive stress.

Table 2: Principal Stresses for Incremental ULE Tab Spacing

ULE Tab Spacing	Max Principal Stress (psi)	Min Principal Stress (psi)
Every 10°	9	-15
Every 15°	40	-44
Every 20°	147	-153

4.2.2. Pivot Clamp

Another method of fastening the residual glass to the final glass was examined due to its ease of implementation. Rather than design a clamp (which is usually costly), a COTS clamp was found from Reid Supply. The chosen clamp is shown in Figure 8 and is commonly used for clamping during woodworking. The clamping force is adjustable between 1 and 50lbs using a spring loaded screw situated behind the pivot. The handle is made of glass-filled Nylon (glass-filled for added strength) thereby respecting the design preference for avoiding a metal-to-glass interface.

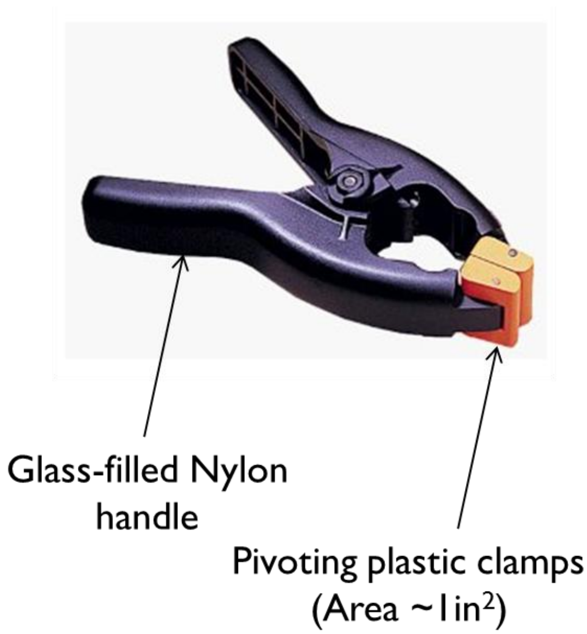


Figure 8: COTS Adjustable Pivoting Spring Clamp

Similar to the ULE tab design, the clamps are bridged across the 0.1-inch kerf in the ULE mirror model using the dimensions of the pads (1.2” wide by 0.5” long). For all analysis, a 10lb clamping force was assumed, in addition to a 1.5in-lb moment arm created by the weight of the clamp overhanging the edge of the mirror. Since the exact plastic of the pads is unknown, they are assumed to be Delrin.

In order to make the model as accurate as possible without overcomplicating the design, the clamp was reduced to Delrin pads. The clamping force was modeled at the top and bottom surfaces of the pads. To simulate the overhanging weight, two springs were connected to each of the pads which met at a point 3 inches offset from the mirror. The offset point was loaded with an additional 0.5-lb weight to simulate the weight of the clamp. This geometry is represented in Figure 9.

Next, a trade study was conducted to determine whether “bonded” or “contact” interfaces were necessary for the pivot clamp model. Mechanica defaults to bonded interfaces which allow the mesh to create nodes along each interface. Contact interfaces assume the interface is free and each component must be properly constrained for an accurate depiction of the stress. Both methods were tested using a fine mesh over a section of the mirror containing the 0.1-inch kerf, and the analysis yielded similar results in each case. The bonded interface was chosen as the conservative estimate having approximately 40psi larger stress.

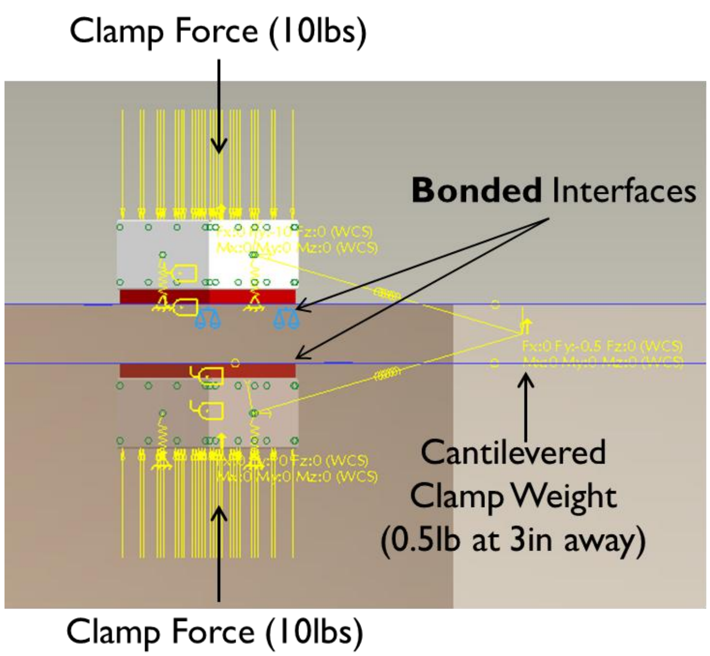


Figure 9: Pivot Clamp Geometry

Figure 10 shows the completed ULE mirror and pivot clamp assembly including the constraints and gravity loads as described for the ULE tab assembly. In addition to the 10, 15, and 20° spacings, a single clamp is added to the mirror before exiting the cut, as shown in the right image of Figure 10. The results of the principal stress analysis are documented in Table 3.

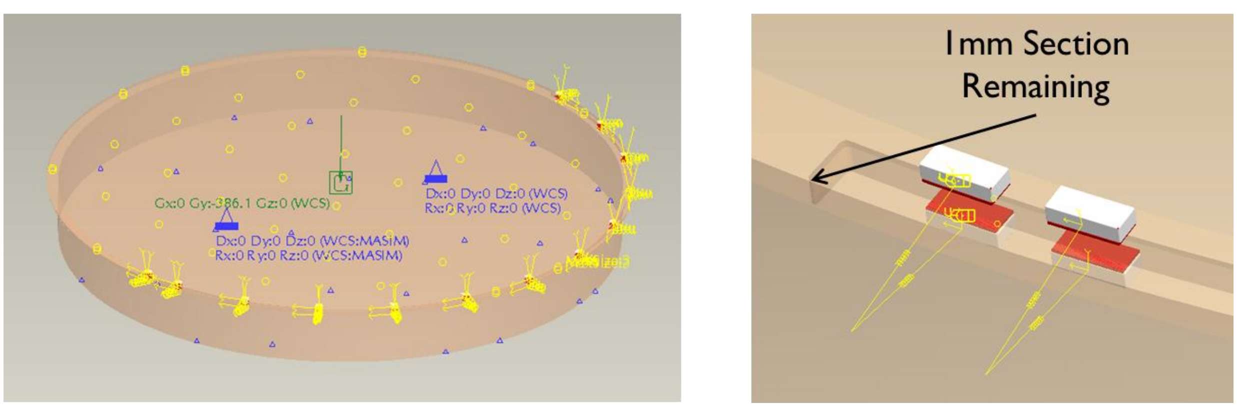


Figure 10: Pivot Clamps Spaced Around a 180° cut

Unlike the case with the ULE tabs, where each tab has to be applied using an adhesive, the clamps can simply be placed on in a matter of seconds. The clamp at the end of the cut was added to reduce stress in the glass at the final 1mm section. Adding this extra clamp moves the maximum stress to another location shown in Figure 11. This image shows the view from underneath the lip with the rectangular outline highlighting where the clamp is located. The majority of the stress is located at the OD of the final part and is maximized underneath the lip due to the moment arm created by the clamp.

The pivot clamp, like the ULE tab, passes the stress requirement for all clamp spacing scenarios. Unlike the ULE tab results, the max and min principal stresses are similar but are not equal and opposite. The compressive force remains relatively constant for each clamp spacing scenario.

Table 3: Principal Stresses for Incremental Pivot Clamp Spacing

Clamp Spacing	Max Principal Stress (psi)	Min Principal Stress (psi)
Every 10°	188	-255
Every 15°	230	-206
Every 20°	254	-242

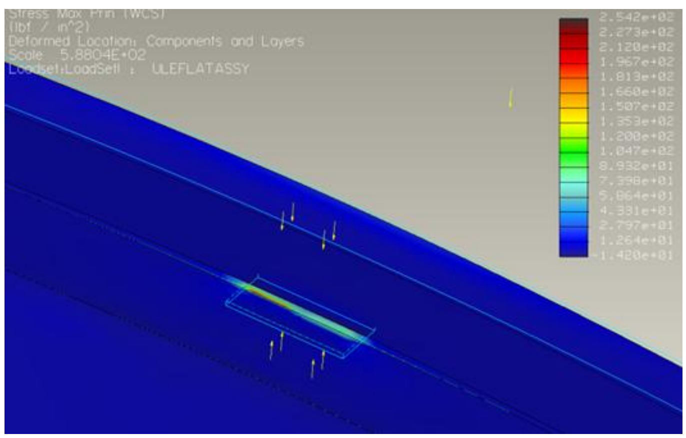


Figure 11: Max Principal Stress Location for Pivot Clamp Assembly

4.3. Adhesive Type

The following section describes the choice of adhesives to be used with the ULE tab design, Unibond 5.0 and Durahold KL16050. Both adhesives are products of Universal Photonics.

Given the geometry of the ULE tab and the density of ULE, the 2.5"x1"x0.5" tab weighs approximately 0.1 pounds. Assuming during handling the tab may exert as much as a 10G force on the mirror and taking into account a safety factor of 5, the required adhesive strength calculates to 20psi.

4.3.1. Unibond 5.0

Unibond 5.0, also referred to as “purple wax”, is a commonly used optical blocking material in the facility in which the ULE mirror edging will be performed. It’s tensile modulus is not documented by Universal Photonics; however, an in-house shear test study shows the tensile stress at adhesive failure to be between 200 and 250psi, giving an additional factor of 10 margin of safety.

To prepare Unibond 5.0, it is heated to 190°F to turn it from a solid to a liquid. A hardening time study was performed to evaluate the time needed to apply the ULE tab to the mirror surface. For the study, the ULE block was heated to 160°F on a hot plate and a surrogate plate of ULE (acting as the mirror) was heated to about 100°F using a heat gun. Two methods were chosen to apply the ULE tab. In the first method, the hot adhesive was painted on the tab and the tab applied directly to the ULE plate. In the second method, the hot adhesive was applied to both the ULE plate and the tab, between which a layer of lens tissue was added for compliance. The first method of direct contact cured at about 3 minutes 30 seconds, with the second method taking almost twice as long at 6 minutes. Both methods are shown below in . Temperatures were monitored using an IR temperature gun.

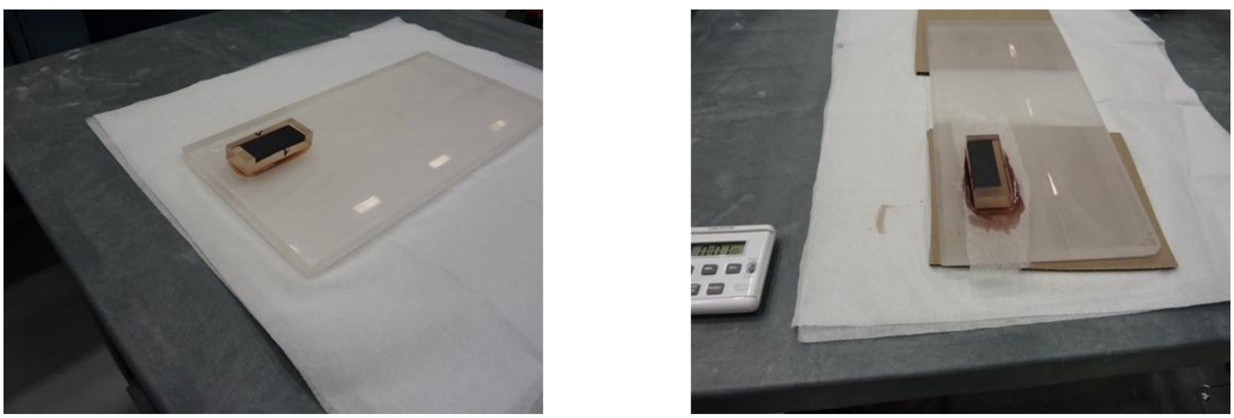


Figure 12: ULE Tab bonded to ULE Plate with Unibond 5.0, Direct Contact (left), with added Lens Tissue (right)

From the requirements, the saw is specified as having a feed rate of 0.025° per second. At this rate the mirror edge is removed at a rate of 1° every 40 seconds, and the ULE tab bonded directly to the mirror surface will have enough time to cure for each tab spacing case studied (10, 15, and 20°).

To remove the ULE tabs once the cut is complete, a heat gun is used to soften the adhesive which takes about 1 minute. During the removal of a 180° segment, foam blocks and/or multiple personnel would be needed to support the residual glass while the ULE tabs are removed. After deblocking the tabs, the residual edge may be detached from the final optic.

4.3.2. Durahold KL16050

A lesser known optical blocking material investigate as part of this design was Durahold KL16050, chosen for its UV curing property. Universal Photonics specifies two UV light sources, a 10mW that cures the adhesive in 3 minutes at a 2-inch distance in air, and a 30mW source that cures the adhesive in 90 seconds for the same distance. The 0.5-inch thick ULE tab transmits down to 250nm wavelengths, allowing the UV source to be applied through the tab. Once cured, the adhesive exhibits a tensile modulus of 925psi and is recorded to have 475psi tensile stress at breakage for shear testing.

While Durahold exhibits a much higher strength than Unibond 5.0, it is not as easy to deblock. Once bonded the tab requires a 176°F solution of detergent and distilled water to be soaked into the bond for over an hour in order to deblock. A 0.5in^2 bond area requires 60 minutes of soak before removal; therefore this adhesive is not ideal for application in the edging process.

4.4. Number of Bridges

The number of bridges required relates directly back to the tab/clamp spacing outlined in section 4.2. Since the principal stresses passed in all cases that were studied, the optimal number of bridges necessary would be 18 given one bridge per 10° (19 for the case of the pivot clamp, where an additional bridge is added to exit the cut). This value was chosen to add redundancy to the design; should one bridge fail at 10° spacings, it is already known that the stresses will not exceed the permissible value of 1000psi should the bridge spacing extend to 20°.

5. Preliminary System Test Plan

The following test plan should be executed prior to beginning edging on the ULE mirror.

- Assemble 3/8" thick float glass in edging setup
- Test the clamp method for a 180° section of the glass
- Apply clamp at approximately 2° into the cut and at 10° increments after
- Test the ULE tab method for a 180° section of the glass
- Before beginning saw, prepare Unibond 5.0 and ULE tabs by placing each on a hot plate for about 30 minutes, checking temperatures using an IR gun
- Apply ULE tab at approximately 2° into the cut and at 10° increments after. Secure ULE tab in place using a strip of Kapton tape.
- Compare time to complete each method and overall evaluation of risk

6. Results of Trade Study

In terms of time, all methods with the exception of using the ULE tab with the Durahold adhesive meet the requirements of the design (due to the unknown deblocking time of the Durahold adhesive). Table 4 describes a more in-depth look at the time needed to complete the mirror edging given each of the parameters outlined in this study. From this table, it is evident that a 180° cut segment is desirable, in which the residual is fastened using pivot clamps. However, should the ULE tab method be chosen as a results of poor testing results with the pivot clamp, Unibond 5.0 is the preferred adhesive.

Table 4: Time Requirements for the ULE Mirror Edging Parameters

Parameter		Time	Preference	Comments
Size of Cut	10° Cuts	6.5hr		Assume 15 minute prep time per cut
	20° Cuts	4.25hr		
	180° Cut	2.25hr	✓	
Bridging Mechanism	ULE Tab	1.75hr		Prep Time plus application time for 15 bridges
	Clamp	0.5hr	✓	
Adhesive	Unibond	2.4hr	✓	Prep time, time to cure 15 bridges, and removal time
	Durahold	>3hr		

In terms of principal stresses, the results from section 4.2 indicate that the ULE tab method exhibits lower stresses than the clamping method; however both methods pass the 1000psi stress requirement by at least a factor of 4. Each method stressed the optic in a different manner. Using ULE tabs, the stress concentrated at the end of the cut while when using pivot clamps, the stress concentrated on the bottom edge of the final lip due to the moment imparted on the glass by the clamp. Between these two scenarios, it is more desirable to have the stress concentrate on the residual glass rather than the final glass, but again both analyses showed that the expected stresses are far less than the design requirement. For this reason the pivot clamp method is a desirable method simply because of its ease of use.

In terms of risk, shorter cuts are desired but cause more imperfections along the edge of the glass. To respect the design preferences and save time, a 180° cut adds a slight amount of risk to the design method should the bridging mechanisms fail. Both the ULE tab and pivot clamp add different amounts of risk to the design. The ULE tab could cause scratches or fracture the mirror if it were accidentally dropped on the mirror surface. Additionally, the tab requires a heat gun to warm the mirror before bonding and to remove the tab after the edging is finishing. Most heat guns are made of metal and would need to be in close proximity to the glass. The pivot clamp is made almost entirely of plastic with small exceptions for the spring and the fasteners. The adjustment for the clamp load is adjustable using a screw, though it is unknown exactly how much force the clamp applies for different turns of the adjustable screw. Faults due to an improper pad pivot joint could cause localized stresses to fracture the mirror, though this is unlikely since the plastic is much softer than the glass.

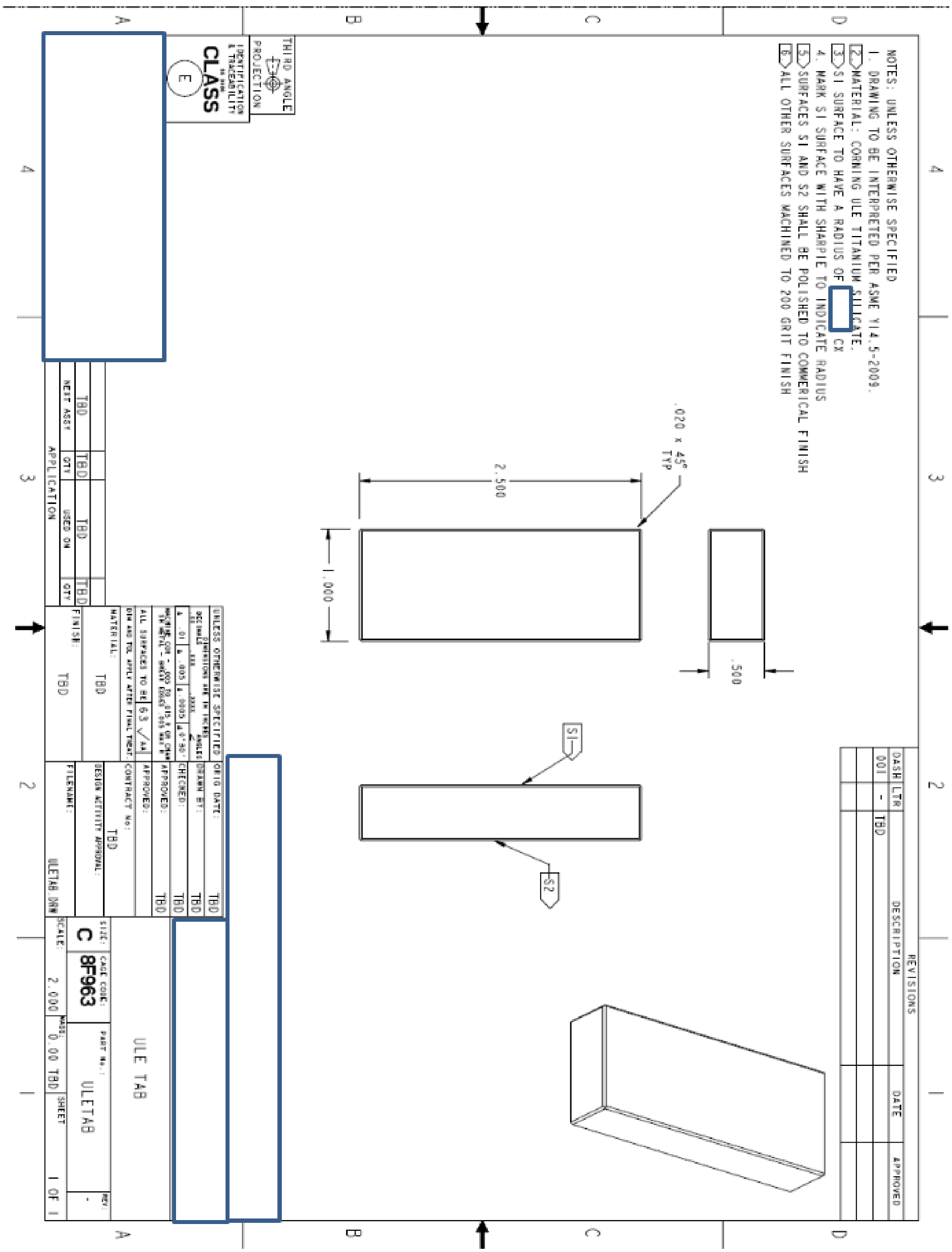
Finally, as mentioned earlier, the number of bridges should be kept to about 18 (or 1 every 10°). This provides redundancy in the design should one of the bridges fail. A summary of these results is provided in Table 5.

Table 5: Overall Results of Trade Study

Size of Cut	Bridging Mechanism	Adhesive (if applicable)	Number of Bridges
• Minimum cut size was determined to be 10° with one bridge necessary to exit the cut. • Maximum cut is 180° with multiple bridges to be able to remove half the residual edge.	• **ULE Tab**– Simple design (one component) but requires more time for application. • **Clamp** – More complex design but faster in situ application time. Adds risk depending on materials used.	• **Unibond 5.0** – Widely used but requires further tensile testing to validate. • **Durahold** – Preferred due to short cure time, but presents new methodology and requires additional hardware (UV lamp).	• Determined once optimal size of cut is finalized.
• **Solution**: Create a 180° cut using multiple bridges to minimize the number of cuts necessary and respect design preferences	• **Solution**: Clamp method provides a faster application time and should be used	• **Solution**: Not necessary; however if clamp method is determined to be unsafe during preliminary system testing, Unibond 5.0 is the adhesive of choice	• **Solution**: Use clamps every 10° to secure the residual to the OD of the final optic, including one clamp just before the exit cut is made.

7. Appendix

7.1. Drawings



7.2. Lessons Learned

After completing this design project, many design considerations and issues were met. First, in regards to bridging using clamps a pivot joint is needed on the pad clamps to be able to spread the load over the entire pad area. This was resolved by choosing a spring clamp with a pivot for the clamp mode and pivots at the pads.

While performing experiments with Unibond 5.0, it was found that the time it took to reach a desirable cure strength was much less than the listed cure time of 30 minutes. Also, in experiments using a sheet of lens tissue for added compliance will significantly increase the cure time. Overall, though, the cure time is comparable to that of the UV curing Durahold adhesive, which is specified to cure in 3 minutes using a 10mW source.

Universal photonics only lists heating Unibond 5.0, though if the bonding components are not heated as well, the thermoplastic cools too quickly and does not exhibit its full strength characteristics. To create a strong bond during testing the ULE tab was heated to 160°F and the surrogate mirror was heated to 100°F.

While running analyses in Mechanica, nuances in meshing were noted. "Point seeding" was used in areas where stress concentrated in the model to more accurately depict the stress in those areas. Point seeding involves creating datum points using reference surfaces; for the case of the ULE mirror the model was seeded in the 1mm area attaching the residual glass to the final optic.

Finally, most of the stress results seen in the clamping study were driven by the clamping force, not the strength of the ULE mirror.

7.3. References

Technical Data: Unibond Water Soluble Thermoplastic. Universal Photonics. Hicksville, NY. www.universalphotonics.com. 2013

Technical Data: Durahold KL16050. Universal Photonics. Hicksville, NY. www.universalphotonics.com. 2013.

Pressure Adjustable Spring Clamp. Reid Supply. http://www.reidsupply.com/sku/AC-3252/. April 2013.