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MAS.862 Final Project: Laser-Material Interactions

Motivation and Overview

Laser micromachining is critical for applications requiring fine feature sizes, such as in microfluidic devices, biomedical sensors, and intricate optical components. However, determining the exact input parameters to achieve a desired cut depth requires experimental refinement for each material and laser wavelength, as there does not appear to be a universal method for determining these values theoretically. Even so there are some guiding principles for which materials are best cut at which wavelengths. CO_2 lasers, for instance, are commonly used for cutting and engraving non-metals. I wanted to better understand the underlying reasons for this and explore the physical precision limits. To begin answering these questions, I designed a series of experiments to determine the minimum cut depth achievable in both opaque and transparent pigmented acrylic samples, aiming to link experimental measurements to material properties and laser parameters.

Background and Theory

Laser Selection Based on Material Absorption

The effectiveness of laser micromachining depends heavily on how well a material absorbs energy at the laser's wavelength. A useful rule of thumb is to select a laser whose emission wavelength aligns with a strong vibrational or electronic absorption band of the target material. This ensures high absorption (and thus low reflectivity), enabling efficient localized heating and precise material removal via vaporization.

CO_2 lasers, which emit at a wavelength of approximately 10.64 μm, fall in the mid-infrared range and are well-matched to the strong vibrational absorption bands of most organic materials, such as polymers. These materials typically have low thermal conductivity, which allows heat to concentrate at the laser's focal point, facilitating clean vaporization and minimal heat-affected zones. Acrylic, therefore, is readily cut by a 10.64 μm CO_2 laser like the XTool P2 due to its strong IR absorption and low thermal conductivity. In contrast, fiber lasers operating near 1.06 μm are poorly suited for cutting transparent polymers like acrylic, which absorb minimally in the near-infrared.

Calculating Skin Depth from Absorption Coefficient

Skin depth, $\delta(\lambda)$, is the depth at which incident light intensity drops to 1/e (~37%) of its original value at the surface due to absorption. It can also be expressed in terms of the absorption coefficient $\alpha(\lambda)$ and the extinction coefficient $\kappa(\lambda)$, where:

$$\delta(\lambda) = \frac{1}{\alpha(\lambda)} = \frac{4\pi\kappa(\lambda)}{\lambda} \quad (1)$$

A higher α means stronger absorption and a smaller skin depth, indicating more efficient energy deposition near the surface. Skin depth provides a useful estimate of how deeply laser light penetrates a material and helps predict the minimum achievable cut or ablation depth. Data from the gold standard in published optical constants (Handbook of Optical Constants of Solids by E.D. Palik) and other works have been added to a very useful refractive index database which provides everything needed for this calculation. Figure 1 shows a simple Python script I made to perform the calculation using these user inputted values.

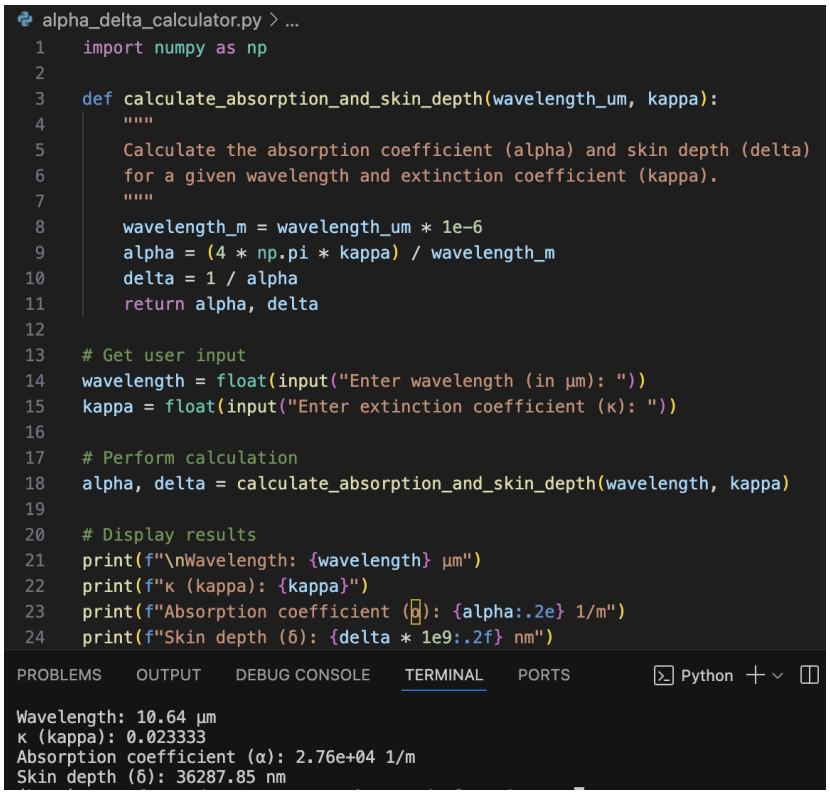

Figure 1: Skin depth calculator with output for clear acrylic at a wavelength of 10.64 µm.

According to Prashant's thesis, using this skin depth equation as a proxy for minimum cut depth is valid when the optical penetration depth is smaller than the Rayleigh range (Z_R) of the laser beam, the distance from the beam waist where the beam radius has increased by a factor of $\sqrt{2}$ and the cross sectional area doubles, as shown in Figure 2.

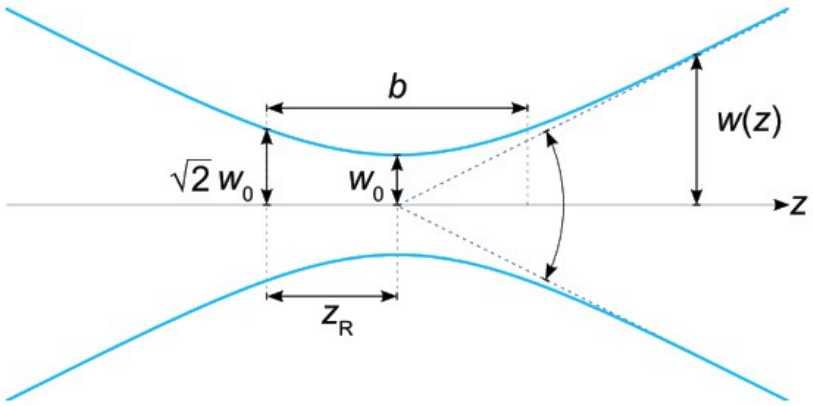

Figure 2: Schematic depiction of Rayleigh range (Z_R) from Go Photonics.

The Rayleigh range (Z_R) was calculated as follows where w_0 is the beam waist radius at the focus and λ is the laser wavelength (both in meters).

$$Z_R = \frac{\pi w_0^{\ 2}}{\lambda} \tag{2}$$

For a typical CO_2 laser with a wavelength of 10.64 μm, focusing to a 100 μm waist radius yields a Rayleigh length of approximately 3 mm, meaning the laser beam remains tightly focused over a distance of about 3 mm before it begins to diverge significantly. Thus, this assumption should hold since the transparent acrylic's calculated skin depth is 36.3 μm (as shown in Figure 1 and Table 1), much smaller than the Z_R of 3 mm.

Experimental Design

The goal of my final project was to begin to understand the what and how behind laser-material interactions in the context of laser micromachining at different wavelengths. As a first step, I sought to understand the relationship between a 10.64 μm wavelength CO_2 laser (in this case the XTool P2, 55W version) and acrylic by finding the minimum cut depth possible in both opaque and transparent pigmented samples.

Calculating Skin Depth

As mentioned previously, I wrote a simple Python script (see Figure 1) to calculate skin depth from absorption coefficients at different wavelengths. In particular, I calculated the skin depth for the wavelengths of laser systems at CBA using data from this resource and added these values to Table 1.

Laser	Wavelength, λ	Extinction Coefficient, κ	Absorption Coefficient, α (m^{-1})	Skin Depth, δ (cm)
XTool P2 (CO_2; 55 W)	10.64 μm	2.3333×10^{-2}	2.76×10^{4}	3.63×10^{-3}
XTool F1 Ultra (Fiber IR; 20 W)	1.064 μm	1.2500×10^{-6}	1.48	6.77
XTool F1 Ultra and S1(Blue Diode; 20 W and 40 W, respectively)	0.455 μm	2.1850×10^{-7}	6.03	16.6

Table 1: Laser-material properties of clear acrylic for skin depth calculations.

Since the 1.064 μm Fiber IR and the 0.455 μm Blue Diode lasers are predicted to have a skin depth on the order of centimeters, these will be unable to cleanly cut transparent acrylic, even at the lowest power and highest speed. This is because the laser is heating up a large volume at the same time which causes internal melting, and since the focus is well below the surface of the material, vaporization can happen on the inside of the material first, which may be what was causing internal cracking and explosions in previous experiments. With a skin depth that long, the focal depth of the lens (Rayleigh range) is what sets the minimum machining depth rather than the skin depth. Because of this, I opted to investigate the XTool P2 CO_2 laser which would have a small skin depth I could measure and compare with theoretical calculations.

Threshold Parameters for Minimal Cutting

To find the parameters at which the XTool P2 CO_2 laser would just barely cut the acrylic, I used the maximum speed available in cut mode (250 mm/s) and determined the power percentage by decreasing by factors of two from 40, to 20, to 10, to 5, to 3. (The XTool software does not accept decimal inputs for power percentage.) With each of these parameters, I cut a horizontal line of length 8 cm onto each sample of both opaque and transparent pigmented acrylics and spaced them vertically by 4 mm. These were then cut out at 7 mm/s and 100% power informed by the XTool Material Settings Library recommendations.

Figure 3: Minimally laser-cut opaque (black, green, red) and transparent (pink, orange, yellow, blue, clear) acrylic samples on the 10,640 nm CO_2 laser.

Cross Section Cuts with a Diamond Saw

I then used a Buehler IsoMet low speed diamond saw to slowly cut a thin sliver out of the center of the stacked samples perpendicularly to the laser markings, marking side down. After collecting them from the ethylene bath beneath the saw blade and air drying, I gently cleaned the top surfaces with a cotton swab to remove any debris.

Figure 4: Process to cut thin cross sections of the minimally laser-cut acrylic samples.

Measuring the Top and Cross-Section Views

After testing out alternatives, I decided to use the Lynx EVO stereo microscope to image the tops and cross-sections of the samples. I set the scale in ImageJ using a metric ruler at the same magnification as the samples and measured the width and depth of the cuts with the Measure tool. For some of the lower power laser cuts, the laser pulses were not connected. Because of this, some samples were not cut by the diamond saw in a way that facilitated a reliable depth measurement.

Results

Microscope Images of Top and Cross-Section Views

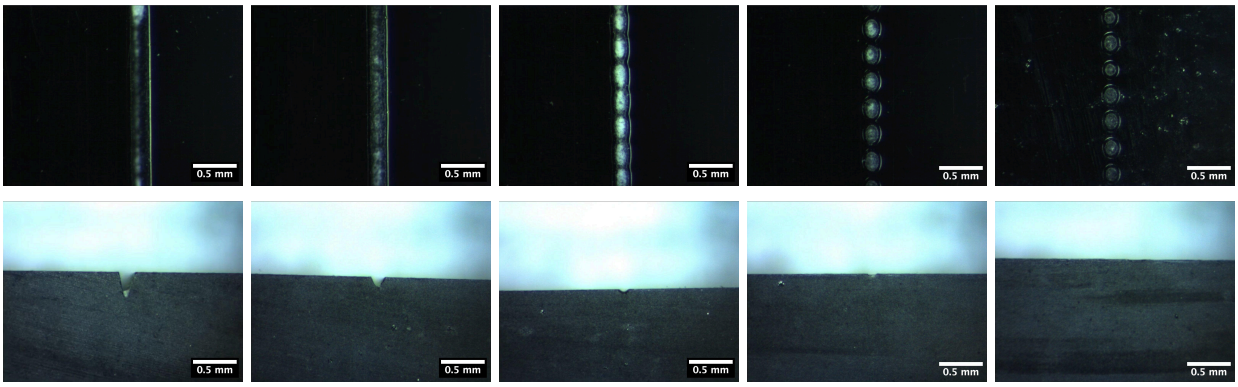

Figure 5: Microscope images of top (top row) and cross-section (bottom row) views of black laser-cut acrylic.

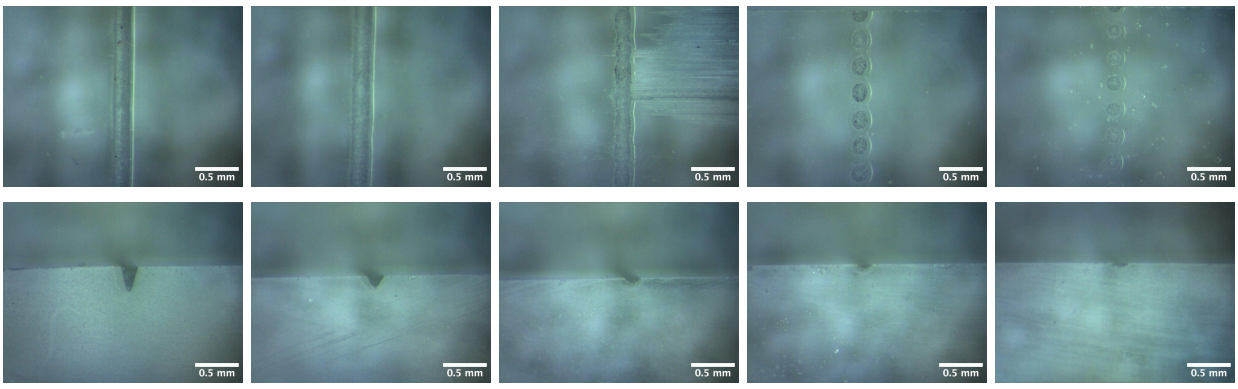

Figure 6: Microscope images of top (top row) and cross-section (bottom row) views of clear laser-cut acrylic.

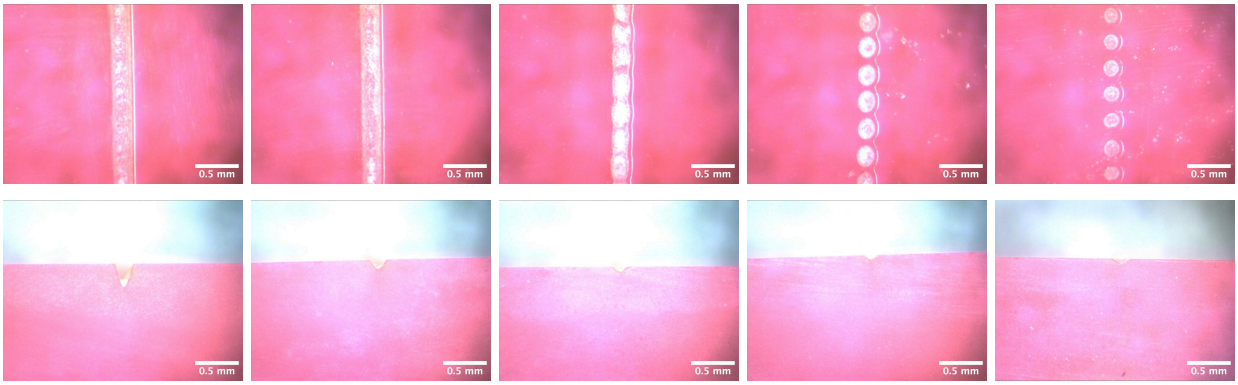

Figure 7: Microscope images of top (top row) and cross-section (bottom row) views of pink transparent laser-cut acrylic.

The CO_2 laser operates in a pulsed mode, as evidenced by visible pulse marks along the cut path (Figures 5-7 above), likely resulting from pulse-width modulation (PWM). The cuts exhibit a pronounced taper, with a high aspect ratio (see Figure 9 for details). Additionally, the pulse width contributes to anisotropic material ablation, elongating features in the direction of laser motion.

Measured Cut Depth

There is no obvious relationship between visible light opacity and cut depth of the acrylics, suggesting that the dye does not significantly enhance laser absorption at 10.64 μm. Therefore, it is likely that the absorption characteristics of the clear base material dominate the interaction, as these dyes are typically only intended to be opaque at visible wavelengths. This means that it is likely valid to use organic materials' absorption coefficient values from the refractive index database and subsequent skin depth calculations to inform cut parameters of dyed versions at IR wavelengths. More tests are needed to definitively confirm this.

Also, as laser power decreases, the cut depth appears to asymptotically approach the material's skin depth confirming that skin depth is a good proxy for minimum cut depth of acrylic, and likely organic materials more broadly. Note that when the pulses were more spaced out at lower powers, the diamond saw cut was not necessarily made at the center of the pulse, so the measured minimum is likely a slight underestimate. Overall, the cut depth scales nonlinearly with laser power, indicating a complex dependence on thermal effects. Since the ablation threshold is nonlinear and the laser is only heating the center of the Gaussian when the power level is low, this can potentially enable machining below the diffraction limit.

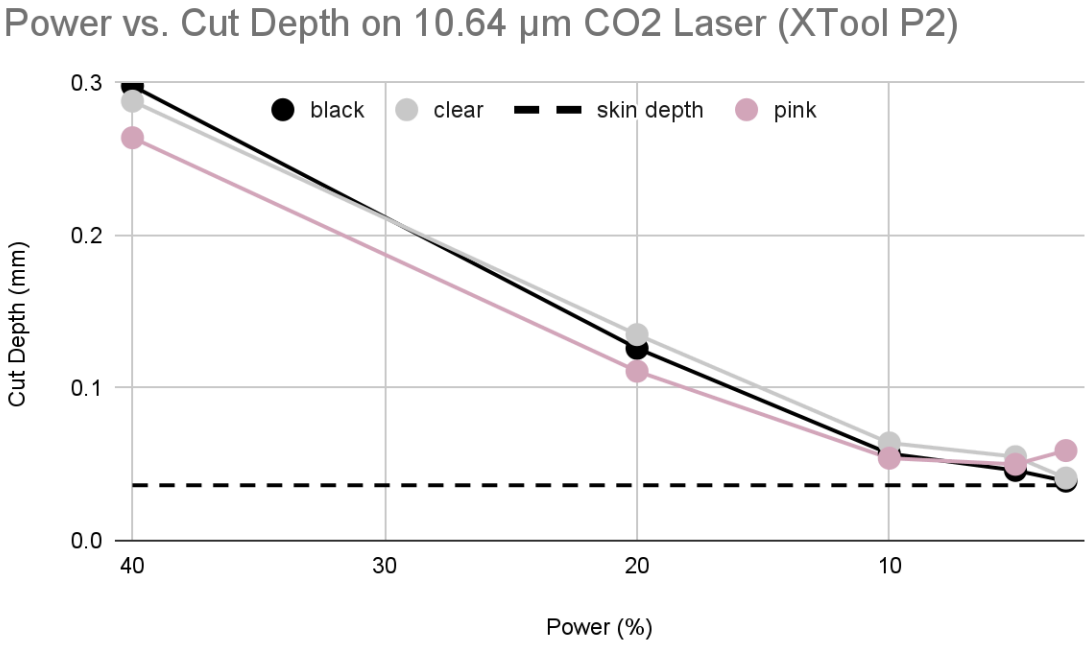

Figure 8: Power vs. cut depth of acrylic samples on 10.64 µm CO_2 laser (XTool P2).

Measured Aspect Ratio

The cuts exhibit a strong taper, with an aspect ratio that decreases nonlinearly with power, likely due to thermal effects. While the cut width remains relatively constant across different power levels, the depth varies significantly, making the aspect ratio primarily dependent on laser power.

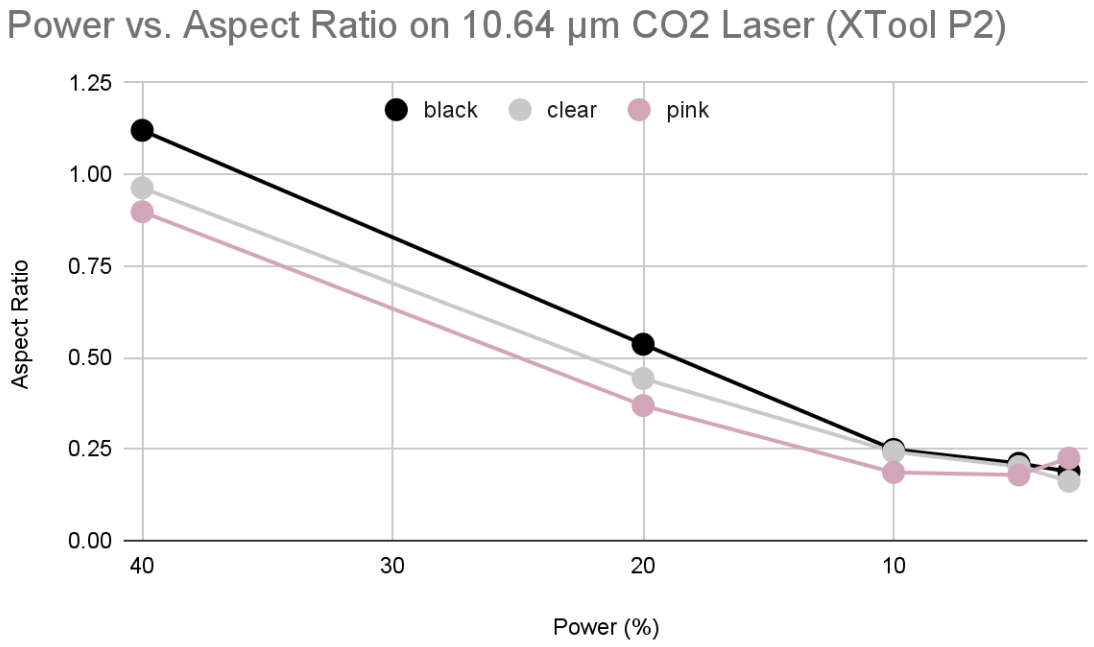

Figure 9: Power vs. aspect ratio of acrylic samples on 10.64 µm CO_2 laser (XTool P2).

Future Work

Characterize Laser's True Operating Parameters

The XTool P2 and S1 lasers do not appear to compensate for their own acceleration or instantaneous velocity when firing pulses, resulting in inconsistent pulse density. This effect is especially pronounced in the S1 and becomes more noticeable at higher power levels. As shown in Figure 10, this issue is most evident in the bottommost 40% power samples where the cuts near the edges (during acceleration and deceleration) are much deeper than in the center (once a constant velocity has been reached).

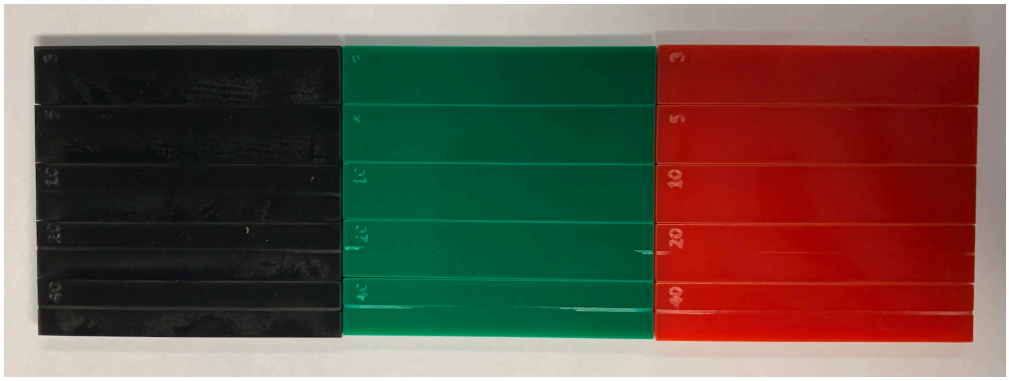

Figure 10: Minimally laser-cut opaque (black, green, red) acrylic samples on the XTool S1 (455 nm) 40 W blue diode laser at 300 mm/s with a power percentage of 40, 20, 10, 5, and 3, respectively.

Therefore, I would like to directly measure its speed using a phone camera at 240 frames per second and compare this to the input parameter of speed. Similarly, I plan to measure the true laser power by measuring the pulse width using a transimpedance amplifier. The power setting in the software is the mean power percentage such that changing the power percentage changes the falling edge of the laser.

Measuring Absorption Coefficient of Dyed Samples

Since the wavelength-dependent absorption coefficients of dyed organics like pigmented acrylic are not well characterized in the literature, I had initially wanted to measure the absorption coefficients of the opaque acrylics. To do so, I heat pressed them with the aim of making them thin enough to be optically transparent. I ramped up to a maximum temperature of 380°F, well above acrylic's melting point of 320°F according to information regarding cast acrylic's properties and response to heat. My attempts have so far been unsuccessful, and the spectrometer readings are close enough to zero to be attributed to noise. There is more work to be done here.

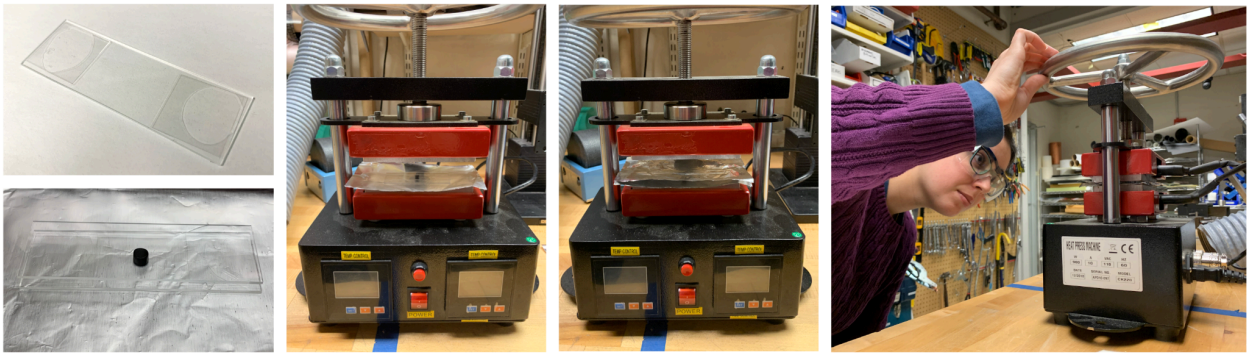

Figure 11: Prepping glass slide with cover slip spacers and heat pressing 6 mm diameter, 3.175 mm height black acrylic cylinder at 380°F.

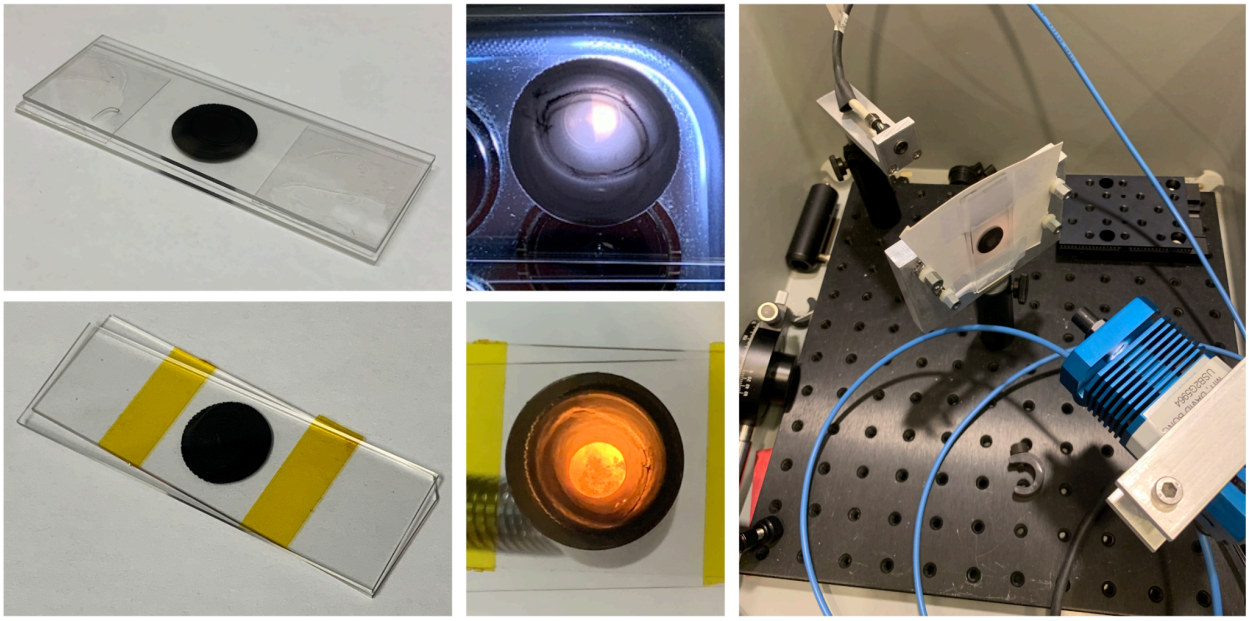

Figure 12: Heat pressing 3.175 mm acrylic sample to 0.37 mm thickness (with cover slip spacers) and 0.30 mm (with kapton tape) insufficiently increased optical transmission for spectrometer measurement.

Consider More Physical Parameters, Wavelengths, and Materials

Part of the motivation behind investigating acrylic is that its thermal conductivity is low enough to make the skin depth the dominant contributor to minimum achievable cut depth. However, when examining other materials like metals, thermal capacity will play an important role. I began writing out some equations for material removal rate (Equation 4) and cut depth rate (Equation 5) based on these but have not yet had a chance to use them.

$$P_{absorbed} = P_{laser}\alpha(\lambda) \tag{3}$$

$$\frac{m}{t} = \frac{P_{absorbed}}{C} \tag{4}$$

$$\frac{\Delta z}{t} = \frac{m}{A\rho t} \tag{5}$$

Here P is power, α is the absorption coefficient as a function of wavelength (λ), m is mass, C is the total heat capacity required for vaporization (for which there are several materials thermal properties databases available), $\frac{\Delta z}{t}$ is the cut depth rate, A is the cross-sectional area, and ρ is the material density. Along with these calculations will come the testing of additional lasers of various wavelengths on different classes of materials.

Acknowledgements

Thanks to Neil for getting excited about my project and ordering acrylic for me to try out and for inviting me to take this course. Thanks to Quentin for brainstorming with me when I was convinced my experiments were bound to fail after a particularly learning-filled Thursday and to Jake for showing me the basics I will need to develop truly intelligent laser micromachining as he has done with 3D printers. Thanks to Alan for giving me the invaluable suggestion to restart the XTool software when even placing a line was taking several minutes. Thanks to Jiaming for helping me pick which microscope to use and to Colin for fixing the settings on the Lynx EVO so my figures would come out looking nice. Thanks to David Bono for letting me use his diamond saw and spectrometer, and thanks to Dan for helping me find a fan to help cool down the heat press between sample runs.