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2012-2013 Clare Boothe Luce Research Scholars Program Reflection

I am extremely grateful to the Clare Boothe Luce Foundation for having supported my research endeavors for a full academic year (Spring 2012 – Fall 2013). My project, *Advanced Prototyping Techniques with Modern Fabrication Methods,* has grown and expanded immensely with the support of this scholarship.

Major Takeaways:

- My summer research experience taught me how to approach and pioneer exploratory work. For the work that my team and I were seeking to produce, there were no known experts in the field; we had to rely on ourselves to uncover solutions to our questions. I also learned to make the distinction between exploration and experimentation which helped me properly scope future projects.
- Disenchantment & maintaining motivation in a long-term project: I have now been with the same research group and project for ~2 years. There have been very rocky moments throughout this time mainly due to the sometimes undefined nature of our work and deliverables. Going through this experience made me realize the importance of communication with team members to gauge sentiments toward and aspirations for a project. I also came to comprehend the drive that I would need to accomplish good work and carry it through to completion. It was inspiring to watch our team turn around from low points to reinvigorate the project, knowing that we each had a hand in it.
- My research project has brought me in contact with some of the best friends, teammates, & mentors that I've had in my life up to this point. I have grown not only academically, but also personally from this experience. I would recommend this experience to other young women at Olin College and would love to relate more of my stories to them.

The Status Quo and Future Directions:

- Attachment 1 (*Acrylic Material Profile*): I was able to study the material poly(methyl methacrylate) and its applications to laser cutting. The study was conducted from engineering, materials science, & machining perspectives.
- Attachment 2 (*Laser Processing of Thermoplastic Materials)*: In a combined effort with Ingrid Hagen-Keith and Avery Louie, I studied the laser processing potential of four thermoplastic polymers in Material Science and Solid State Chemistry.
- Attachment 3 (*LCLAB: Trainee Handbook)*: An introductory guide to prototyping with the laser cutter meant specifically for students at Olin College. This is our first production run which is currently being integrated into FBE. A future iteration is to come.
- Attachment 4 (*LCLAB: Advanced Prototyping Guides, a sample)*: These prototyping guides, taking the form of mini magazines will be disseminated to Olin and also the larger hobbyist laser cutting community. The current issue on advanced joinery techniques will be produced in 2 weeks. We have acquired SAG funding for this project.

I would like to especially thank my teammates Ingrid Hagen-Keith, Mary Morse, & Essie Yu (Summer 2013) as well as my advisors Dr. Lawrence Neeley & Dr. Aaron Hoover for accompanying me on this journey. Also, thank you Professor Jon Stolk for your guidance in the materials science aspects of this project.

Acrylic Material Profile

Annie Zeng
Olin College of Engineering
Fall 2013

I. Overview

Poly(methyl methacrylate), known commonly as acrylic, is a transparent thermoplastic polymer. Acrylic is a choice material for laser cutting due to the ease with which it is machined.

Some desirable qualities of PMMA include high light transmission and the aesthetic appeal of transparency. PMMA is widely used for illuminated as well as non-illuminated display signs. Trophies and memorabilia often use cast acrylic as the base material due to the high visual contrast produced by engraving the material. Furthermore, acrylic is often used as a shatterproof glass substitute. It is more weather resistant than other plastics as polystyrene and polyethylene and therefore often found in outdoor applications.

II. Manufacturing Process

Two manufacturing techniques segregate the main types of acrylic: casting and polymer extrusion. Variations of acrylic, as mirrored or colored plastics, are becoming more accessible and popular as well.

Cast Acrylic

Cast acrylic is manufactured by pouring the polymer into a casting cell which consists of two glass sheets between which a rubber gasket is placed to determine the thickness of the final sheet. The cell is completely filled with acrylic resin which is then clamped together to ensure an even pressure across the sheet as the material polymerizes and shrinks. The cell is then taken through a heating cycle and is possibly annealed to reduce internal stresses. Due to the fabrication process, the tolerance in thickness of a cast sheet varies greater than extruded acrylic. It is also more expensive to make. However, cast acrylic has reduced residual stresses and therefore greater resistance to cracking when compared to its extruded counterpart.

Extruded Acrylic

Extruded acrylic is manufactured by melting acrylic resin pellets and squeezing the melted material through a die into a molten sheet whose thickness is determined by the spacing of the die. The molten sheets then pass through a set of cooling rolls where it is post-processed. As a result of this manufacturing process, extruded acrylic is more even in thickness, is faster to manufacture, and cheaper to purchase than cast acrylic.

III. Material Specifications

There are various standards for the specification of PMMA plastic sheet. The ASTM D4802-10 and ISO 7823-1:2003 are two common standards.

ASTM provides four major categories for the specification of acrylic sheets (ASTM International). A summary of the four are provided below.

Category A-1: Cell-cast PMMA sheets that represent the best optical quality and are characterized by the highest long-term stress and chemical resistance.

Category A-2: PMMA sheets manufactured by the continuous-casting method which has better thickness control than Category A-1, but lower optical quality.

Category B-1: PMMA sheets from a variety of manufacturing methods. Possesses lower chemical, heat, and stress-craze resistance than the A Categories, but generally has better optical qualities and thickness control than A-2.

Category B-2: Extruded PMMA sheets which excellent thickness control but reduced long-term stress, chemical resistance, optical quality, and thermal stability.

Depending on the application, you may want to select an acrylic sheet for its optical quality, weather resistance, and/or thickness specifications if tight tolerances are to be met.

IV. Material composition and impact on mechanical properties

Poly(methyl methacrylate) is derived from the polymerization of methyl acrylate. Its monomer is a mobile liquid with a characteristic sweet odor.

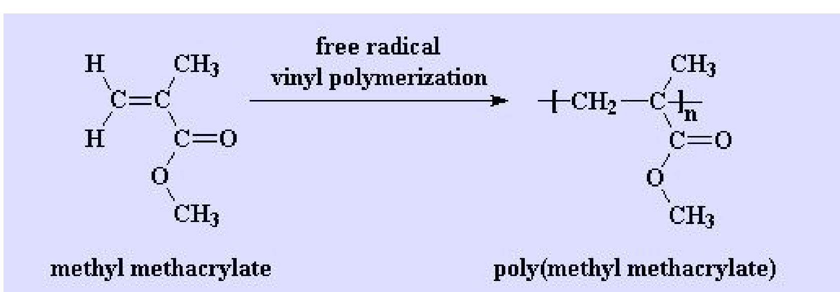


Figure 1 Polymerization of poly(methyl methacrylate) from methyl methacrylate. The final monomer is shown on the right. (Polymer Science Learning Center, Department of Polymer Science, University of Southern Mississippi)

Most commercial acrylics are amorphous, linear polymers with a wide range of molecular weights. The difference in molecular weight determines the amount of entanglement of polymer chains; a high molecular weight contributes to extensive chain entanglement and therefore a more rigid material. However, the syndiotactic nature of acrylic polymers (orientation of side chains are alternating in space) does not enable the polymers chains to pack so closely as to form a crystalline material.

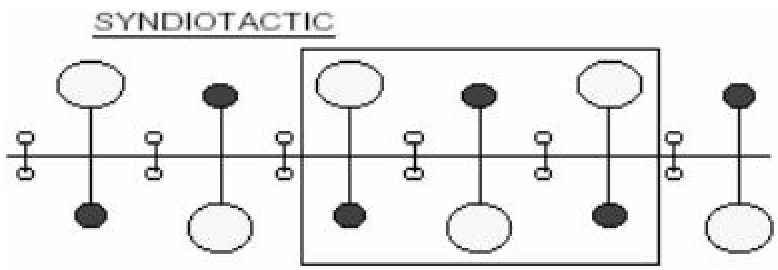


Figure 2 Block diagram of syndiotactic orientation of monomers in PMMA chain.

Manufacturing variations between cast and extruded acrylics result in sheets with different mechanical properties. Casting produces a homogenous (polymer chain orientation is random) material with similar properties in all directions. On the other hand, extrusion aligns polymer chains, resulting in a heterogeneous sheet with properties which vary depending on the extrusion direction. The polymer is often stronger in the direction parallel to the molecular orientation. When cast acrylic is annealed in its heating cycle, it reduces the amount of residual stresses in the polymer as compared to its extruded counterpart. There is often more tension in extruded acrylic which causes it to be more prone to brittle fracture.

PMMA also has a 92% transmissivity of light, giving it its transparent quality even in great thicknesses. The polymer is not very chemically resistant. Aliphatic alcohols can cause crazing and cracking of PMMA.

V. Material removal mechanism

Acrylic is laser machined via material vaporization. This is in contrast to most other thermoplastics which are cut by melt shearing due to acrylic's relatively low vaporization point. When heated above the glass transition temperature (about 100°C), PMMA becomes rubbery, a state which extends for about 60°C. Raising the temperature above this point causes decomposition.

According to FTIR analysis of cast and extruded acrylic samples purchased from McMaster-Carr, the material is very absorptive of the 10.6 micrometer CO_2 laser wavelength. Combined with the low vaporization temperature of acrylic, the material is able to go from a solid to gaseous phase upon laser heating. This is highly beneficial in regard to laser machining because it results in higher precision parts with a small laser kerf.

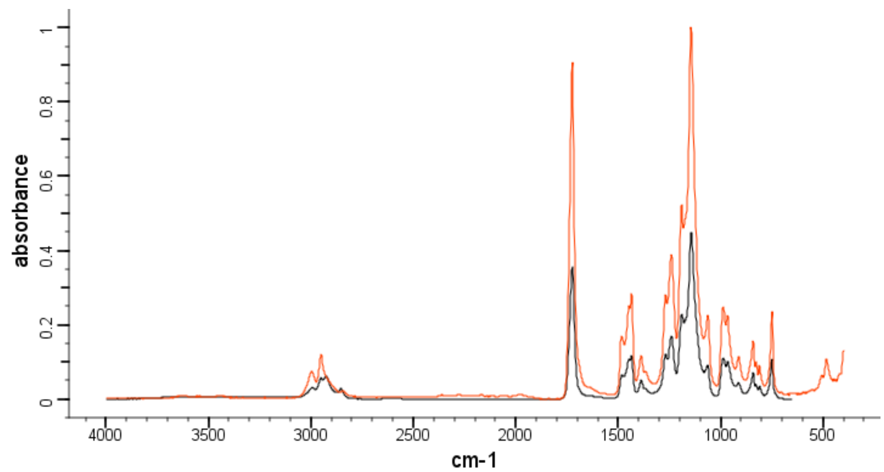


Figure 3 FTIR analysis of cast acrylic from McMaster-Carr showing high absorbance at 10.6 micrometers (940 cm^{-1}). (Bio-Rad Laboratories, Inc.)

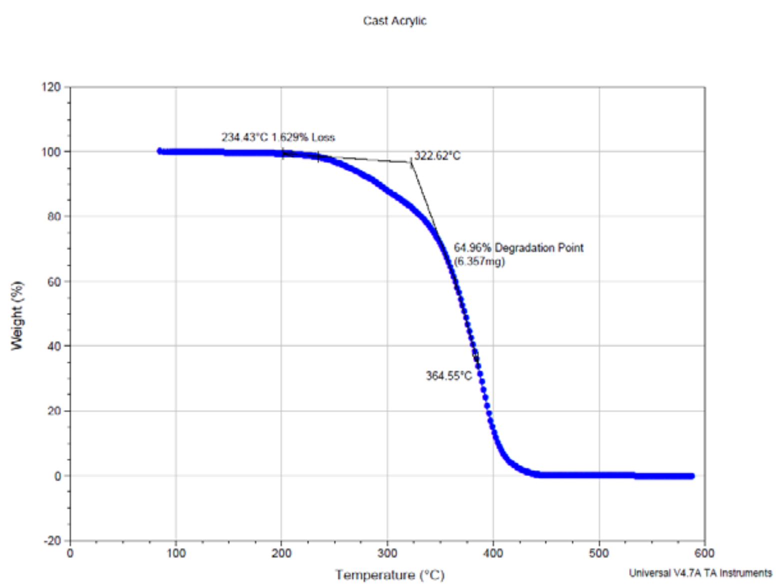


Figure 4 TGA analysis of cast acrylic places its degradation temperature at about 322.62°C. Extruded acrylic is vaporized at a slightly higher temperature (~340°C).

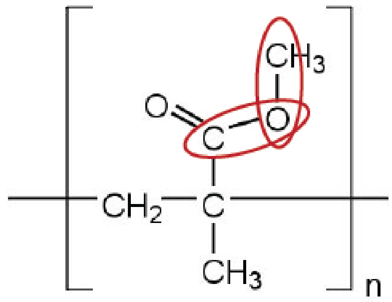


Figure 5 The polymer structure of both cast and extruded acrylic both contain a characteristic C-O bond which is highly absorptive of the 10.6 micrometer laser wavelength. This C-O bond serves as a bucket, collecting heat that the laser inputs into the system. The material directly affected by the laser is then able to rise to its vaporization temperature to be removed.

PMMA is initially synthesized from a free radical polymerization of the monomer methyl methacrylate. Upon heating, the molecules of the amorphous polymer start to rearrange continuously, and then the backbone of the linear polymer begins to degrade (molecular scission). Thermal degradation of PMMA at about 300-400^{o}C is most likely due to depolymerization of the chain from a free radical reaction. When PMMA is laser machined via vaporization, it gives off a distinctive smell which is attributed to the vapors of methyl methacrylate, monomers generated by the molecular scission. Please refer to “Thermal Degradation of PMMA” by Zen Ziyan for a more in-depth look at the thermal degradation process of PMMA.

VI. Techniques

Trade Secrets: Vector Cutting Extruded Acrylic

Some of the generic masking films that acrylic comes with contain paraffin (a wax) which can contribute to excessive flare-ups and distortion of the material when laser cutting. Therefore, to be safe, it is often better to remove the film and re-mask with your own artist’s or tack tape.

Flashback is when excess laser energy reflects off of the cutting bed onto the underside of the stock, resulting in undesired markings or distortions. Change the cutting bed to either a honeycomb or aluminum lamella bed in order to allow the beam energy to pass through the empty spaces. If a change in the cutting bed is not enough to avoid flashback, the acrylic sheet can be raised off of the laser bed before cutting. The beam will then pass through entirely without reflection.

Often, the desired finish on an extruded acrylic cut edge is a glossy and nearly flame-polished look which is a result of melt generated by the heat of the laser resolidifying on the side of the material. As a general rule of thumb, shorter, higher-powered pulses of the laser beam (high frequency + high power combination) allow the acrylic to reach its vaporization point in a shorter period of time as opposed to merely melting. A note on the polished edge: although it is aesthetically pleasing, a polished edge damages the material's mechanical integrity. The resolidification of melt along the cut edge contributes to residual stresses, traps microscopic air bubbles, and makes the piece more prone to cracking.

When laser machining very thick acrylic or performing very intricate cuts, it is often easy to heat distort the material as the power is raised to cut through the thicker material or the nearby acrylic is not given enough time to cool down in the case of adjacent, intricate vector cuts. Create a heat sink for the material by masking both sides of the acrylic with transfer tape and lightly dampening the masking with a spray bottle. Be careful not to leave 'puddles' of water on the material as they can severely reduce cutting depth.

Trade Secrets: Engraving Cast Acrylic

Engraving acrylic on the underside of the material allows the image to be seen through the thickness of the piece. Mirror your graphic in your cut file to produce the correct final engraving.

When engraving graphics which span large areas, the fine, horizontal lines of engraving can cause the final image to look coarse. Lower the laser bed, and shift the piece from the optimum focus level by just the slightest bit so that the spot size of the laser is increased and the raster strokes are overlapping to achieve a smoother, blending effect.

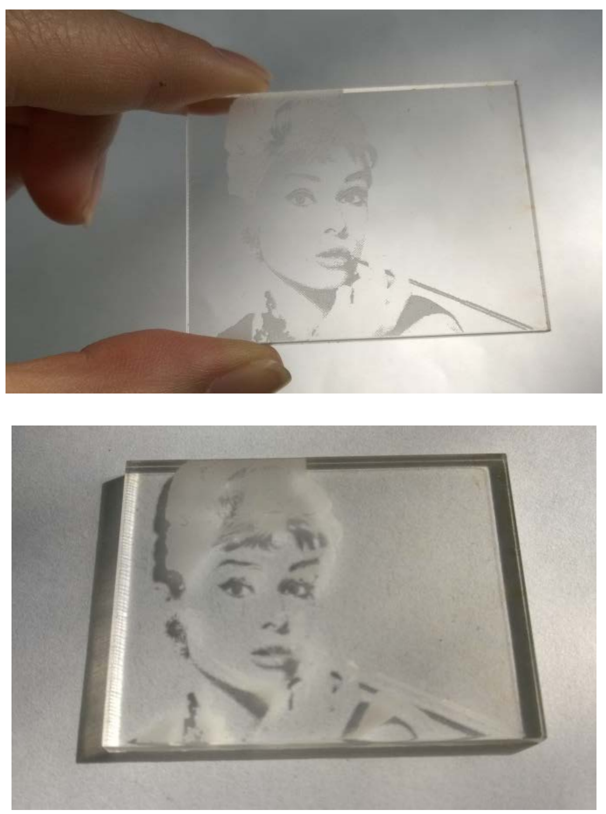


Figure 6 Engraved cast acrylic provides a unique, frosted image contrast. Shadows cast by the engraving are very distinct and sharp representations of the original image.

Trade Secrets: Engraving Mirrored Acrylic

Single surface mirrored acrylics come with a reflective side and an opaque backing on the opposite surface. When engraving mirrored acrylic, a double image will occur if engraving on the reflective surface (you can engrave on the back side instead). When vector cutting mirrored acrylic, cut with the mirrored surface up and don't worry about the laser reflecting off of the material because it will be absorbed by the acrylic first.

Some Warning about Finishing Acrylic

Never clean acrylic with paper towels because they will grate the material like sandpaper, reducing its transparency and giving it a grainy texture. Also, alcohol or ammonia-based cleaners will cause acrylic that has been cut with a polished edge to crack along the surface.

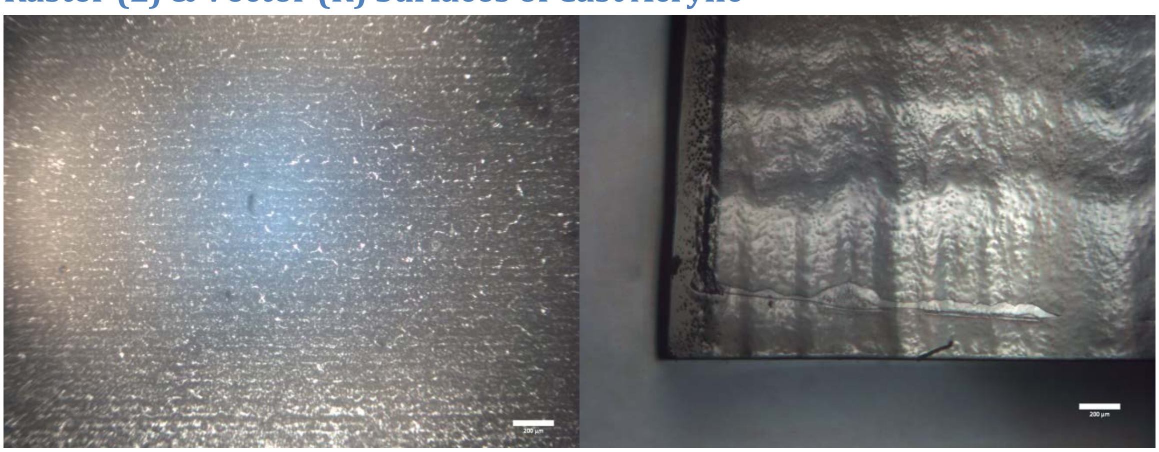
VII. Acrylic Sources

Clear, colored, and mirrored cast acrylic sheets can be purchased on McMaster-Carr in a variety of sizes. Perspex by Lucite International is another high-quality, albeit expensive brand of cast and extruded acrylics. Plaskolite, Inc. produces a variety of extruded acrylic sheets. J. Freeman, Inc. is a local source for bulk quantities of extruded acrylic.

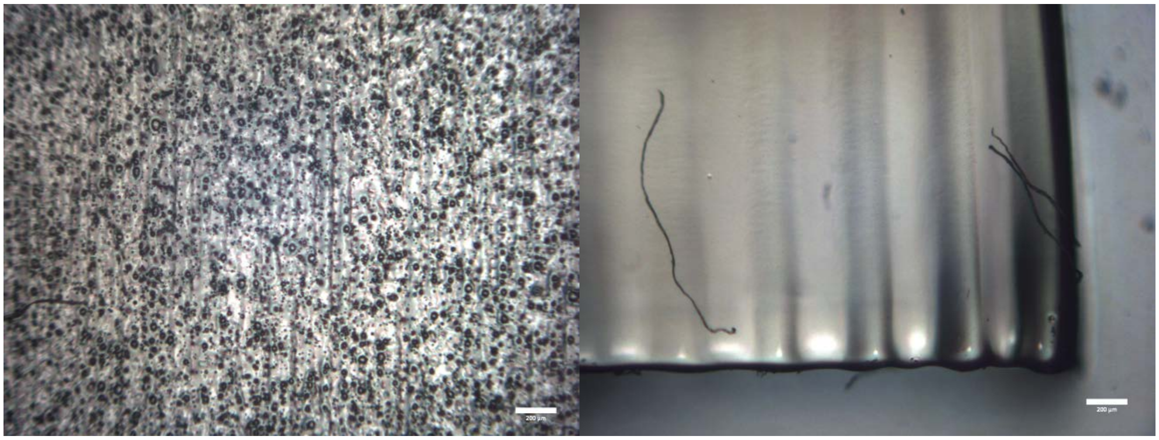
VIII. Appendix

Following are images taken on an optical microscope at 5x magnification of raster engraved and vector-cut surfaces of cast and extruded PMMA.

Raster (L) & Vector (R) Surfaces of Cast Acrylic



Raster (L) & Vector (R) Surfaces of Extruded Acrylic



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LASER PROCESSING OF THERMOPLASTIC POLYMERS

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EXECUTIVE SUMMARY

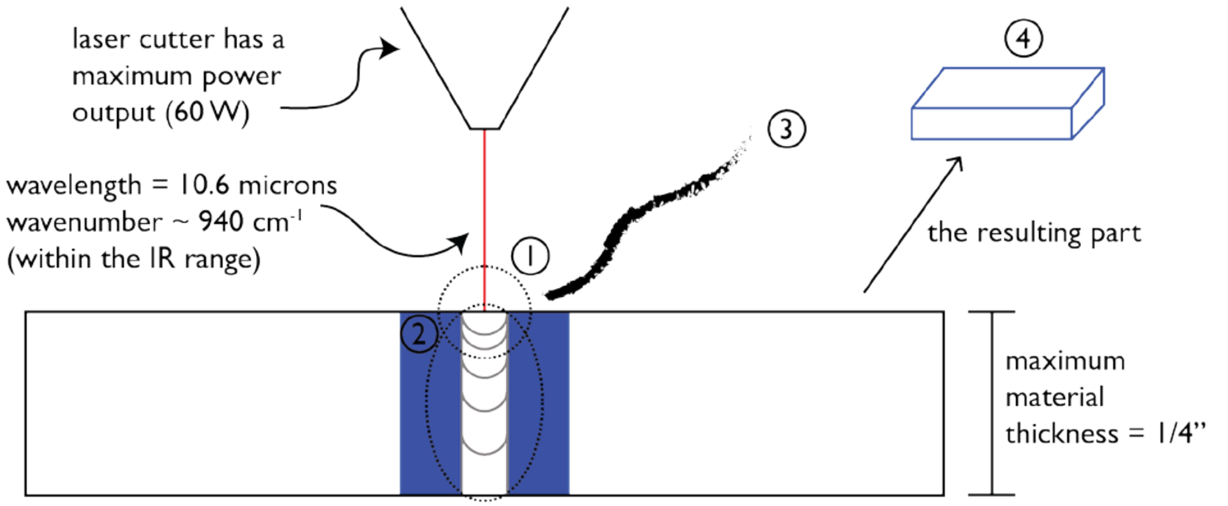
The goal of this project was to determine how polymer thermal properties determine the surface finish of a laser cut part. The laser system used was a 60W Epilog Helix, a hobbyist-grade CO_2 laser delivering a monochromatic wavelength of 10.6 micrometers (wavenumber: 940 cm^{-1}). We explored five thermoplastics: polyacetal homopolymer (Delrin), cast polymethyl methacrylate (C-PMMA), extruded polymethyl methacrylate (X-PMMA), isotactic polypropylene (PP), and high density polyethylene (HPDE). Throughout the project, we ran samples of each unprocessed material through the Fourier transform infrared spectrometer (FTIR), thermogravimetric analysis machine (TGA) and differential scanning calorimeter (DSC) to learn about their thermal properties. We also examined the cut surface of the materials after laser processing at settings suggested by the laser cutter manual. In our explorations, we determined that the materials with a C-O group, lower heat capacity, lower thermal conductivity, and a degradation point below 400^{o}C (Delrin, C-PMMA, X-PMMA) tend have a smoother cut surface when laser processed with a 60 W laser. These materials tend to be laser cut via vaporization. Materials that do not fit this profile (PP and HDPE) tend to have greater melt zones, resulting in cut parts that are both smaller than and possess greater variations in shape from the specifications. They are less suited for processing with a 60 W laser. For the future, we suggest exploration of the heat-affected zones of the material and properties of the resolidified melt that inevitably results from laser processing. We also advise acquisition of another thermoplastic with C-O bonds in order to compare its cut mechanism with both PMMA and Delrin.

LASER PROCESSING

Laser processing is a digital manufacturing method that uses lasers to cut, etch, engrave or mark parts from a sheet of stock material. The first commercially-available CO2 laser cutters that resemble those available today were sold by Laser World AG of Switzerland in 1975 to cut holes in cow bells. Laser cutters are now cheaper and available to the public in lower power forms. Laser cutters exert minimal stress on the sheet of material (as compared to a blade) and do not need to be clamped (reducing distortion during manufacture). The narrow kerf width allows for reproduction of intricate parts with extreme ease at low to no labor cost. Cut parts are extremely accurate and have a high quality edge finish.

Thermoplastics are materials that become pliable above a specific temperature but return to a solid state after cooling. This process is repeatable and reversible. When laser processing, a thermoplastic can be cut via vaporization (the material is vaporized into gas and then sucked away via the air filter and air assist associated with the laser cutter), melt shearing (the material melts into molten plastic that is blown away with air assist), or chemical degradation (the material is degraded to carbon smoke which is sucked away via the air filter and air assist).

In Figure 1, the laser processing mechanism for thermoplastics is outlined.



Step 1 (Absorbance): Due to their chemical structure, certain materials are better equiped to absorb the laser's wavelength. Within the range of 970-1250 cm^{-1}, C-O bonds within a material experience stretch vibrations (which create heat).

Step 2 (Heat Capacity & Thermal Conductivity): The material deals with the heat that is being generated based upon its heat capacity (the material's ability to absorb heat from its surroundings) and its thermal conductivity (the material's ability to transfer heat). Materials with a lower heat capacity and lower thermal conductivity generally produce better cut surfaces as they require less energy to reach their vaporization point and do not result in excessive residual melt.

Step 3 (Vaporization/Melting): Materials with a degradation point below 400°C, in our experiments, tend to cut by mainly by vaporization. Otherwise, the materials melt and are then blown away by the laser cutter's air assist.

Step 4 (Cut surface of part): Each material has a distinctive cut surface based on their material properties and cutting parameters.

Figure 1 Laser machining process of thermoplastic polymers.

BRIEF DISCUSSION OF MATERIAL PROPERTIES

POLYACETAL HOMOPOLYMER (DELRIN)

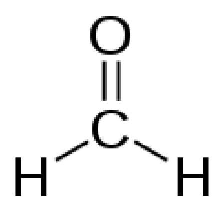


Figure 2 Polyoxymethylene is formed by polymerizing pure formaldehyde.

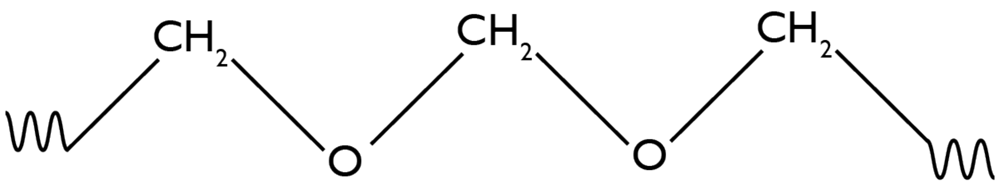


Figure 3 Polymer chain of delrin.

Our FTIR comparison with the MatWeb data indicates that our material is polyacetal. We know we ordered Delrin from our supplier so our test confirms the McMaster-Carr order. Delrin is a polyoxymethylene homopolymer owned by DuPont. Polyoxymethylene is formed by polymerizing extremely pure formaldehyde. The process for creating Delrin was researched extensively to create a material that is tough and stable. Four processes are known to degrade Delrin:

1. Stepwise thermal- or base-catalysed hydrolytic depolymerisation (cleavage of polymers by the introduction of water)
2. Oxidative attack leading to chain scission and therefore depolymerization (forceful introduction of oxygen atoms)
3. Acid-catalysed cleavage of C-O bond
4. Thermal depolymerization via scission of the C-O bond occurring above 270^{o}C

Based on what we know about laser processing, we anticipate that thermal depolymerization of of the C-O bonds will occur when laser cutting the material. Delrin forms a linear, flexible chain backbone with little to no branching. It is therefore highly crystalline (75-85%) and pack closely together with a melting point at 175^{o}C. Delrin needs to be capped with end groups acetate or methoxyl. Sheets of Delrin are generally produced via extrusion.

POLYMETHYL METHACRYLATE

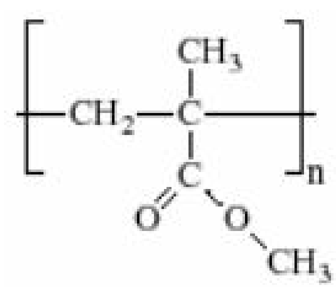


Figure 4 Methyl methacrylate monomer of PMMA.

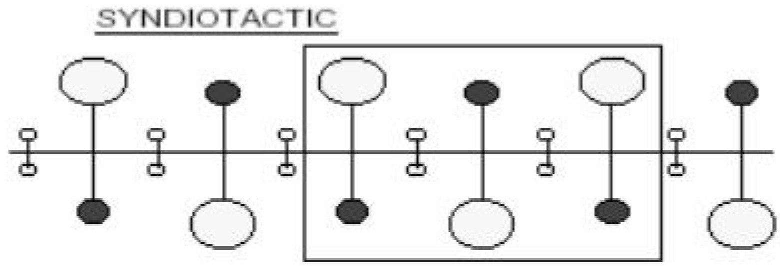


Figure 5 Block diagram of syndiotactic orientation of monomers in PMMA chain.

PMMA is an amorphous, linear polymer of the acrylic class. Running our sample of X-PMMA through the FTIR confirmed our possession of 85% syndiotactic polymethyl methacrylate. Syndiotacticity refers to the alternate positions of molecular groups along the polymer chain.

PMMA is synthesized from a free radical polymerization of the monomer methyl methacrylate. Upon heating, the molecules of the amorphous polymer start to rearrange continuously and then the backbone of the linear polymer begins to degrade (molecular scission). Thermal degradation of PMMA at about 300-400^{o}C is due to depolymerization of the chain from a free radical reaction. When PMMA is laser machined, it gives off a distinctive smell which is attributed to the vapors of methyl methacrylate, monomers generated by the molecular scission.

EXTRUDED POLYMETHYL METHACRYLATE (X-PMMA)

X-PMMA is manufactured by squeezing acrylic resin through a die of a certain thickness in order to produce molten sheets. These sheets are then run through cooling rollers. As a result of the manufacturing process, X-PMMA has an apparent extrusion direction which aligns molecular chains in a common orientation. This then allows secondary forces to play a greater part between the interactions of the syndiotactic chains. This contributes to the higher degradation temperature of X-PMMA in comparison to C-PMMA. Extruded sheets also have less variation in thickness across due to the manufacturing process.

CAST POLYMETHYL METHACRYLATE (C-PMMA)

The process of casting acrylic consists of pouring the polymer into a casting cell which consists of two glass sheets separated by a gasket. The cell is then clamped together as the material is allowed to polymerize and shrink. Then, the material can be annealed to reduce internal stresses. Annealing gives C-PMMA generally better mechanical properties than X-PMMA. However, due to cell casting, the resultant sheet varies more in thickness across than similar extruded sheets.

POLYPROPYLENE (PP)

According to MatWeb, our FTIR data confirms that the material we received is isotactic polypropylene.

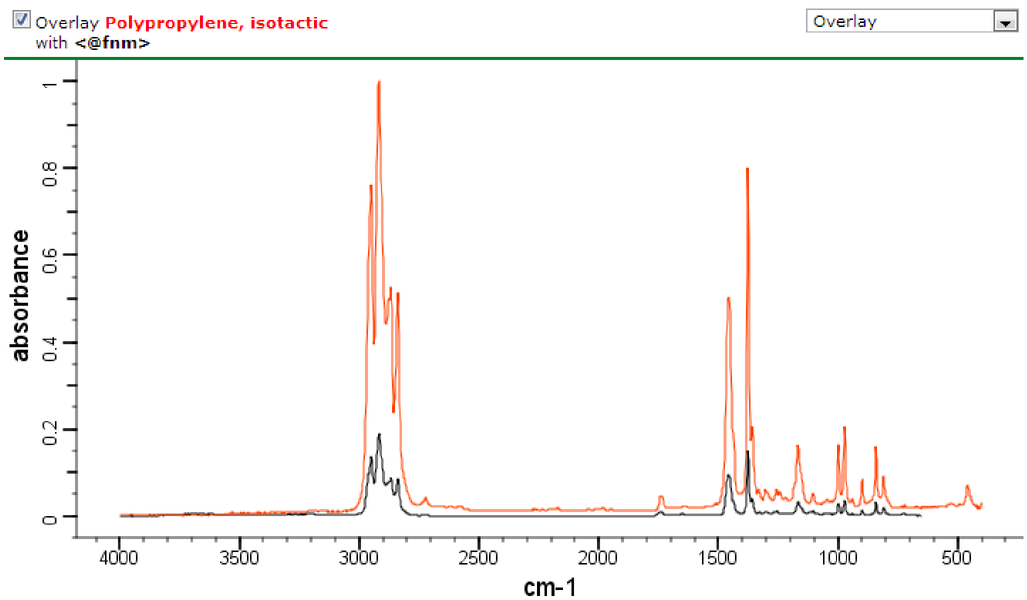


Figure 6 FTIR absorption spectrum for isotactic polypropylene.

The red data is from the MatWeb database and the black data is from the FTIR data we collected. As can be seen, the correlation is nearly identical.

Isotactic refers to the stereoisomerism of the molecules. An isotactic configuration involves the zig-zag pattern of the carbon chain atoms. In the case of PP, it is important to note the 3D nature of its isotactic form where propene monomers form a hydrocarbon isotactic chain (see Figure 5). Because the material is isotactic, it is better able to stack itself and form Van der Waal bonds, making the melting point higher (160^{o}C).

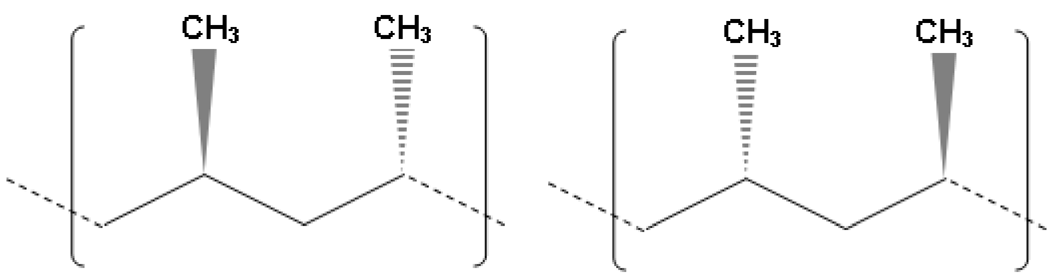


Figure 7 Isotactic polypropylene chain.

Polypropylene is a formed by separating propylene molecules from propane (a petroleum product). The propylene molecules are then polymerized to create various stereoisometric formations of the material within one vessel. The types are separated and processed further to get the purest product.

Polypropylene crystallises in a regular helix formed from linear chains. Polypropylene can be easily degraded through photo-oxidation through UV radiation . UV rays have a wavelength 400-100 nm so we anticipate that that the laser's IR rays will not be as significant as Delrin.

ABSORPTION OF CO_2 LASER WAVELENGTH

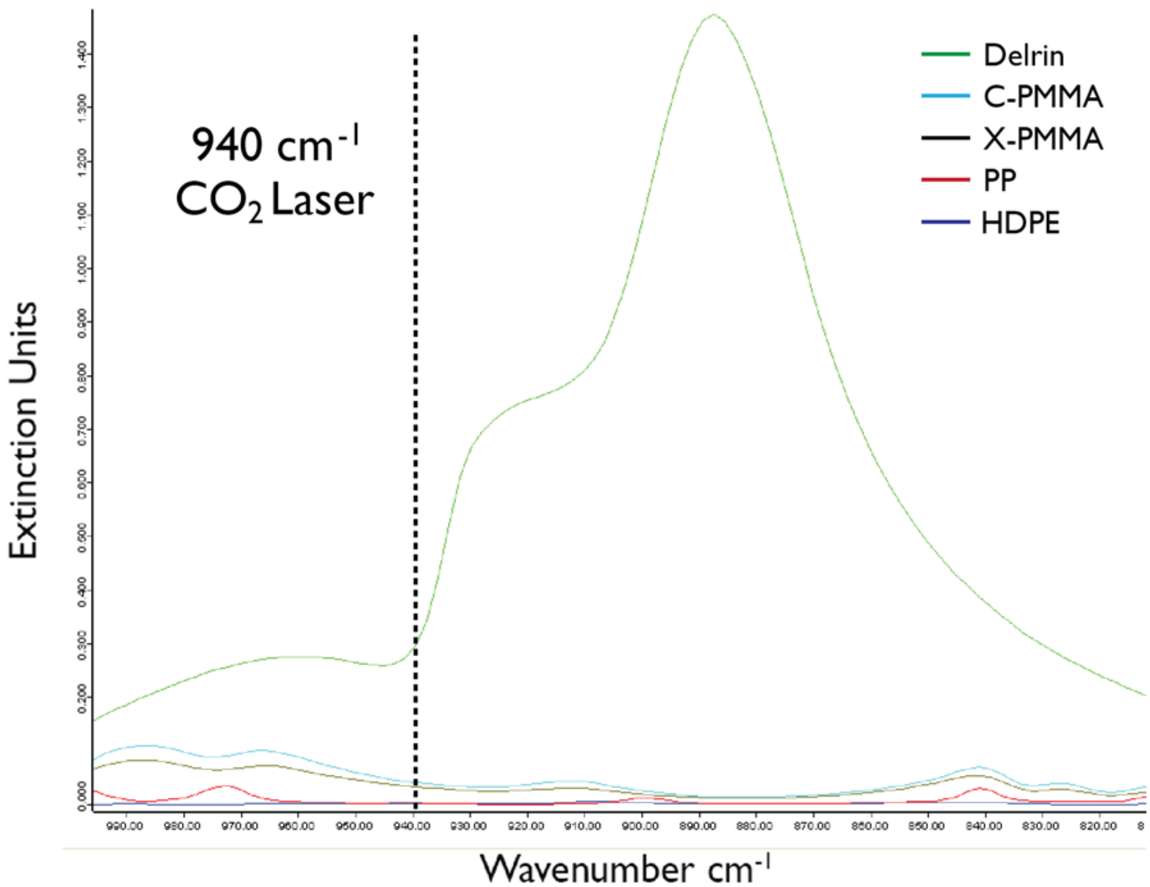
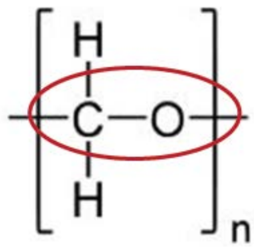


Figure 8 Close-up of FTIR absorption spectrum of Delrin, C-PMMA, X-PMMA, PP and HDPE about the CO_2 laser wavelength. The 10.6 micrometer CO_2 wavelength translates to a wavenumber of 940 cm^{-1}. An extinction unit of 0 corresponds to light travelling through the material without loss while a value greater than 0 corresponds to light absorption. It can be seen here that the absorption of CO_2 laser radiation is greatest in Delrin, and then consecutively in C-PMMA, X-PMMA, PP and HDPE which inversely correlates with the quality of cuts that we were able to make on each material.



Delrin: The polymer structure of polyoxymethylene shows a simple, repeating carbon-oxygen backbone. It is this C-O bond which is highly absorptive of frequencies about the range of the laser cutter (~970-1250 cm^{-1}). The C-O bond stretches when hit with the laser, absorbing heat. It takes more energy to stretch than bend a bond. Therefore, stretching vibration results in significant heating of the laser processed area.

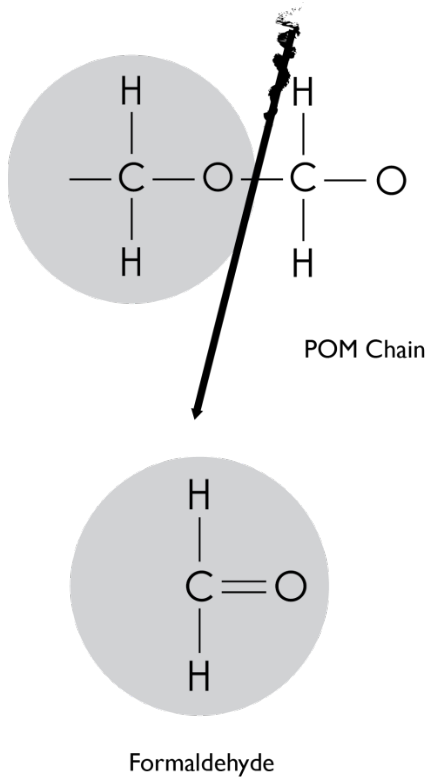
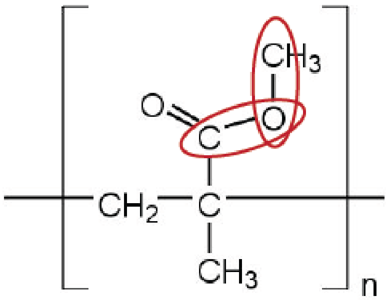
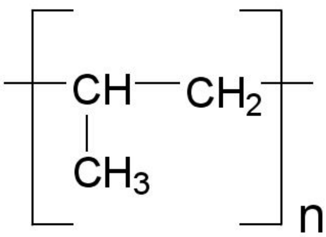


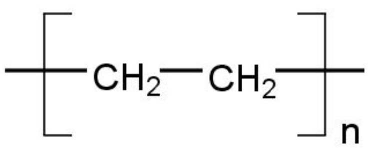
Figure 9 Delrin is known to form formaldehyde upon laser treatment. INGRID CITE THIS AND ADD MORE TO IT



PMMA: The polymer structure of both cast and extruded acrylic also contain the characteristic C-O bond found in Delrin. PMMA and Delrin respond to laser machining in extremely similar ways: they are two of the few materials known to laser machine via vaporization. We believe that it is this C-O bond which serves as a bucket, collecting heat that the laser inputs into the system. The material directly affected by the laser is then able to be raised to its vaporization temperature to be removed.



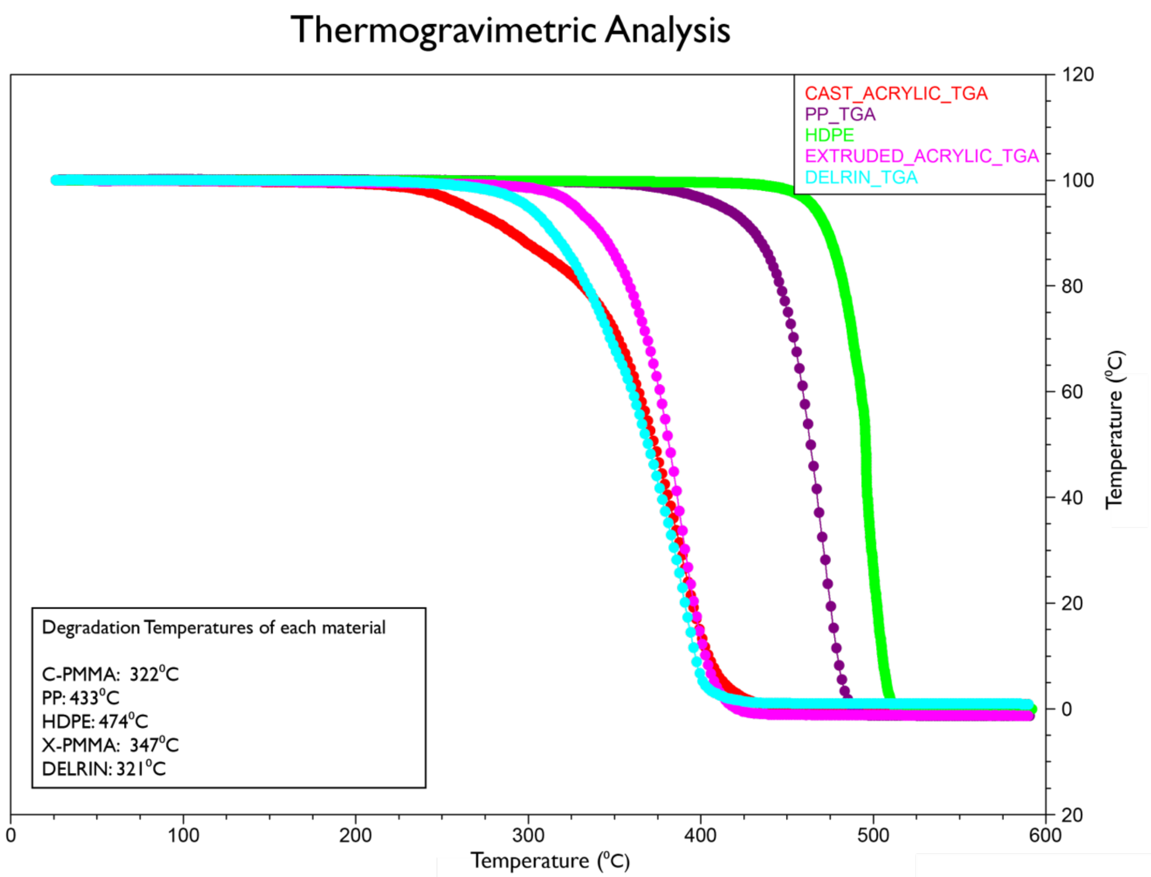
PP: The polymer structure of polypropylene does not possess a C-O bond, making the absorption of frequencies about the range of the laser cutter (~970-1250 cm^{-1}) more diffuse. Heat absorption is less focused in the laser processing area. As a result, the material does not heat up enough to create a distinct zone of high energy density. This material is known to be cut by melt shearing and analysis of the molecular structure supports this claim. To achieve melt shearing however, the material needs only to be heated to its melt temperature (160^{o}C).



HDPE: Similar to PP, the polymer structure of polypropylene does not possess a C-O bond making the absorption of frequencies about the range of the laser cutter (~970-1250 cm-1) more diffuse. HDPE has a relatively low melt temperature compared to the other plastics due to having low intermolecular forces, but a high degradation temperature. As a result, this material cuts by melt shearing.

DEGRADATION PROPERTIES (TGA)

Running thermogravimetric analysis of samples of each material rendered the following results:



As can be seen, the materials with the degradation points below 400°C are Delrin, C-PMMA, and X-PMMA, are all materials that are known to cut by vaporization. Materials with a degradation points above 400°C (HDPE and PP) are the materials known to cut by melt shearing. This proves to be an extremely powerful predictor of whether a material will cut well or poorly. Note that this is not the sole factor that determines laserability - the absorbance, thermal conductivity and heat capacity all interact to produce a certain cut surface.

THERMAL CONDUCTIVITY AND HEAT CAPACITY

Materials that are easier to degrade are cut more easily than materials that are more difficult to degrade. Vaporisation cutting also leaves a better surface finish, and minimizes the warping of the part. While the degradation temperature observed in our TGA analysis is the driving factor, other thermal properties change how the material cuts. We quantified through the “heat capacity per volume” and “heat required to heat 1 cm3 to degradation temperature”.

The heat capacity per volume is signifies the amount of energy the laser needs to dump into the materials to raise 1 cm3 1 degree kelvin. Normally this is described as heat per gram kelvin, but since the laser beam has a constant cross section, it makes more sense to talk about volume as opposed to mass being removed. This is especially important because these plastics do not have identical densities. As you can see in the table, POM and HDPE have similar heat capacity per volume, while PP and PMMA have lower heat capacities for per volume.

This implies that POM should cut like HDPE, which we have observed to be not true. This is because we have not taken into account the degradation temperature that needs to be reached for each material. This is done by taking the degradation temperature and multiplying by the heat capacity per volume yielding the heat required to raise one cm3 to the degradation temperature. This is the critical parameter along with laser wavelength absorbance that determines how a material will cut. Looking at this parameter we see that materials with lower required energy to raise a volume to the degradation temperature cut by vaporization.

Thermal conductivity has an influence on cut as well. High thermal conductivity means that heat will diffuse across the part quickly, and that it will take even more energy to heat the cut zone. The only material with a higher conductivity is HDPE, which explains the particularly wide kerf that was observed in that part, which was probably caused by a very wide heated area being sheared by the air. It was wider than the cut in the PP probably because of HDPEs higher thermal conductivity and lower melt temperature.

CULMINATION OF ABSORBANCE, THERMAL CONDUCTIVITY, AND HEAT CAPACITY

	POM	**PP**	**X-PMMA**	**C-PMMA**	**HDPE**
Absorbance at 939 cm-1 (ranked)	#1	#4	#3	#2	#5
Thermal conductivity (W/mK)	.23-.37	.1-.22	.2	.2	.42-.51
Melt temperature (C)	175	160	160	160	121
*Heat capacity per volume (J/Kcm3)**	2.1	1.62	1.652	1.652	2.09
Degradation Temperature (C)	321	433	347	322	474
Heat required for 1cm3 to reach degradation temp (J)	674	701.46	573.44	531.94	990

*Heat capacity per volume is calculated from the specific heat (J/gK) and density(g/cm3) of the polymers. Volume (as opposed to mass) is more representative of the energy required to remove material as seen as the volume under the laser.

To culminate the thermal knowledge gained, a clear connection can be made between the laserability and a degradation temperature that is lower than 400ºC. The materials all had relatively similar specific heats. The materials all have a specific heat that can then be extrapolated to the value in the final row of Table 1. This row demonstrates the heat required to make 1 cm^3 reach its degradation temperature (J). Note that the order of increasing heat corresponds loosely to the material's laserability in ascending order.

The thermal conductivity of the materials were fairly close together (~0.2 W/mK) except that of HDPE with a thermal conductivity of 0.42-0.51 W/mK. This difference may account for the enormous melt zone seen in the microscopy.

CUT SURFACE IMAGING

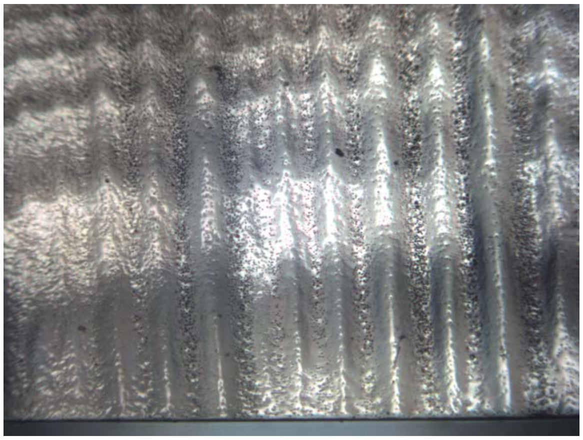


Figure 10 C-PMMA: face of cut edge

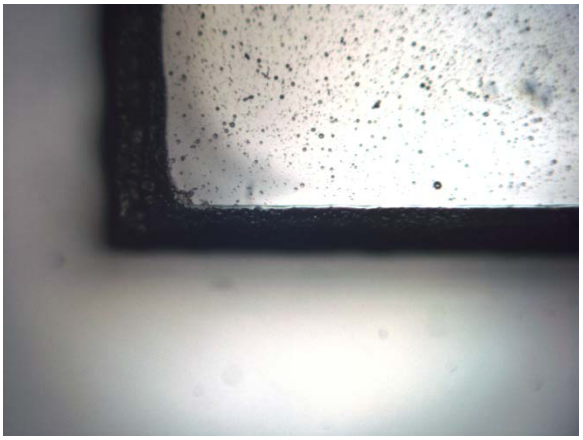


Figure 11 C-PMMA: top surface

In Figure 8, the striations made by the laser pulsing on and off are apparent. Note that the piece has no “grain”. On the same image, horizontal ripples of decreasing frequency can be seen going from the top to bottom surface which is in contact with the laser bed. The laser is focused on the surface of the material while cutting, generating the highest energy density at that location. Due to the location of the focus and the relatively low thermal conductivity of C-PMMA, the horizontal ripples can be attributed to the temperature gradient down the cut edge and the resulting differences in thickness of material removed. Since the top of the acrylic is in focus throughout the frame, it can be determined that the piece remained relatively flat and the heat affected zone was not extensive. From Figure 9, it can be seen that the cut edges are not entirely parallel. This taper is in part due to the focus location.

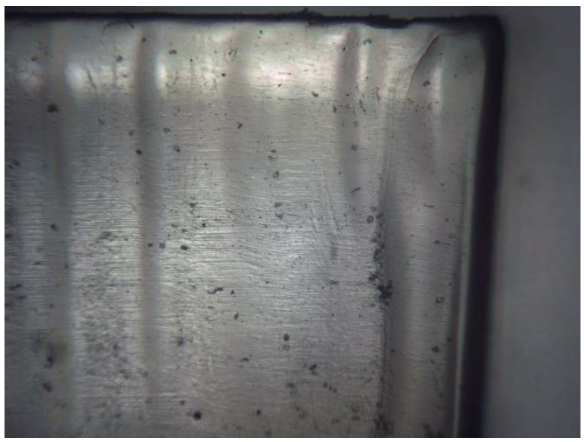


Figure 12 X-PMMA: face of cut edge

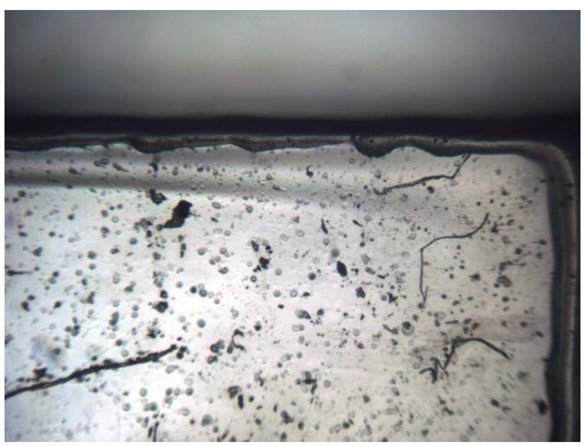


Figure 13 X-PMMA: top surface

The X-PMMA was cut with the same settings as the C-PMMA. However, more melt can be seen on the cut edge of X-PMMA. It is easier to flame polish X-PMMA. This may be attributable to the higher molecular orientation from extrusion. Amorphous C-PMMA is has more entangled linear chains which may deter its ability to be flame polished. The “grain” pattern in Figure 10 is a manifestation of molecular alignment along the extrusion direction. In Figure 11, there is a definite fold or bump at the top edge of the plastic. This only occurred on two of the four sides of the piece, and is probably related to the direction that the air assist blows. It appears to have been formed by melting, or at least passing the glass transition temperature, and then being deformed by the force of the air.

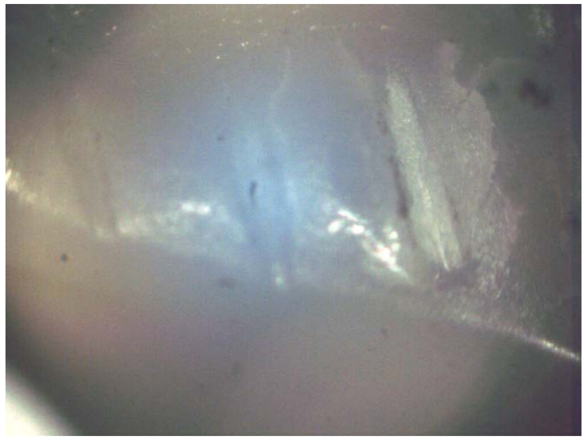


Figure 14 HDPE: face of cut surface

Figure 15 HDPE: top surface

The HDPE images (Figure 12 and 13) demonstrate that the part was incredibly warped by the heat of the laser cutting. The left image is of one of the cut surfaces, and the right image is of the top of the piece. It can be noted that this is little difference between the two images as the whole part basically became molten and then re-solidified. The melt temperature for HDPE is 121^{o}C which is significantly lower than 474^{o}C. The laser cannot supply the necessary energy to vaporize the material, therefore it makes sense that the material is cut with melt shearing. Unfortunately, the whole part tends to melt as well as the edges, making the quality of the part non-existent and the cut surface a melted mess.

Figure 16 PP: top surface

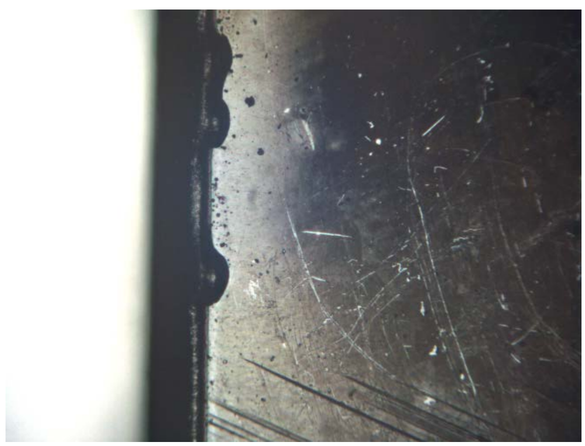


Figure 17 Delrin: top surface

Here is a comparison of PP (Figure 16) and Delrin (Figure 17) edges. The PP edge is severely melted and the lip created by the melt is folded over the piece, creating a rounded corner and a round edge profile. The Delrin edge is fairly straight with some divots, but the surface is not melted or rounded. This is because Delrin vaporizes, while PP is displaced by air from the cutter, which rounds and bends the melting edge of the part. Delrin has a lower degradation temperature (321^{o}C) than PP (433^{o}C). Delrin also has C-O bond meaning it easily absorbs the energy required to vaporize. Despite its lower thermal conductivity (0.1-0.23 W/mK) and heat capacity (1.62 J/K cm^3) compared to Delrin (0.23-0.37 W/mK and 2.1 1.62 J/K cm, respectively), the PP sample has more melt. Perhaps in this case, thermal conductivity and heat capacity play a smaller role than the absorbance of the 940 cm^{-1} by the C-O bonds in Delrin.

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Laser Cut Like a Boss: *Trainee Handbook*

Version 1

By Mary Morse, Ingrid Hagen-Keith & Annie Zeng
Vol. I Issue I

What is this book?

This handbook was written by Annie Zeng, Ingrid Hagen-Keith and Mary Morse. Throughout the semester, we will be producing a set of laser cutting handbooks. The handbooks will touch upon basic topics, like how to create proper cut files and cutting with the specific laser cutters in the machine shop. They will also present more advanced topics, such as laser cutter-specific alternative joinery and cutting exotic materials.

This issue is targeted to new and developing laser cutting students. It briefly presents various topics involved in laser cutting. For more advanced discussions of these topics, read our future issues!

This is prototype 1 of our Trainee Handbook. We understand that it is not perfect, and we want your help to make it better. Please, read through this book, ask us questions, mark it up and give us feedback! Email the NINJAs at laser@lists.olin.edu.

Rough Table of Contents

The following list is the rough table of contents for this issue:

The purpose of each section is to briefly introduce beginner concepts.

Safety

The laser cutter is a printer that can set your stock on fire and cause excessive flare-ups. In practice, the laser cutter is as safe to operate as any other machine in the shop if common sense, vigilance, and thorough training is internalized and practiced. The machine should be used and maintained with respect to promote safe usage.

LASER SAFETY

The Epilog and Trotec Laser Systems contain two lasers. They both enclose a class 4 CO_2 laser which emits intensive and invisible laser radiation. These lasers can start fires, cause damage to the skin, and are a hazard to the eye when viewed directly and from reflections. The second laser is a Red Dot Pointer which is considered safe if it is not viewed directly or through reflections.

FIRE SAFETY

Make sure you have easy access to and know how to operate the fire extinguisher before you execute any cut, especially with a new material. Do not ever walk away from a machine when it is executing a job.

FUME SAFETY

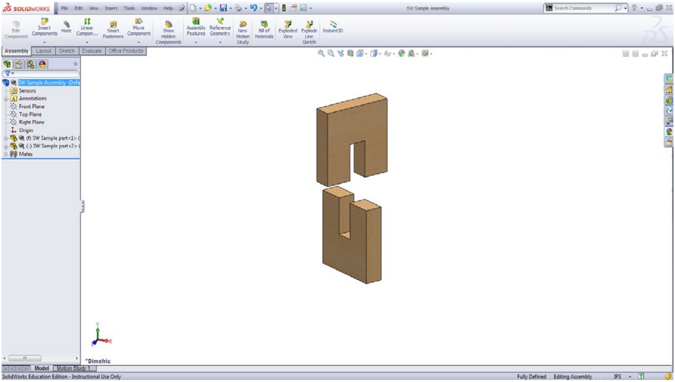
Make sure the air exhaust is open and functioning. If you see or smell excessive fumes during cutting, stop the job immediately.

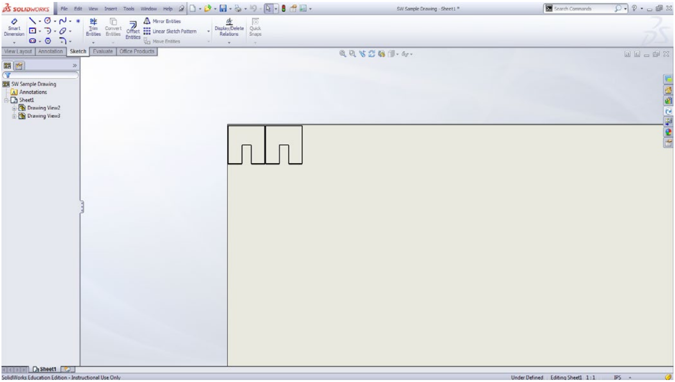
CUT FILES

Creating cut files for a laser cutting is pretty straight forward once acquainted with each software. In the following pages, we will **outline** the file creation methods for SolidWorks and Adobe Illustrator.

To improve further improve your skills, we suggest reading each machine's manual and a good amount of practice. Consult a NINJA or email lasers@lists.olin.edu for more advanced questions.

FILE CREATION IN SOLIDWORKS





STEPS

1) Model your parts with the appropriate tolerances.
2) Make a new custom drawing file that is the size of the laser cutter bed or smaller (just keep track of the size of your cut file).
3) Place your parts on the cut file with the view you want to laser cut. Do not overlap a part corner with the corner of a sheet. Do not import annotations. There should be no centermarks or centerlines in your drawing. Outlines of parts should be solid lines.
4) Ensure that hidden lines are removed.
5) Ensure that the scale of your parts is 1:1. This may involve a custom scale.
6) There should be at least 2 mm distance between parts.
7) Set the line thicknesses to 0.002 inches for vector lines. If the cut file includes only vector cuts, use the following steps to set up the file: Options-> Document Properties-> Line Thickness-> Set all line thicknesses to 0.002 in.-> OK

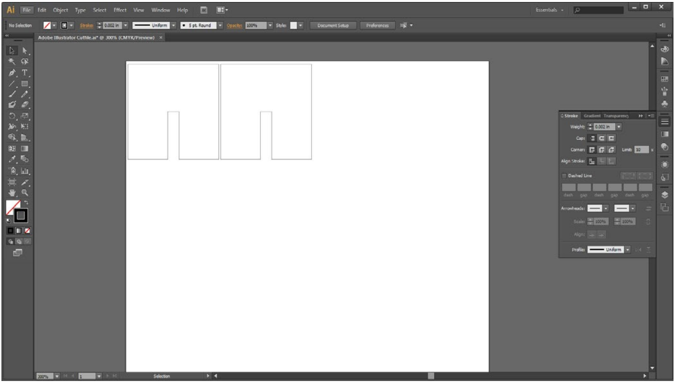
Tricks of the Trade

Rastered text can be placed into a drawing file using the Note button.

Vector cut text must be included at the part level: Sketch-> Text-> Select a curve that the text will be on and type->Extrude Cut-> All Bodies.

You can insert a **picture** into a SolidWorks drawing file using Insert-> Picture. You can then place the picture based on co-ordinates or grabbing.

FILE CREATION IN ADOBE ILLUSTRATOR



STEPS

1) Make a new Illustrator file that is the size of the laser cutter bed or smaller (just make sure you keep track of your sheet's dimensions).
2) Draw your parts using the line or pen tool. Do not overlap a part corner with the corner of a sheet. Ensure that the anchors of the lines are connected.
3) Ensure parts are 2 mm apart.
4) Set the stroke for desired vector cut lines to 0.002 in. If you want a rastered line, the stroke must be greater than 0.002 in.

Tricks of the Trade

For **rastered text** in Illustrator, just type and place as you please.

If you want to **vector cut text**, type your text. Then set the fill to empty and set the stroke weight to 0.002 in.

Convert images to greyscale so that your have an idea of what the **rastered image** will look like. Black sections will be darker than lighter grey sections. White will be rastered extremely lightly as a set of light dots.

MACHINES

The machines in the shop are carefully maintained and should be treated with absolute respect. That being said, they are **tools** with an enormous capacity to do amazing things. This section describes how to print the **most basic** files. For more information, read the manual or experiment!

PRINTING ON THE EPILOG

The Epilog Legend is a powerful laser cutter ideal for experimentation with a high level of control. It can accommodate stock that is 32 in. x 20 in. The z-axis spans 9 in.

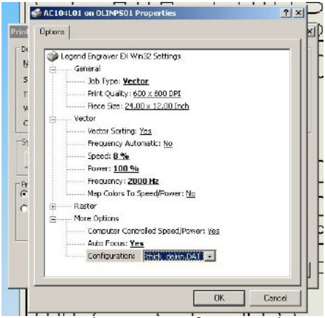
This laser cutter vector cuts or rasters based upon line thickness. Lines that are 0.002 in. or less vector cut while lines with a greater thickness will raster.

If you wish to increase the speed of your job, make the drawing file smaller. Just make sure you follow step 1!

To increase mastery on this laser cutter, read the *Color Mapping* section from the manual.

STEPS

1) Ensure that the resolution and scale are properly configured using: File-> Page Setup-> Set Scale to 100%.
2) If using the machine shop computer, double check that the line thickness are what you intended in your original cut file.
3) You may then proceed with the printing process: File-> Print. Choose AC104L01 as the desired printer. The number of copies will always be 1 copy.
4)Click Properties. This will open the Epilog Driver.



5) Set your piece size to the size of your drawing/Illustrator file. Ensure you have the correct job type. Please refer to the material sections in this book and "Safely experimenting with laser cutter settings" for more in-dept settings information.
6) Press Print. The Epilog will receive the order. Using the toggle wheel, select Jobs->View. Give the laser cutter a minute when doing this. If you can see your cut file, then press Jobs->Run. This will run the job with the settings you sent at the computer level. (See Focus section to get the ideal cut).

PRINTING ON THE TROTEC

The Trotec Speedy 300 is a straight-forward, intuitive machine with custom driver software conducive to creative manipulation. It can accommodate stock that is 29 in. x 17 in. The z-axis spans ~8 in.

This laser cutter vector cuts or rasters based upon line color. Lines with a RGB of 0, 0, 0 will vector cut while lines with an RGB value of 255, 0, 0 will raster.

Note that these RGB values must be used! If the numbers are even slightly off, the job will not print as you expect.

When creating cut files for this machine, your piece size should be limited to 28 in. x 16 in.

STEPS

1) Ensure that the resolution and scale are properly configured using: File-> Page Setup-> Set Scale to 100%.
2) If using the machine shop computer, double check that the line colors are what you intended in your original cut file.
3) You may then proceed with the printing process: File-> Print. Choose the Trotec printer. After pressing OK, the Trotec settings driver will open.
4) The settings driver will allow you to set the size, material, and settings. You will usually want the Process Mode to be set to Standard.
5) If your job involves rastering *and* vector cuts, you will want to set Halftone to on. If it involves only vector cuts, you should set the Halftone off.
6) In general, you will always want Cut Line set to None. See the Trotec manual if you want more information on this.
7) After all this, press OK. This will open the Trotec job control panel.
8) Drag and drop your job from the jobs queue into the workspace. To view your job's lines, click the checkbox at the bottom of the Jobs panel.
9) Note that on the Trotec, you move the head using the panel on the machine. The position of the laser head can be seen on the Trotec Jon Control software as well. This means that you can move the laser head to a specific location on your material and then drag and drop the job to snap with the laser head cross hatch. So exciting!
10) Connect with the laser cutter and then laser cut away after pressing Run.

CUTTING

Laser cutters are more advanced than a simple printer that you press and go. Through **manipulation of setting and setup** like speed, power, frequency/resolution, focus, kerf, and jigging, you can cut a variety of **complex, exciting** jobs like the Mary's pumpkin above.

This section will help you start thinking about laser cutting and settings **creatively.** The best way to learn is through thoughtful experimentation.

SAFELY EXPERIMENTING WITH SETTINGS

The laser cutter is a fantastic prototyping and manufacturing method. It gives a high level of control and is very user-friendly. That being said, there are dangers to using the laser cutter. Harmful fumes and particulates may be produced in the process of cutting and a fire could be started.

Fires do occasionally happen in the shop and it should not be a source of shame if they occur. They can be extremely dangerous, damaging to the laser cutter, and ultimately huge pain.

However, this should not preclude individuals from experimenting with the laser cutter. Experimenting should be done intelligently and with care. In the following pages, we will conceptually explain speed, power, and frequency/ resolution. Once you understand these settings, it will be easier to think about setting experimentation in a safer manner than mere guessing.

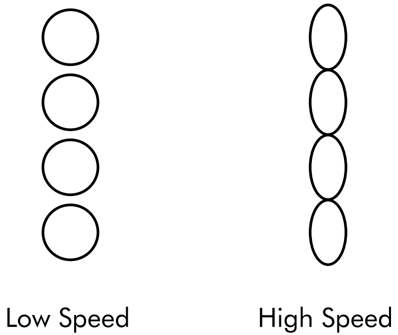
A laser cutter is an **energy transfer method** that can be used to melt, vaporize, or degrade a material. You can vary how long energy is transferred to a section of a material (speed), how much energy is transferred to a section (power), and the spacing of the energy transfer to the material (frequency or resolution for vector cuts and raster engraving, respectively). There are other ways to vary energy transfer but these are the most central to laser cutting.

SPEED

Speed indicates how fast the laser head moves. Lower speed allows more time for the laser beam to dwell on a particular spot which means more energy is transferred to the material. On the other hand, higher speed results in less time for the laser beam to apply a certain amount of energy on a particular spot on the material.

Speed is measured in m/min and is often expressed as %. Maximum speed differs for each type and model of laser cutter machine.

To reduce edge modifications like charring and thermal damage, you want to increase the speed so that the air assist can quickly access the recently cut zones.



Use the info-graphic above to help you think about speed as a parameter of energy transfer.

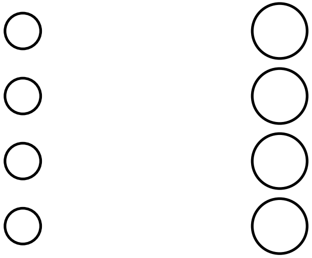
POWER

Power indicates the rate at which energy is transferred in the laser beam.

Power is measured in W, and it is often displayed as a percentage (%) of maximum power. Maximum power differs for each model of laser cutter.

Lower power applies less energy per pulse on the material; higher power applies more energy per pulse on the material.

In general higher power means deeper cuts than lower power.



Low Power High Power

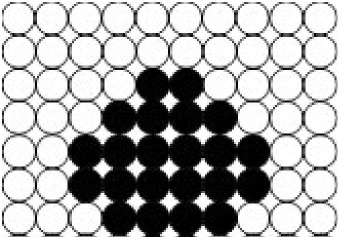
Use the info-graphic above to help you think about power as a parameter of energy transfer.

RESOLUTION (FOR RASTER ENGRAVING)

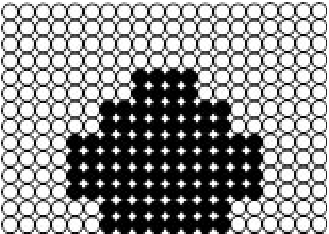
Resolution indicates the density of pulses (measured in dots/inch, DPI).

Higher resolutions give clearer and more detailed the prints.

Since each pulse applies the same amount of energy regardless of resolution settings, higher resolutions deliver energy at a higher density than lower resolutions. At particularly high resolutions, the dots printed overlap meaning most of the image is printed twice, making for a darker, deeper image.



Low Resolution



High Resolution

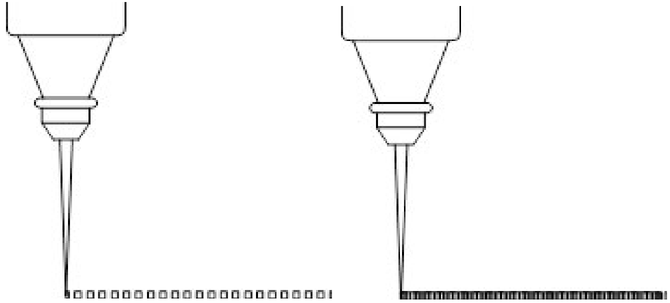
Use the infographic above to help you think about resolution as a parameter of energy transfer.

FREQUENCY (FOR VECTOR CUTTING)

Frequency indicates the number of pulses fired per second (measured in pulses fired/second, PPS, or Hz).

The higher the frequency, the denser the dots on each path, and therefore the more dense the energy applied on the material.

Both resolution and frequency are similar in that both are concerned with the number of pulses fired in an area. The major difference between the two is that resolution determines the quality of the image clarity or an area of a shape that is rastered, while frequency determines the quality of a line.



Low Frequency High Frequency

Use the info-graphic above to help you think about frequency as a parameter of energy transfer.

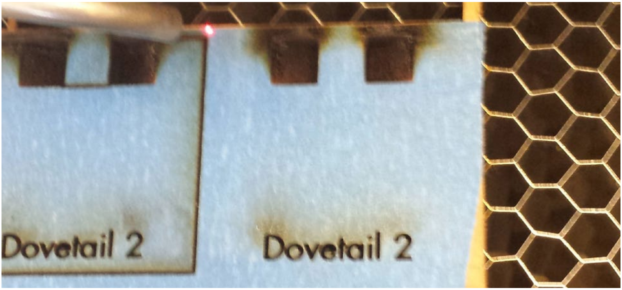
EXTRA FACTORS AFFECTING ENERGY TRANSFER AND CUT QUALITY

You can affect the outcome of a cut by also varying other conditions:

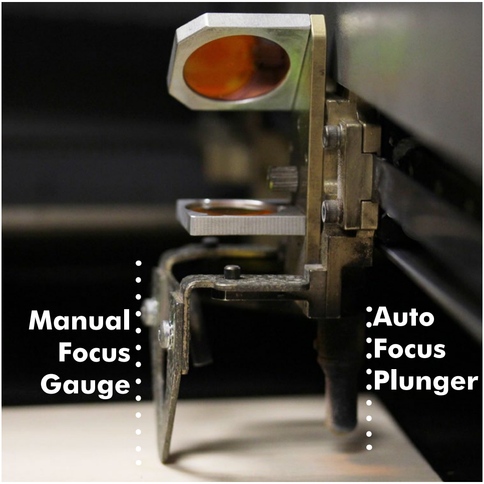
You can change the **number of passes** (i.e. the number of times you run the same job). This distributes the amount of energy necessary to complete a desired job over a longer period of time, which can avoid issues like charring or incomplete cuts.

As a job is running, you can stop it and **focus** on the material again. This ensures that the energy interacting with the material is the most concentrated on the top of the material.

You can **mask** a material with painters tape. This reduces char or melt from spilling onto the material. Note that you may have to change the settings between a mask and un-masked material. Note in the image below that the char is only on the tape and not on the final pieces. Hooray!

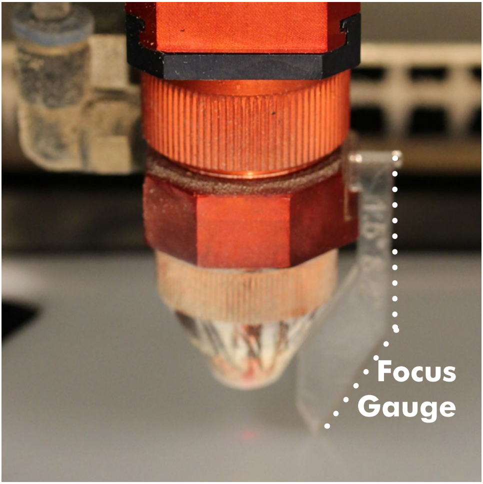


MANUAL FOCUS - EPILOG



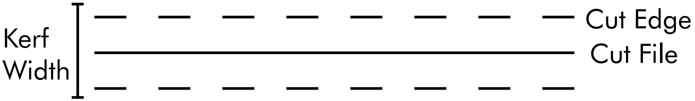
1. Mount the manual focus gauge onto the laser head.
2. First choose the location where you would like to focus. To do this navigate to the 'Service' on the Epilog LCD. Then select 'Move X/Y'. Now you can use the arrow keys to move the laser head. Press Enter to select a location.
3. Now press the 'Focus' button and use the knob to jog the table up and down. Raise the laser bed until the tip of the gauge just touches the surface of your material.

MANUAL FOCUS - TROTEC



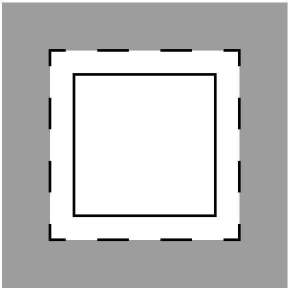
1. Hang the focus gauge from the ledge on the laser head.
2. Raise the material using the up and down arrows until the tip of the focusing tool just touches the surface of the material.

KERF

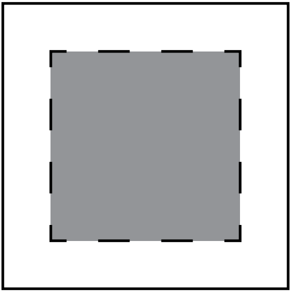


Kerf is the width of the cut made by the laser. It changes the finished size of your cut piece. If you are designing something with very tight tolerances you may want to adjust for the kerf. Kerf width changes with every cut, so it is important to take new measurements each time you are going to adjust.

Effect of Kerf

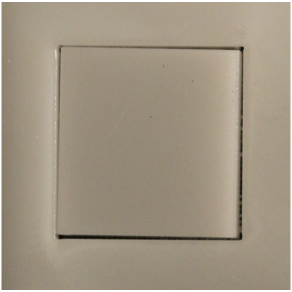


Holes get larger



Outer edges move inward

ADJUST FOR KERF



Cut a test square

Measure the square piece and the hole it left behind in the stock

The kerf width can be measured as the difference between the outer and inner measurements taken. Compensating for kerf is easy. Just add or subtract half the kerf width from the edges of your cutfile.

JIGGING AND FIXTURING

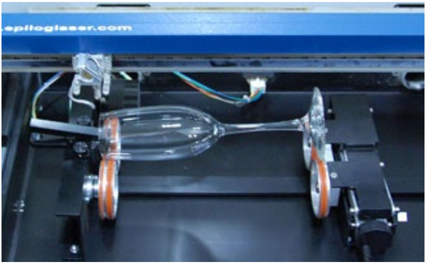
LIGHT MATERIALS

Thin, light materials should be taped down or secured with heavy objects at the edges to ensure that the air vent does not move the piece around while a job is running. Materials that tend to shift around in the bed can also be secured creating a negative mold (e.g. a circular cutout on MDF to hold a circular dog-tag).

WARPED MATERIALS

Warped materials are difficult to machine because the laser cutter cannot dynamically adjust its focus to compensate for thickness changes in material. This might be less of a problem for materials with a greater tolerance for the range of focus, as plastics. However, always try to smooth out warped objects before cutting or reduce curvature by weighing sections down with heavier objects. Either manually focus on the mid-plane between the maximum and minimum heights of the stock or refocus when you get to the warped section.

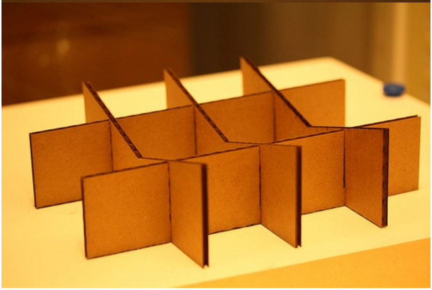
CYLINDRICAL OBJECTS



Cylindrical objects can be fixed and machined via an additional rotary device which is secured into the laser bed.

Credits: Epilog

IRREGULARLY-SHAPED OBJECTS



Custom jigs may need to be created for irregularly shaped objects. Luckily, you have access to a laser cutter, which is great for making a quick, cardboard fixture.

Credits: Mary Morse

MATERIALS

The laser cutter focuses primarily on cutting **planar stock**. Laser cutter can cut a variety of materials at a maximum thickness of about 1/4”.

You cannot cut thick sheet metal, polycarbonate, vinyl, or PVC on the laser cutter as these materials produce toxic gases and can damage the machine.

This section introduces the **common** laser cut materials at Olin and discusses special techniques.

MATERIAL: ACRYLIC

- A transparent thermoplastic polymer.
- There are two main types of acrylic: extruded and cast which differ due to manufacturing technique. Extruded acrylic is often more even in thickness across the sheet than cast.
- Machines via vaporization.

Fig. 1Engraved cast acrylic sign. Fig. 2 Intricate cut on acrylic. Then thermoformed to induce curvature.

Credits: Fig. 1 Epilog; Fig. 2 Danger Awesome

Tips & Tricks: Engraving Acrylic (Extruded vs. Cast)

- Use cast instead of extruded acrylic for rastering to have greater image contrast. Cast acrylic rasters to a frosted, white appearance.

- When engraving large areas of acrylic, fine horizontal lines from the scanning laser beam can make the image look grainy. Shift the piece from the optimum focus level by ~1.6mm so that the size of the beam is increased to achieve a blending effect.
- Flip the image of your raster file to engrave on the bottom of the material in order to view the image through the transparent piece.

Tips & Tricks: Vector Cutting Acrylic

- A glistening melt edge can be achieved on acrylic by vaporizing instead of melting the material. Use a high frequency/power and low speed combination to provide more energy to the cut zone. The shiny edge is a result of re-solidified melt, which reduces the mechanical integrity of the material.
- Unwanted markings (flashback) can occur on the back of your acrylic piece when it is cut directly on the metal bed. The excess laser energy is reflected off of the aluminum, onto the material. Avoid flashback by raising the stock a few inches above the bed before cutting.

ACRYLIC SETTINGS

Epilog 75W 32EX Legend

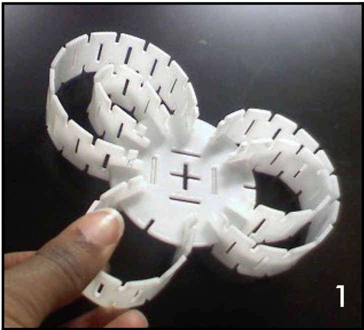
R or V?	Thickness	Speed	Power	DPI/Freq	Comments
R	All	100	30	600	
V	1/8″	25	100	N/A	
V	3/8-1/2″	15	100	N/A	
V	3/8-1/2″	6	100	N/A	

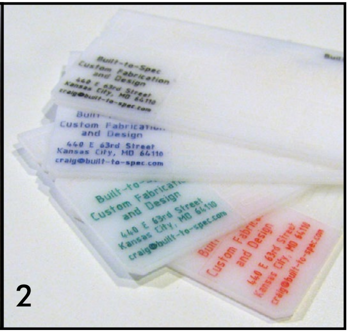
Trotec Speedy 300

R or V?	Thickness	Speed	Power	DPI/Freq	Comments

MATERIAL: DELRIN

- An opaque engineering thermoplastic material
- Ideal for laser cutting high precision, low friction parts
- Laser machined by vaporization of material similar to acrylic due to its low vaporization point.





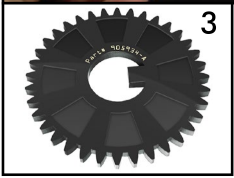


Fig. 1Rougher edges created by manipulating frequency allow friction hold. Fig. 2 Raster image contrast is provided with dry-erase marker blotting. W. 3 Laser-cut delrin can be used for high precision, low friction gears

Credits: Fig. 3 http://www.ulsinc.com/material-profile/delrin#prettyPhoto; Fig. 2 http://www.built-to-spec.com/blog/2012/05/12/adding-colored-etching-to-laser-cut-parts/; Fig. 1 http://makezine.com/2010/01/14/letters-from-the-fab-academy-part-1/

Tips & Tricks: Engraving Delrin

- Engraved delrin is always white. Engraved white delrin provides little image contrast. If more contrast is desired, the rastered area can be blotted with a colorful dry-erase marker. Prototype with this technique before finalizing designs.

Tips & Tricks: Vector Cutting Delrin

- Laser cut edges of Delrin are consistently smooth and have reasonable dimensional stability. Material should be machined at a high frequency/power and low speed combination similar to acrylic.
- It is important to place a material layer below Delrin or to prop it on a stand when vector cutting; otherwise, flash-back (see acrylic) will occur on the underside of the stock.
- Delrin is a slippery material. A rougher surface finish can be induced on your parts by decreasing the frequency of the laser cutter to create “teeth-like” features on cut edges for friction holds.

DELRIN SETTINGS

Epilog 75W 32EX Legend

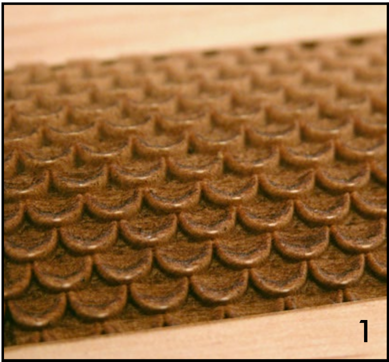
R or V?	Thickness	Speed	Power	DPI/Freq	Comments

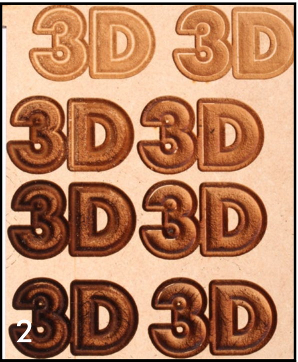
Trotec Speedy 300

R or V?	Thickness	Speed	Power	DPI/Freq	Comments

MATERIAL: MEDIUM DENSITY FIBREBOARD (MDF)

- A wood-composite combined with wax and resin under high temperatures and pressures.
- More homogeneous and therefore easier laser-machined than natural woods.
- Cut by chemical degradation (combustion), leaving a black carbon residue upon laser heating.





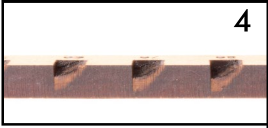


Fig. 1-3 3D mode. Fig. 4 Depth rastering on MDF

Credit Fig. 1: Epilog

Tips & Tricks: Engraving MDF

- Engraved MDF discolors to an orange-brown which gets darker with increasing laser energy density. Mask the material to avoid surface residue from resin and adhesives released from the material upon heating.
- MDF engraves really well with grayscales and in 3D mode if your laser system possesses this setting. Great variation in height and color result.

Tips & Tricks: Vector Cutting MDF

- Thinner sheets of MDF can be cut through with a single pass. However anything above ~3mm (~1/8”) is best machined with multiple passes to improve cut quality.
- Soot which collects on the cut edges can be removed with a dry towel that does not leave fibers on the material, or even better with a chamois cloth or eraser.
- Similar to engraving MDF, it is useful to mask the material before vector cutting to reduce surface build-up of residue.

MDF SETTINGS

Epilog 75W 32EX Legend

R or V?	Thickness	Speed	Power	DPI/Freq	Comments

Trotec Speedy 300

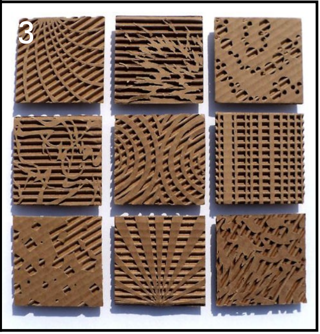
R or V?	Thickness	Speed	Power	DPI/Freq	Comments

MATERIAL: CORRUGATED CARDBOARD

- A wood-based composite material made up of layers of corrugated paperboard.
- Mainly used for packaging and shipping.
- Since cardboard is a widely available material, it is ideal for quick prototyping.
- Since wood fibers have a burning point that is much lower than their melting temperature, cardboard is laser machined by chemical degradation.

Credits: Fig. 1 http://www.instructables.com/id/Spherical-Corrugated cardboard-Lamp/; Fig. 2 Laser Brothers; Fig. 3 http://media-cache-ak0.pinimg.com/736x/c6/13/c4/c613c4d13227a981756ec7e368b4c419.jpg

Fig. 1Direction of cardboard flutes creates aesthetic effect. Fig. 2 Lunch box of cardboard layers. Fig. 3 Selective removal of cardboard layers.



Tips & Tricks: Vector Cutting Cardboard

- Laser cut edges of corrugated cardboard will be have some residual carbon leaving the edges a dark brown or black color. This will be difficult to eliminate entirely, but may be reduced by fine tuning the settings.
- The precision of the laser cutter allows you to select the individual layers which you cut through. You can vector cut a pattern out of the top layer of the corrugated cardboard, then selectively peel away certain parts. Wetting the top surface of the corrugated cardboard with a Q-tip may make peeling it away cleaner and easier. When peeled away dry, the material has a tendency to tear and leave small pieces that make the finished product look messy.

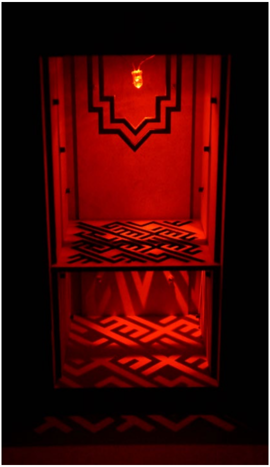
CARDBOARD SETTINGS

Epilog 75W 32EX Legend

R or V?	Thickness	Speed	Power	DPI/Freq	Comments

Trotec Speedy 300

R or V?	Thickness	Speed	Power	DPI/Freq	Comments



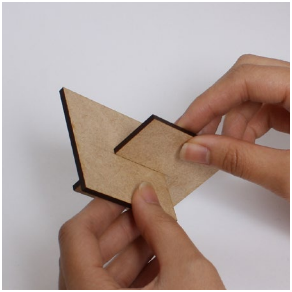
JOINTS

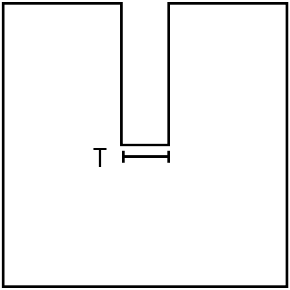
Through a combination of woodworking and laser cutting specific joints, you can create beautiful and mechanically sturdy **structures and mechanisms**, like Annie and Ingrid's lantern.

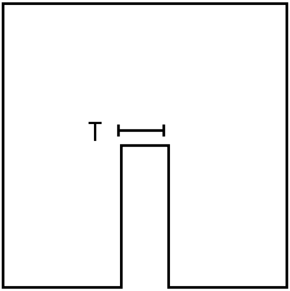
This section showcases three **beginner joints**: the slot, finger, and mortise and tenon joints. Get inspired by joints by exploring what the internet has to offer and examining woodworking or plastic joinery methods!

SLOT JOINTS

The slot joint is a very simple joint to design and construct. Finished pieces are assembled by sliding into slots at right angles to one another.



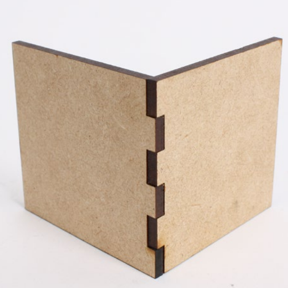


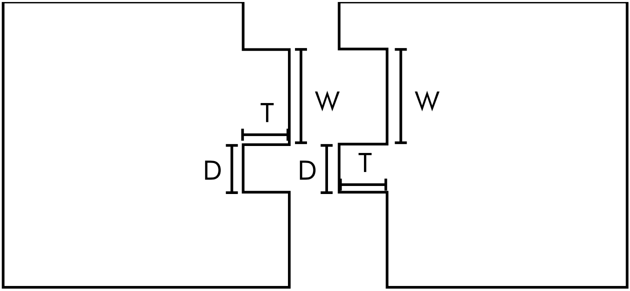


The only crucial dimension is the width of the slot, T, which corresponds to the thickness of the material being used.

FINGER JOINTS

Finger joints are a simple way to join two perpendicular pieces of material at an edge. The joint can be secured by using

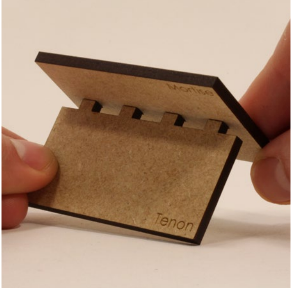


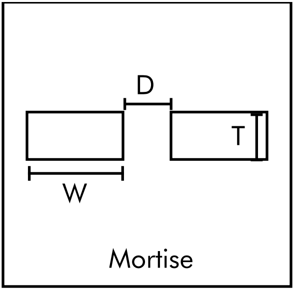


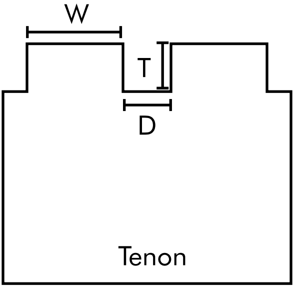
W - Width of finger
D - Distance between fingers
T - Thickness of material

MORTISE & TENON

The mortise & tenon allows you to attach two pieces of material at a right angle to form T shaped joint. The joint is often glued or press fit to create a strong, permanent connection.







W - width of mortise
D - Distance between mortises
T - Thickness of material

ADDITIONAL RESOURCES

- Epilog Legend 32x Manual: *http://www.epilogfiles.com/extt_manual.pdf*

- Trotec Speedy 300
  - Software manual: *http://www.troteclaser.com/en-US/* Support/Documents/JobControl-Manual-EN.pdf
  - Laser System manual: *http://www.troteclaser.com/en-US/Support/Documents/Speedy-300-Manual-EN.pdf*

- *CO_2 Laser Cutting* by John Powell

- *LIA Guide to Laser Cutting* by the Laser Institute of America

- For inspiration:
  - TLC: http://thelasercutter.blogspot.com/
  - Pinterest, MakeZine & Instructables
  - Laser Brothers Facebook Page
  - Snijlab: https://www.snijlab.nl/en/p/29/examples
  - University of Buenos Aires, Morphology and Digital Fabrication Lab: http://workshopmyt.blogspot.com/
  - University of Minnesota, College of Art: http://blog.lib.umn.edu/artdept/lasercutter/

BRAINSTORMING & FEEDBACK

MAINTENANCE

Maintenance is possibly one of the most significant aspects to laser cutting. A poorly kept machine and work area reduce cut/engraving quality and increase the likelihood of a fire hazard.

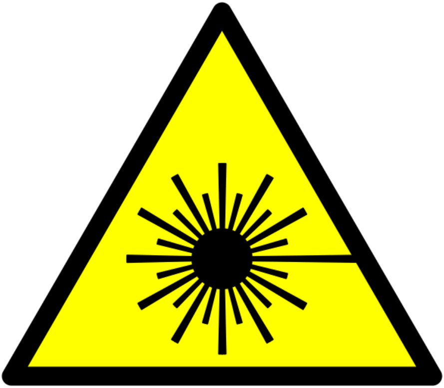
Clean-Up Checklist

All **WIPE-DOWN** procedures should be done with a wet paper towel, Windex, or isopropyl alcohol.

1. **WIPE DOWN** the periphery of the laser bed (ruler area).
2. **WIPE DOWN** the auto-focus plunger.
3. The external optics system can incur a build-up of debris from excessive flare-ups. This can reduce the quality of the cut produced. ONLY clean the mirror and focus lens if you have been trained to do so. If not, inform someone in the shop of the debris/residue.
4. **REMOVE** any small, residual pieces of stock from the cutting bed left from the job.
5. **EMPTY** the crumb tray.
6. **REMOVE** clutter around the machine to keep the area clear of combustible materials.

Wait! Before you cut, did you?

- Test your settings?
- Measure the kerf?
- Fix material securely to the bed?
- Focus?
- Turn on air filters/ ventilation?



Got a question or feedback?

Email the NINJAs at lasers@lists.olin.edu

Laser Cut Like a Boss

Vol. I Issue 1 ©2014

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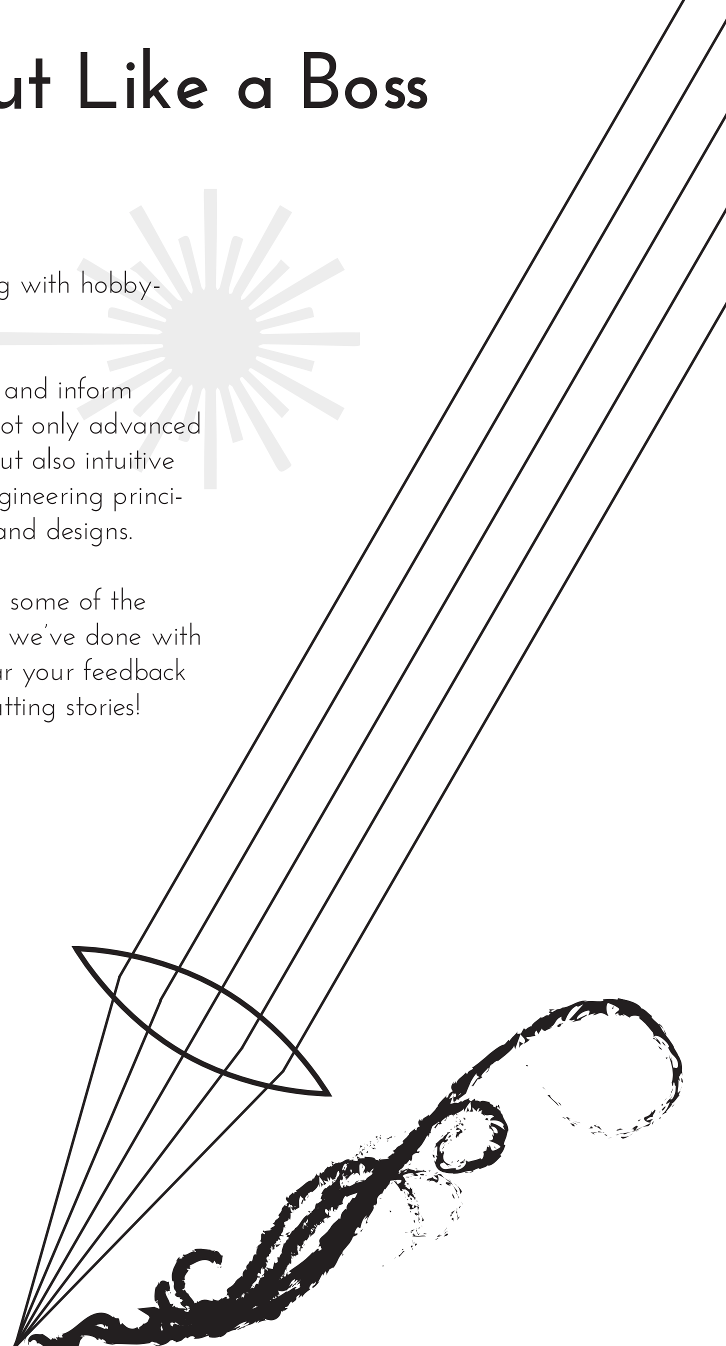
Laser Cut Like a Boss

Vol. I Issue 1 01.11.14

A guide to prototyping with hobbyist-grade laser cutters.

The mission: to inspire and inform others by presenting not only advanced fabrication methods, but also intuitive explanations of the engineering principals behind methods and designs.

A way for us to share some of the work and explorations we've done with you! We'd love to hear your feedback and your own laser cutting stories!



The *Like A Boss* philosophy is built around the central belief in the mastery of your craft, whatever you choose it to be. From blacksmithing to cooking, you are intentional with your learning and acquisition of skills— then innovative and thoughtful in your exploratory work. You may not know how to accomplish all facets of a task from the onset, but you have the confidence and collection of skills to attack the problem and execute a solution fitting solution.

Fundamentals

What is the difference between vector cutting and raster engraving?

Vector cutting is an operation used to pierce or score a material with the laser cutter. When it is compared to operations on traditional CNC tools as the manual mill, it is akin to profiling.

Raster engraving is an operation used to bring the thickness of the material down in depth. It is akin to facing on a vertical knee mill.

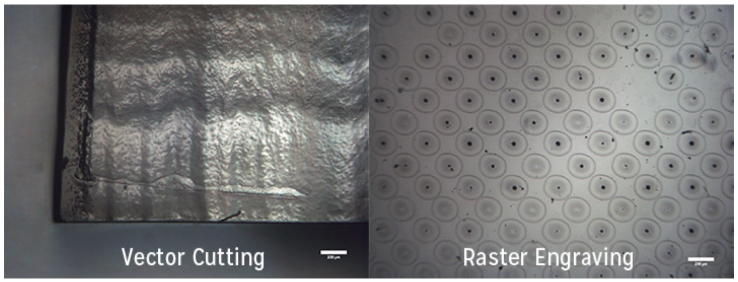


Fig. 1 Juxtaposition of vector cutting and raster engraving on cast acrylic. Jobs were done on a 60W Epilog Helix. Vector settings: S/P/F 20/100/5000. Raster settings: S/P/DPI 100/30/600. Images were taken with an optical microscope at 5x magnification.

Recommended Resources

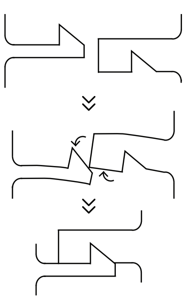
LIA Guide to Laser Cutting by the Laser Institute of America

CO_2 Laser Cutting by John Powell

The contrast in these two operations can be seen in the printer-like dot pattern generated by rastering and the vertical ripples due to the pulsing frequency of the laser while vector cutting.

Snap-fit Joints & Compliance

What is a snap-fit joint?



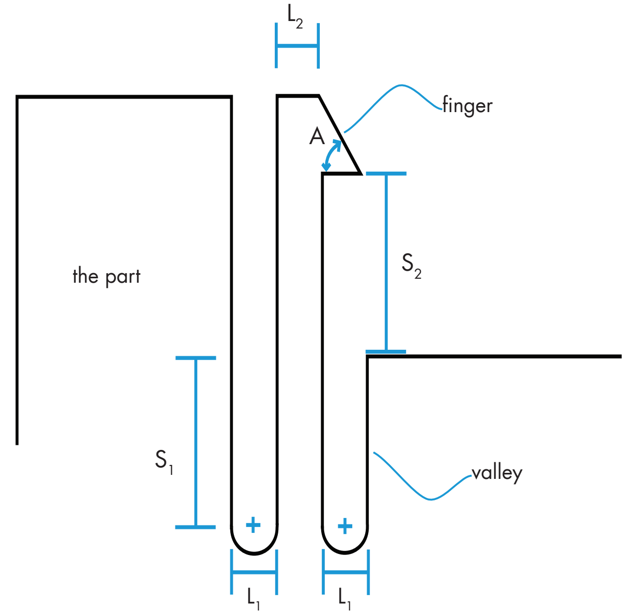
A snap fit joint is a compliant mechanism that works by briefly deflecting the protruding part of a piece so that it catches in a depression in another piece.

Compliance refers to a structure's ability to briefly bend or twist and then return to its original orientation. It relies on the material's elastic properties.

How do you effectively design a snap-fit joint?

Recommended Resources

Handbook of Compliant Mechanisms by Larry Howell, Spencer Magleby, & Brian Olsen.

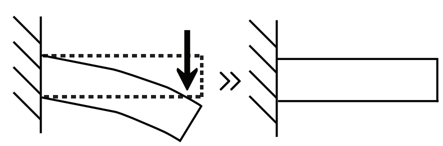


You want your snap fit joint to be strong enough to effectively hold together your structure and withstand loads. However, you also need your snap fit joint to be flexible enough to deflect the appropriate amount without snapping off the finger.

Given this, we suggest the following rules of thumb when designing your snap-fit joints:

1) Having two wide (L_1), deep (S_1) valleys beside the finger reduces the chances of material breaking and allows for compliance in both directions
2) A very thin finger (L_2) will be more flexible but less snug
3) S_2 should equal the thickness of the interfacing material (see the example pieces)
4) Ensure that the angle (A) is large, otherwise the finger will over-bend and snap as it is engaged

How do snap-fit joints work?



Most snap-fit joints are simple cantilever snaps. A cantilever is a beam that is anchored on one end. Cantilevers easily support forces applied to its length by bending i.e. redirecting the load to the supported end.