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A rapid tooling method using ultrasonic welding and machining

Nicholas James Hennessy
Iowa State University

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by

Nicholas J. Hennessy

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Matthew Frank, Major Professor
Frank Peters
Scott Chumbley

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ABSTRACT

The overarching objective of this work is to develop a rapid manufacturing process that produces plastic pattern tooling. The process is considered a hybrid approach to tooling because it will involve bonding sheets of plastic through ultrasonic welding and machining the desired features into each layer. In order to realize this new system, there are several sub objectives that are satisfied in this work; 1) the development and refinement of the bonding process, 2) process planning methods for inter and intra slab processing and 3) machine integration and testing. In this work a method is presented for determining energy director location. A pattern tool was created using this method for energy director location to verify the entirety with process planning, ultrasonic welding, and machining integrated together.

CHAPTER 1: INTRODUCTION

1.1 Overview of Tooling

The landscape of modern manufacturing has changed considerably over the last few decades. Whereas machines have become more advanced and automated, the core set of processes used to make components remains generally the same. These processes include casting, machining, injection molding, stamping, forging, powder metallurgy, etc. In the overwhelming majority of processes, some form of tooling is required. These tools could take the form of cutting tools, dies, fixtures, gauges, jigs, molds, and patterns. These types of tooling are generally created by skilled craftsman or machinist. Although Additive Manufacturing (AM) is providing an alternative that is highly automated, it is still critical to increase automation in conventional processes. This thesis will address a new, automated way to make tooling for formative processes, specifically pattern tooling for the sand casting industry.

1.2 Introduction to Pattern Tooling

One common manufacturing process that uses tooling is the sand casting process for metals. In sand casting, a mold is made out of sand by impressing the form from tooling called a pattern. The steps of the mold making are illustrated in Figure 1.1. There are five distinct steps in the sand casting process: patternmaking, coremaking, molding, melting and pouring, and

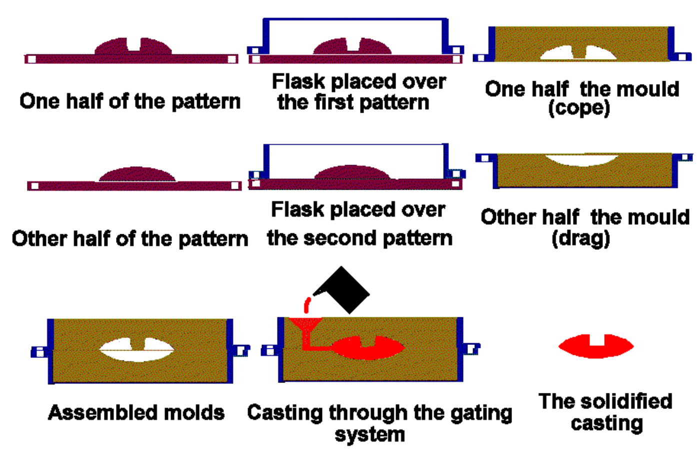

Figure 1.1: Sand casting process [1]

cleaning. The tooling portion of the sand casting process is in the patternmaking. Small patterns can be made in one piece, whereas larger patterns are often made in multiple pieces and glued together. Patterns can be made out of wood, plastic, metal, or other materials. This type of tooling requires draft and no undercut features so that the sand can be pulled off the pattern. Current practice in industry relies on a highly skilled craftsman to make this tooling. As a response to this, there have been numerous attempts to deliver solutions for casting using Additive Manufacturing.

The driver for making components using AM is largely due to the time and investment required for conventional tooling. As the world marketplace is changing faster than ever, companies are looking for solutions to reduce the lead times of their products. Also, as the need for mass customization increases, tooling needs to be made much faster and more cost effectively.

In the term “rapid prototyping”, the term rapid can be defined as going from a computer aided design (CAD) model to part manufacturing in a short period of time, with little to no human interaction. Using this definition, many systems have been developed to try and achieve the goal of rapid tooling; where purely additive systems have dominated the efforts. These additive systems include Laminated Object Manufacturing (LOM), 3-Dimensional Printing (3DP), Fused Deposition Modeling (FDM), and Stereolithography (SLA). The advantages of systems like these include the ability to create parts with complex geometries, relatively small lead time for parts, little skill is required to run the machines, and almost no material is wasted in the process. On the other hand, slow build rates, limited component sizes, poor interlaminate strength and the need to post process the components are some of the common issues of purely additive systems [2].

A new approach to rapid tooling has been under development at the Iowa State University Rapid Manufacturing and Prototyping Laboratory, called Rapid Pattern Manufacturing or RPM [3]. This method of rapid tooling uses a hybrid process in the automated manufacturing of pattern tooling for castings. A hybrid rapid tooling process is one that combines additive manufacturing along with a subtractive process. Hybrid systems tend to be considerably faster and more accurate than conventional additive systems [4]. The Rapid Pattern Maker consists of a work platform table, a 3-axis CNC router, a material handling system, a glue application system, and a material feed stack (Figure 1.2). The RPM approach utilizes a layer-by-layer build style, similar to AM processes. A layer (wood slab) is picked up from the material feed stack by the material handling system, sprayed with glue and then added to the stack on the work platform table. After each layer is added, a machine tool mills the true 3D features for each layer [5]. A sample of a part made can be seen in Figure 1.3.

Figure 1.2: Rapid Pattern Maker at Iowa State University

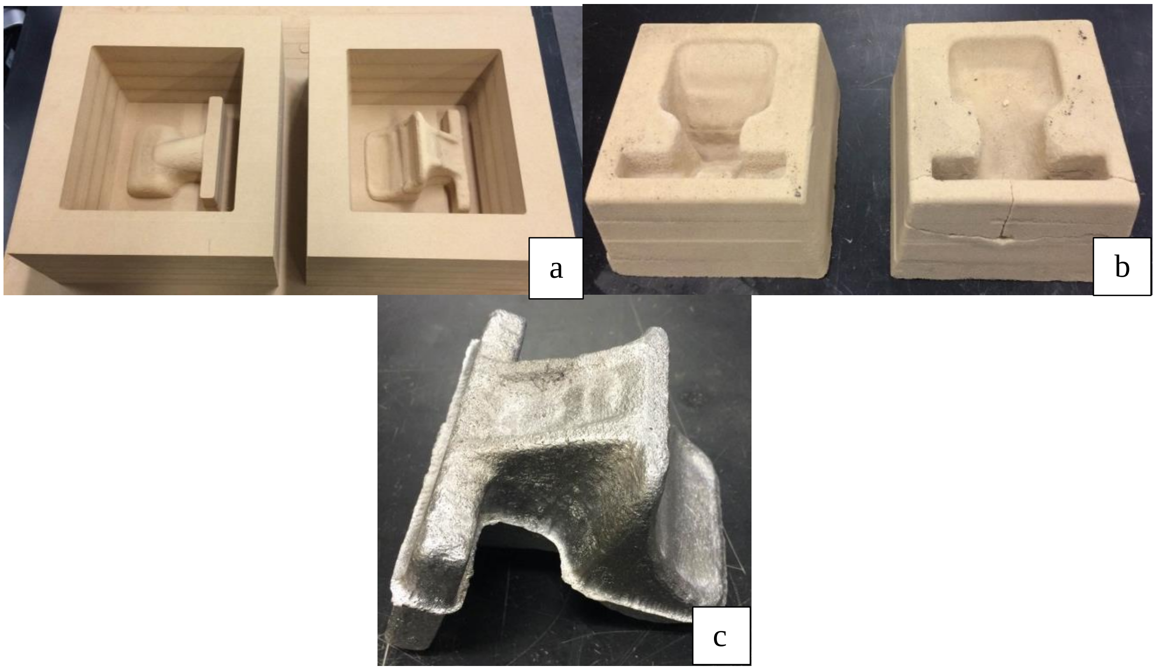

Figure 1.3: Samples from the RPM process, (a) wood patterns, (b) sand molds, and (c) resulting metal part

The current rapid pattern maker is optimized for the use of wood, but this causes obvious limitations. In the sand casting industry with medium or large production runs, the foundry may want to switch from wood to plastic or even metal patterns. If a method for rapid pattern manufacturing of plastic tooling could be realized, the concept of RPM could now serve higher speed production, with longer lasting tools. In this way, we would not only have a short run or prototyping solution, but perhaps a new approach to longer term tooling. Therefore, this paper will focus on a new approach to the bonding of plastics slabs using ultrasonic welding.

1.3 Research Objectives

The overarching objective of this work is to develop a rapid manufacturing process that produces plastic tooling. The process is considered a hybrid approach to tooling because it will involve bonding sheets of plastic through ultrasonic welding and machining the desired features into each layer. In order to realize this new system, there are several sub objectives that need to be satisfied; 1) the development and refinement of the bonding process, 2) process planning methods for inter and intra slab processing and 3) machine integration and testing

1.4 Thesis Organization

The following chapters are presented as follows. Chapter 2 will provide a more extensive literature review of tooling research. Chapter 3 will be in the form of a journal paper presenting the overall technical solution method, while chapter 4 will present a general conclusion and future work.

CHAPTER 2: LITERATURE REVIEW

Since the late 1980s, many derivatives of rapid prototyping and machining technologies have become available for use within the casting industry for prototyping pattern tooling. This chapter will present an overview of research in these areas.

5-axis Machining

In conventional methods of pattern making, a skilled technician uses a 3-axis machine tool; however, they will often face issues with limited tool length or "reach". One of the ways around this issue is the use of a 5-axis machine tool. 5-axis machining can allow the machine to get into areas inaccessible to a conventional 3-axis mill as well as reduce the number of setups. When setups are reduced, the dimensional errors tend to decrease as well. When using multiple axes, the user can possibly avoid collision conditions when reaching to machine the deep pattern cavities. There are challenges with using 5-axis machining, for one, the systems are considerably more expensive than their 3-axis counterparts. Moreover, as axes are added, the complexity of the programing increases and this requires an exceptionally well trained technician. As could be expected, the number of technicians that can effectively program 5-axis machines is limited [6]. Consequently, there has been work done in the automated path planning for finishing and creating tooling using 5-axis machining [7-8].

Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM) was one of the first AM systems used in the casting industry for short run and prototyping patterns. LOM is a process which bonds sheets of paper or plastic foils, where the paper itself acts as the layer. The 2 ½ D shape of the layer is cut by a laser operating on the X-Y plane. The laser also hatches the support material in the form of squares that are broken or scraped away after building. LOM parts surface finish depend on the thickness of material used [9]. LOM was able to be used to make large patterns that were reasonably durable and could handle compressive loads very well. On the other hand, LOM parts do not hold up well when tensile loads are place on it due to interlaminate strength issues. Also, dimensional error would occur due to expansion of the part in the presence of moisture [10]. For these and many other reasons, the traditional paper based LOM is generally not found in use today.

3D Printing (3DP)

3D printing involves using inkjet printing technology to place droplets of binder on to layers of powder or other materials. The building platform the material is resting on moves down and another layer of powder is spread over the building area. This process iterates until a part is complete, where the loose (not printed) powder serves as the support structures for the part [11]. Rooks (2002) conducted a case study which yielded that 3D printing provides great accuracy and repeatability compared to other AM technologies but is plagued by slow build rates [12].

3D printing has been used in a variety of capacities in the casting industry. One of the most popular is directly printing sand molds. ExOne makes multiple high-resolution sand printing machines. These printed sand molds have a high degree of accuracy and good surface finish. The issue with this particular technology is only one part can be made using the mold printed, as well as the large investment cost of the machine [13]. In another less conventional way, this technology can be used to make to make small plastic patterns for sand casting [2].

Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) builds parts by extruding semi-molten plastic through a nozzle onto a build platform. After all the features are created in the layer, the next layer is created by laying more semi-molten plastic onto the previous layer. Multiple iterations of this process continue to form a part [2]. This layering of semi molten material causes interlaminate strength issues as well as limited surface finish [14]. These properties limit the design of molds to be made by the process [15]. FDM technology is a fairly inexpensive way to make patterns, but the most common limitation is the size of the build envelope in FDM machines [16].

Solvent Weld Freeform Fabrication (SWIFT)

SWIFT is a method developed by Cormier and Taylor (2001) for creating tooling by bonding slabs of plastic together using solvent welding and machining the outer contour of the plastic slab. The solvent welding process uses a masking solution that goes on the surfaces which do not need to be bonded. After the masking solution is applied, an acetone solution is applied to the slab. The slab of plastic is then placed onto the previous layer in the build envelope. The acetone dissolves surfaces on both layers creating a crosslinking of polymers between the two layers which blends the two surfaces together [17].

Shape Deposition Manufacturing (SDM)

SDM is a hybrid process combining material deposition and material removal. The process starts with dividing layers within the model into three categories: no undercuts, only undercuts, and layers with both. Material is deposited near net shape in the build envelope. The layer is then machined to the shape desired based on the layer type. The application for casting would be to deposit material followed by machining the layer contour of the part into the material laid up. This method can use multiple materials as long as it can be deposited fairly easily [18-19].

CHAPTER 3: A RAPID TOOLING METHOD USING ULTRASONIC WELDING AND MACHINING

Nicholas J. Hennessy, Matthew C. Frank
Department of Industrial and Manufacturing Systems Engineering
Iowa State University, Ames, IA 50010, USA

Abstract

This paper presents a hybrid approach to rapid pattern tooling using ultrasonic welding and machining. The method allows for plastic pattern tooling to be created automatically using a layer-based approach. The methods in this paper will enable further automation of a process planning system for the location and orientation of the energy directors required for welding each layer. The method was tested and verified by creating a test pattern and a sand mold was generated using the pattern.

3.1 Introduction

The landscape of modern manufacturing has changed considerably over the last few decades. As the world and marketplace are changing faster than ever, manufacturing companies are looking for solutions to reduce the lead times and customize products. The cost driver for these products is largely due to the long term nature of the tooling. Long term meaning the time and large investment needed to create the tooling. The long term nature of the tooling creation process has to be changed. The tooling needs to be faster, cheaper, and easier to make so a long term investment isn't required.

A new approach to rapid tooling has been under development at the Iowa State University Rapid Manufacturing and Prototyping Laboratory, called Rapid Pattern Manufacturing [1]. This method of rapid tooling uses a hybrid process in the automated manufacturing of pattern. The Rapid Pattern Maker at Iowa State University consists of a work platform table, a 3-axis CNC router, a material handling system, a glue application system, and a material feed stack all integrated together into one machine to build wood pattern tooling. This approach utilizes a layer-by-layer build style. A layer is picked up from the material feed stack by the material handling system, sprayed with glue and then added to the stack on the work platform table. After each layer is added, a machine tool mills the features with each layer [2].

The current rapid pattern maker is optimized for the use of wood, but has limitations. In the sand casting industry, there are needs for other materials besides wood. For example, in medium or large production runs, the sand casting industry moves from wood to plastic or metal patterns. If a method for rapid pattern manufacturing of plastic tooling could be realized, the concept of Rapid Pattern Manufacturing could now serve higher speed production, and, equally important longer lasting tools. In this way, we would not only have a short run or prototyping solution, but perhaps a new approach to longer term tooling. Therefore, this paper will focus on a new approach to bonding the slabs, using ultrasonic welding.

3.2 Related Works

Since the late 1980s, many derivatives of rapid prototyping and machining technologies have become available for use within the casting industry for prototyping pattern tooling.

In conventional methods of pattern making, a skilled machinist will often face issues with limited tool length or "reach". One of the ways around this issue is the use of a 5-axis machine tool. There are challenges with using 5-axis machining, for one, the systems are considerably more expensive than their 3-axis counterparts. Also, as axes are added, the number of technicians that can effectively program the added axes becomes limited [3]. Consequently, there has been work done for the automated path planning for finishing and creating tooling [4-5].

Laminated Object Manufacturing (LOM) was one of the first AM systems used in the casting industry for short run and prototyping patterns. LOM was able to be used to make large patterns that were reasonably durable and could handle compressive loads very well. On the other hand, LOM parts do not hold up well when tensile loads are place on it due to interlaminate strength issues. Also, dimensional error would occur due to expansion of the part in the presence of moisture [6-7]. For these and many other reasons, the traditional paper based LOM is generally not found in use today.

3D printing has been used in a variety of capacities in the casting industry. One of the most popular is directly printing sand molds. ExOne makes multiple high-resolution sand printing machines. These printed sand molds have a high degree of accuracy and good surface finish. The issue with this particular technology is one part can be made using the mold printed, as well as the large investment cost of the machine [8]. In another less conventional way, this technology can be used to make to make small patterns for sand casting [9]. Rooks (2002) conducted a case study which yielded that 3D printing provides great accuracy and repeatability compared to other AM technologies but is plagued by slow build rates [10].

Fused Deposition Modeling (FDM) has been used in the casting industry to make small pattern tooling, but the layering of semi molten material causes interlaminate strength issues as well as limited surface finish [11]. These properties limit the design of molds to be made by the process [12]. FDM technology is a fairly inexpensive way to make patterns, but the most common limitation is the size of the build envelope in FDM machines [13].

SWIFT is a *hybrid* method developed by Cormier and Taylor (2001) for creating tooling by bonding slabs of plastic together using solvent welding and subsequently machining the outer contour of each the plastic slabs [14]. SDM is a *hybrid* process combining material deposition and material removal. Material is deposited near net shape in the form of a layer. The layer is then machined to the shape desired based on the layer type. This method can use multiple materials as long as it can be deposited fairly easy [15-16].

All of these methods for rapid tooling have their place. However, movement to a more durable, long term plastic tooling solution is warranted. Ultrasonic welding and machining for pattern tooling is a solution for that movement.

3.3 Process Overview

The proposed rapid tooling system utilizes ultrasonic welding and machining together to create patterns for the sand casting industry. This system would be considered a *hybrid* approach to tooling since it combines additive and subtractive methods. The process involves bonding slabs of plastic using ultrasonic welding and then subsequently machining the features into each layer (Figure 3.1). This method creates pattern tooling that would appear on the surface to be homogeneous but on the interior would truly be a layer-based approach.

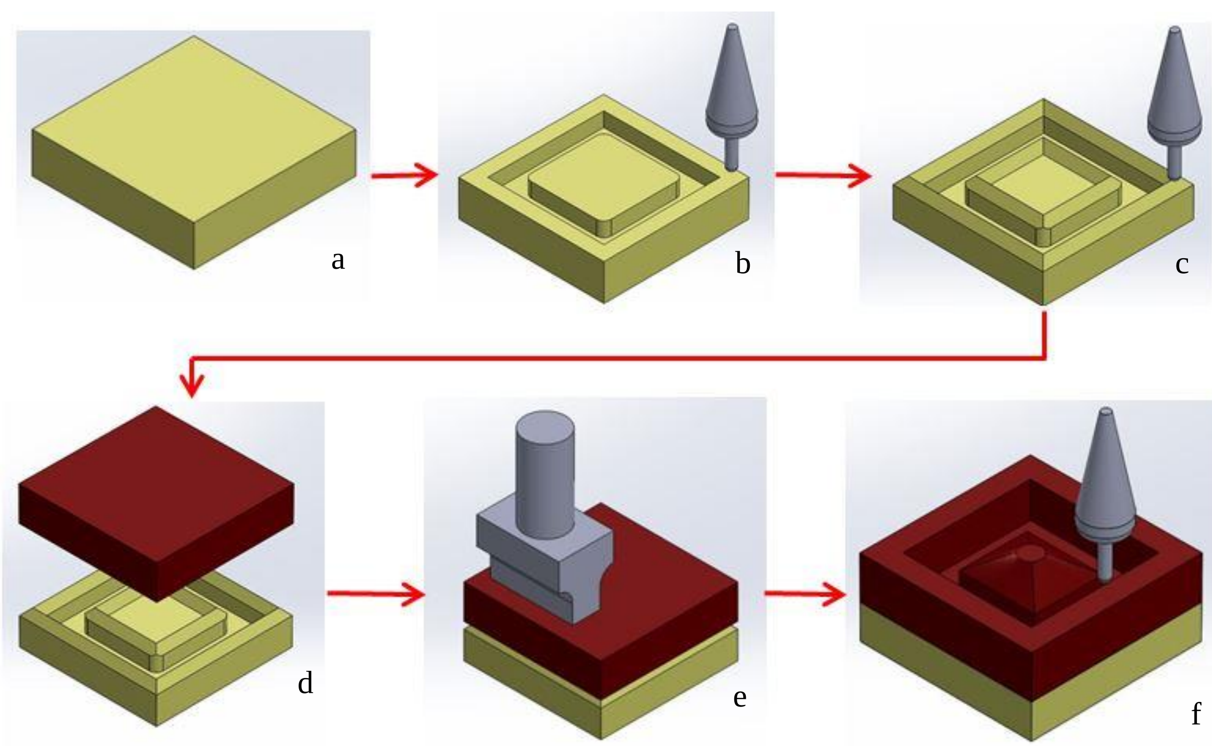

Figure 3.1: Ultrasonic tooling process, (a) slab is deposited, (b) contours of the layer are machined, (c) energy directors are machined, (d) next slab deposited, (e) layers are ultrasonically welded together, (f) next layer contours are machined

For each layer deposited, the first operation in the process is machining the 3D tooling geometry of the layer (Figure 3.1b). This will be accomplished using CNC machining with flat- and ball-end mills used. The second operation is to machine "energy directors" into the top most surface of each layer (Figure 3.1c), which will be accomplished by using a chamfer-end mill. An example of an energy director can be seen in Figure 3.2. The energy directors are where all the

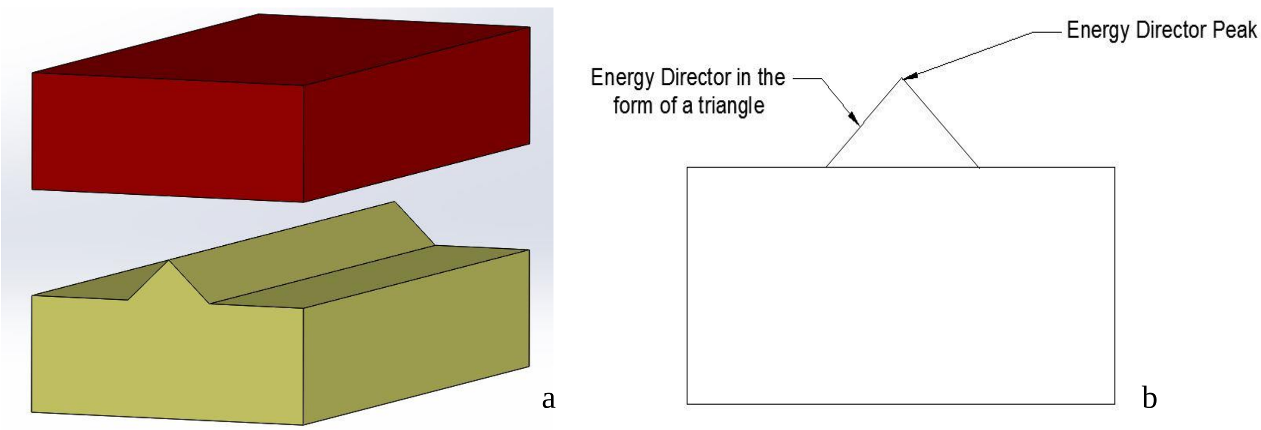

Figure 3.2: Energy director (a) the 3d director (b) the 2d cross section of the director

energy from the ultrasonic welder gets absorbed when welding the layers together. The energy is in the form of friction between layer n and layer n+1. The friction generates heat and starts the weld pool at the top of the triangles and transfers to the base of the energy directors The ultrasonic welder delivers this energy to weld layer n and n+1 (Figure 3.3). When the welding is complete it holds the pressure for a set amount of time while crosslinking occurs. The layers need to be held in place using physical guides while the welder makes its initial weld. The resonation of the ultrasonic welder tends to cause movement of the material unless initially secured. After the initial weld is made, it is tacked in place and the guides can be removed. After ultrasonic welding is complete on a layer, the machining of the next layer takes place

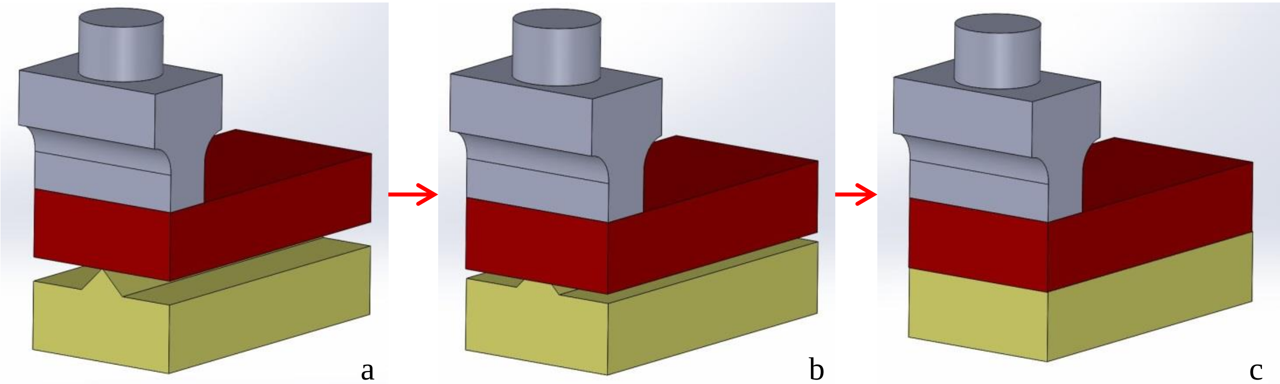

Figure 3.3: Ultrasonic welding progression (a) horn starts to oscillate; (b) the weld pool is moving through the energy director, (c) the welding is complete with a bond of the two layers

(Figure 3.1f). This entire process continues to iterate layer after layer until the process is complete.

While the notion of layer based manufacturing is not new, this paper introduces the ultrasonic bonding of the layers and combines it with machining to create pattern tooling rather than an assembly. Hence, the focus of this work is in enabling the automated and functional welding of pattern tooling.

There are many parameters to consider and control when trying to make ultrasonic welding and machining a viable option for pattern tooling. These same parameters also make automating the entire process difficult. Some of these parameters include strength of materials, welder strength, energy director height and density, maximum and minimum slab thickness, and energy director location and orientation. To have a completely automated system, all of these parameters must be addressed.

One of the most advantageous properties of ultrasonic welding is the variety of materials possible; including interlaminating different materials within the same part. After selecting the stock material with the desired properties, the evaluation for the suitability of ultrasonically welding slabs together begins. Each type of polymer will have multiple different factors impacting the weldability and performance of the weld. Almost every aspect of this process is driven by the amount of energy emitted from the ultrasonic welder. The amount of energy emitted is determined by the type of ultrasonic welder and the number of ultrasonic welding horns used in the process. Within the ultrasonic welder, there are three components, 1) the generator, 2) the converter, and 3) the booster, along with several other parameters such as trigger pressure, weld time, and hold time [17].

The strength of the ultrasonic welder determines the maximum size of energy directors possible. In the case of using this technology for pattern tooling, the larger the energy director the better. Typically more energy directors and larger energy directors give the tooling more strength and durability. This must be balanced with the applicability of strength. The strength needs to be only as much as pattern tooling requires. With more energy directors, time will be lost in processing in terms of machining and welding.

In general, the largest possible layer thickness should be chosen to reduce processing time. However, the slab can be, at maximum, the length of the shortest cutting tool available. This is important because smaller diameter tools allow for greater accessibility and feature resolution, but small diameter tools will generally only have short lengths available. Another factor to consider is, as the energy moves through the top slab of material, a dampening occurs which will have an effect on the maximum layer thickness also.

In order to realize a completely automated method for ultrasonically welding and machining pattern tooling, these factors will all need to be integrated together to make sure the correct welding parameters, slab thickness, energy director density, height, location, and orientation are used for the materials. This paper will address specifically the challenge of the assignment of location for energy directors using an automated algorithm.

3.4 Process Planning
3.4.1 Variable Definitions

The goal with any rapid system is to reduce the process planning time, the skill needed to process plan, and ideally for it to be completely automated. For this work, a set of variables and equations are defined for the energy director layout and planning problem. In Figures 3.4 and 3.5, the different variables that dictate the process planning can be seen.

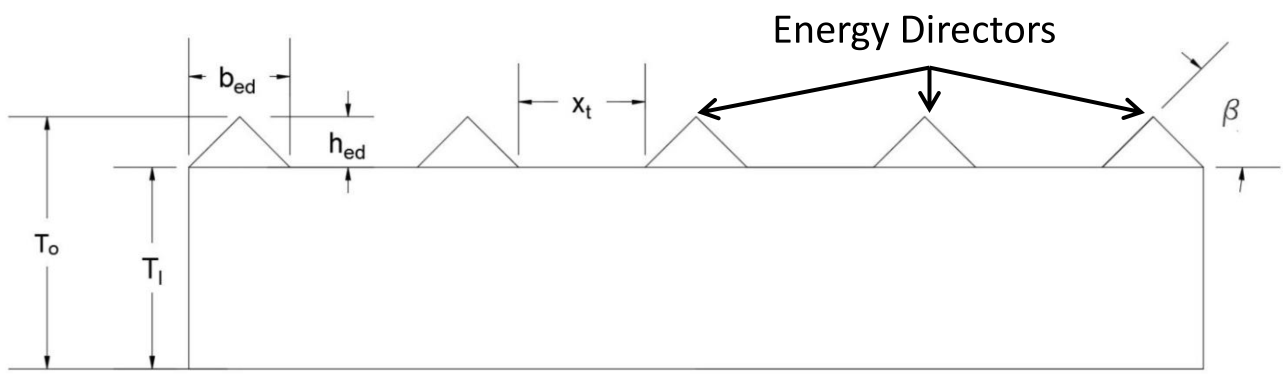

Figure 3.4: System of variables for energy director assignment

Where:

T_o = Overall thickness of the layer

T_l = Thickness of layer

$h_{ed} = T_o - T_l$ = energy director height

β = Angle of energy director

x_t = Distance between base of energy directors

b_{ed} = Base of energy director

A slab thickness for the stock material should be selected based on the chosen overall thickness of the layer (T_o). The energy director height will be selected to maximize the strength of the weld. The options for the height of the energy directors are directly dependent on the strength of the welder and number of welding horns. The angle of the energy director is dictated by the type of polymer; amorphous polymers typically have an angle of 45° while crystalline polymers use a 60° angle [18]. The base width of the energy director will then be a function of the height of the energy director and the angle of the energy directors. The distance between the energy director bases (x_t) could range from the cutter diameter of the smallest chamfer end mill being used to some maximum allowable distance. This value influences the density of the directors in turn, the strength of the part.

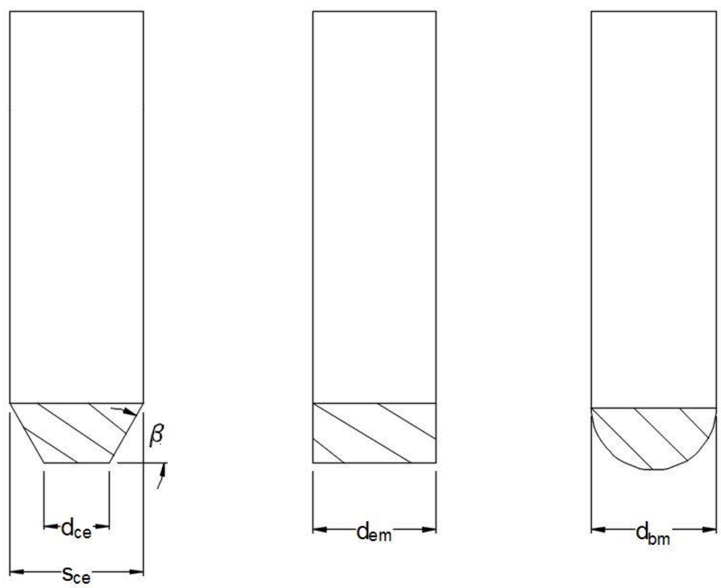

Figure 3.5: Candidate tool geometries used in the process

d_{ce} = cutter diameter of the chamfer-end mill

d_{em} = diameter of the flat-end mill

d_{bm} = diameter ball-end mill

β = degree of chamfer

s_{ce} = shank diameter of the chamfer end mill

The methods for energy director planning are directly based on the tools selected for machining. The flat-end mill will be used for roughing operations, and the ball-end mill will be used for the finishing operations on the contour geometry of the layer. Energy director creation is accomplished using a chamfer tool. The designed energy director angle and height will dicate the chamfer tool degree β, and the depth of the chamfer on the tool. The directors will be formed by the s_{ce} tool following the contour lines created by the offsets, which will be discussed in the proceeding section, with a left and right cutter compensation within a CAM package (Figure 3.6).

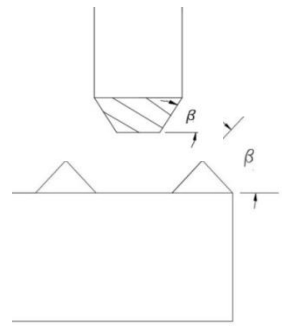

Figure 3.6: Chamfer end mill creates the energy directors

3.4.2 Offsets

The process planning method is based on offsets from the outer and inner chains of the slice geometry. For the exterior chains of the slice geometry, the energy director peaks will be defined by an offset inward. For an interior chain, the energy director will be an outward offset. The offset determines the peak of the energy director (Figure 3.7).

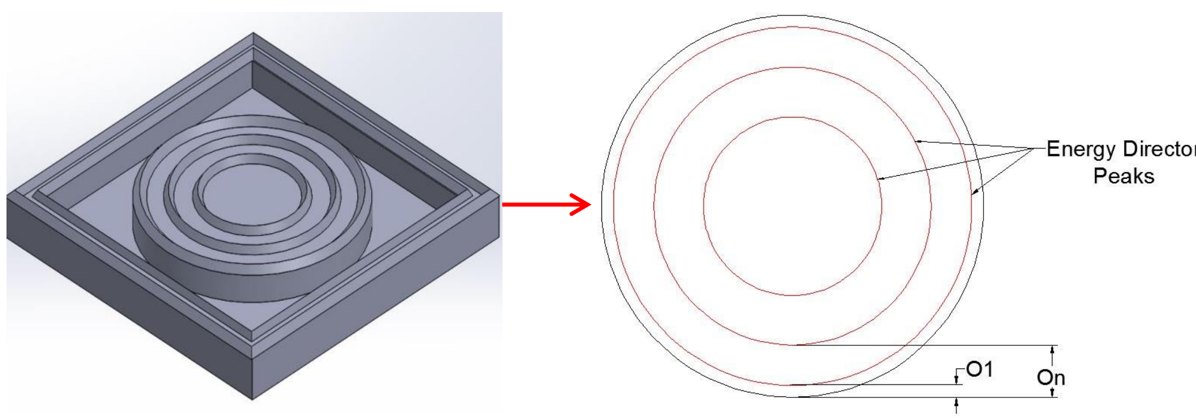

Figure 3.7: Energy director peak locations a) in CAD model b) 2d cross section view (wall left out for clarity)

$$O_1 = .5(h_{ed}/\tan(\beta))$$

$$O_n = (2n-1)*(h_{ed}/\tan(\beta)) + (n-1)d_{ce}$$

The first offset will be set to approximately half the offset of the ensuing offsets; effectively moving the director peak closer to the layer edge. This smaller offset will provide more weld material at the outer edge which will provide a solid fusion of the two layers at the final pattern tool surface. As such, the energy director on the edge will have a truncated triangular cross section (Figure 3.8). During processing when the weld bead moves through the energy director, it will force the extra material to the outside of the joint.

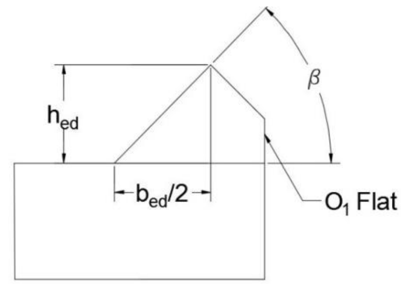

Figure 3.8: Outer edge energy director with truncated geometry (flat) due to offset O_1

For interior chains of the slice geometry, there will only be one offset using the O_1 function to offset outward. Multiple offsets of the outer chains will be generated to define peaks for rows of energy directors. These multiple rows of directors will give the part strength (Figure 3.7). If an offset from the outer chain intersects with an offset from the inner chain, then the segment in between the two intersection points of the offsets will be deleted.

This solution is based on the assumption that there will be no distances between the exterior chains smaller than the minimum offset value. In this case, as the distance between the offsets of the exterior chains approach .125”, the energy directors will merge from two energy directors into one (Figure 3.9).

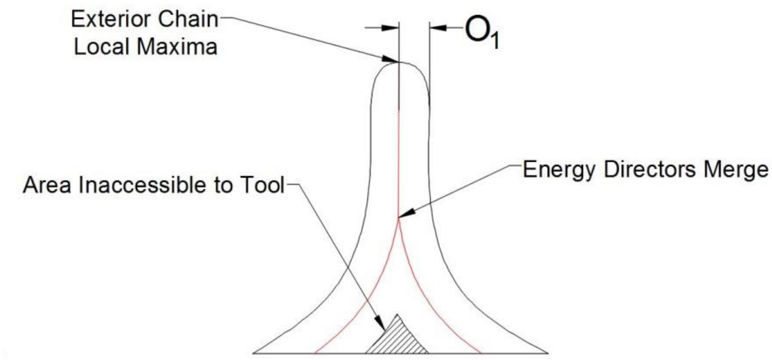

Figure 3.9: Merging of energy directors

In offset functions, the offsets are terminated at the point where the offset lines intersect. A line will have to be placed in this region from the energy director merge point to the exterior chain maxima. The area inaccessible to the chamfered end mill is in the hatched region (Figure 3.9). As the tool diameter for the chamfer end mill gets larger so does the inaccessible region. This inaccessible material has to be removed or the flat section remaining will dissipate the welding energy and not allow bonding. The solution to this issue is to evaluate the distances between the peaks of the same offset (p_d) to find if or when it equals s_{ce}. If this occurs, an arc with the radius of s_{ce} /2 will be assigned with the end points where $s_{ce}=p_d$. After this happens a single offset will be used to follow the contour of the section with a cross section smaller than s_{ce}. Once the intersection occurs with the arc with a radius of s_{ce} /2 and outer chain, the energy director line peak line will terminate.

Figure 3.10 shows a situation where a considerable amount of material is inaccessible by the s_{ce} cutting tool. In this case, the distance between the peaks of the energy director is measured to determine when the distance (p_d) is equal to the s_{ce} (Figure 3.10). An arc with a radius of s_{ce} /2 will be assigned with the end points where p_d is equal to s_{ce}. For O_1, there will be

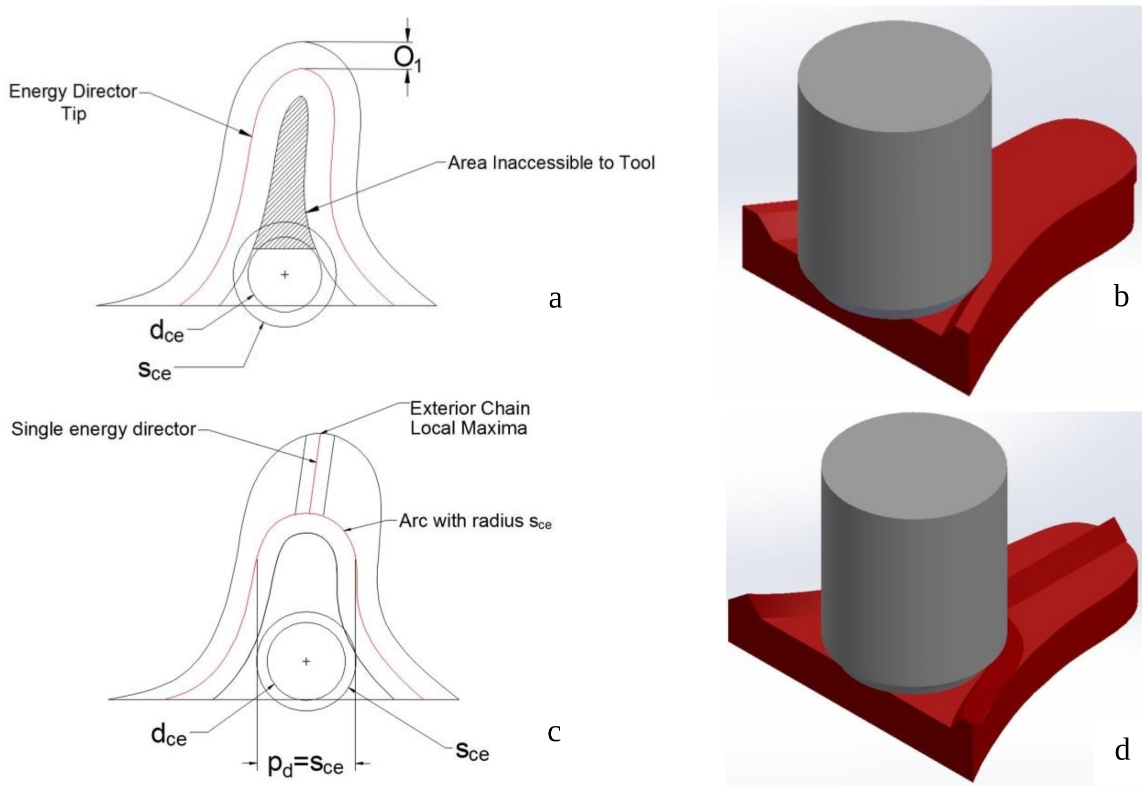

Figure 3.10: Inaccessible material and solution (a,b) Inaccessible material in hatched region (c,d) Solution for removal of the material

an extension line that will follow the contour of the exterior chain from the arc with the radius s_{ce} to the exterior chain local maxima. It will terminate when it intersects with the arc as well as the outer chain. This will extension line will only be applied for the first offset. Other offsets inward will be deemed acceptable to have the arc without the extension line. If further research notes that a considerable amount of strength is added if the extensions lines are used for every offset then it can be easily added.

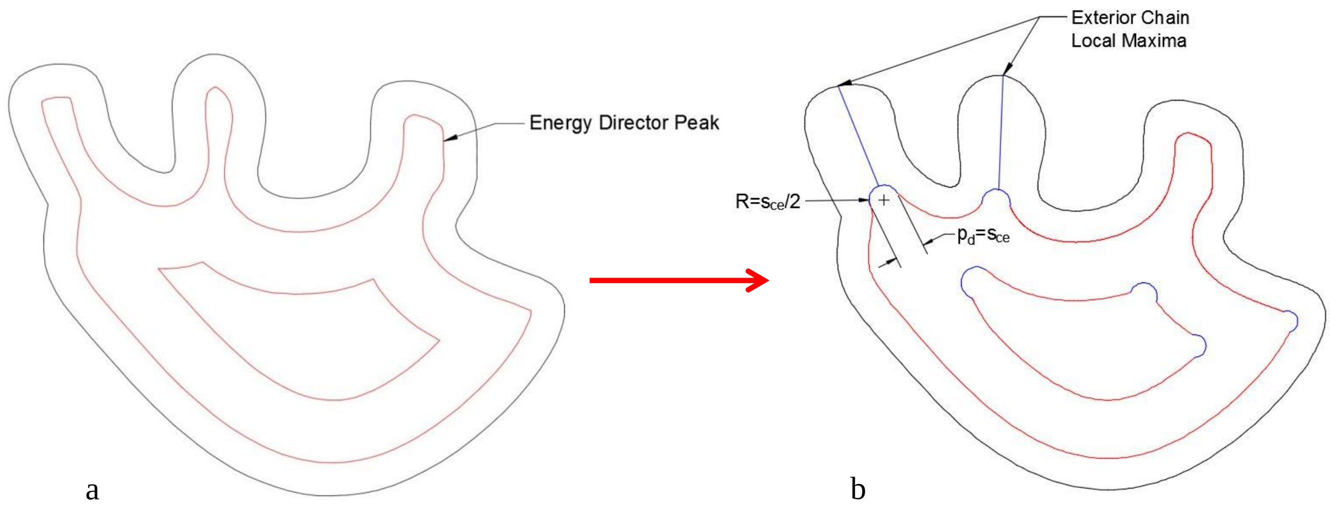

Figure 3.11: a) original offset pattern b) arc and extension line generation

Figure 3.11 is an example of how the offsets would look when the distance between the peaks defined by the same offset are equal to s_{ce}. The blue lines show the changes in the energy director locations. Notice, the one region did not change because the cross section was larger than s_{ce}. The sharp interior corners of O_n will get machined with both the d_{ce} tool as well as a chamfer end mill with d_{ce}=0 to remove the material between the extension line and arc.

3.4.3 Algorithms

The best way to implement the algorithms for ultrasonic welding and machining would be to create an add on to a CAM package. A CAM package already has many of the needed functions to carry out the automation of path planning. CAM has the ability to set offsets based on the approaches previously discussed and to generate tool paths for machining. The tool paths generated by the CAM package will shape the energy directors and the contours of the layers.

Preparation and Offsetting

To execute the offsets within a CAM package for the process planning, there will be several inputs and operations which will need to occur. The required inputs to the system are as follows: 1) energy director height (h_{ed}), layer thickness (T_o), energy director angle (β), and the diameter of the chamfer-end mill (s_{ce}). To begin the process, a solid model is imported and tessellated into STL file which is sliced as a multiple of T_l. The next step is an algorithm that evaluates slice files based on whether they are interior or exterior, as follows:

Offset outer chains inward: $O_1 = .5(h_{ed}/\tan(\beta))$ $O_n = (2n-1)*(h_{ed}/\tan(\beta)) + (n-1)d_{ce}$
Offset inner chains outward: $O_1 = .5(h_{ed}/\tan(\beta))$
Distances between peaks of the same offset are evaluated for the following cases:
If $p_d = s_{ce}$
For offset 1
Arc is generated from the two points where $p_d = s_{ce}$ with a radi of $s_{ce}/2$
Previous offset curve between the two points where $p_d = s_{ce}$ is deleted
Generate extension line following the contour of exterior chain from the arc generated to the exterior chain local maxima
For offset n
Arc is generated from the two points where $p_d = s_{ce}$ with a radi of s_{ce}
Previous offset curve between the two points where $p_d = s_{ce}$ is deleted

Output: Layer n

Tool path planning

For a given layer, the operations proceed as follows for the contouring of the layer; 1) Tool containment boundary is set, 2) Rough pocket milling (d_{em}), then 3) Finish ball milling (d_{bm}). For the energy director creation, the steps are 1) chamfered end mill (d_{ce}) follows the contours generated using both a left and right cutter compensation and then 2) a chamfer end mill with a d_{ce} = 0 will make sure all material is removed from corners of the arc and extension line. These steps are illustrated in the flow chart of Figure 3.12.

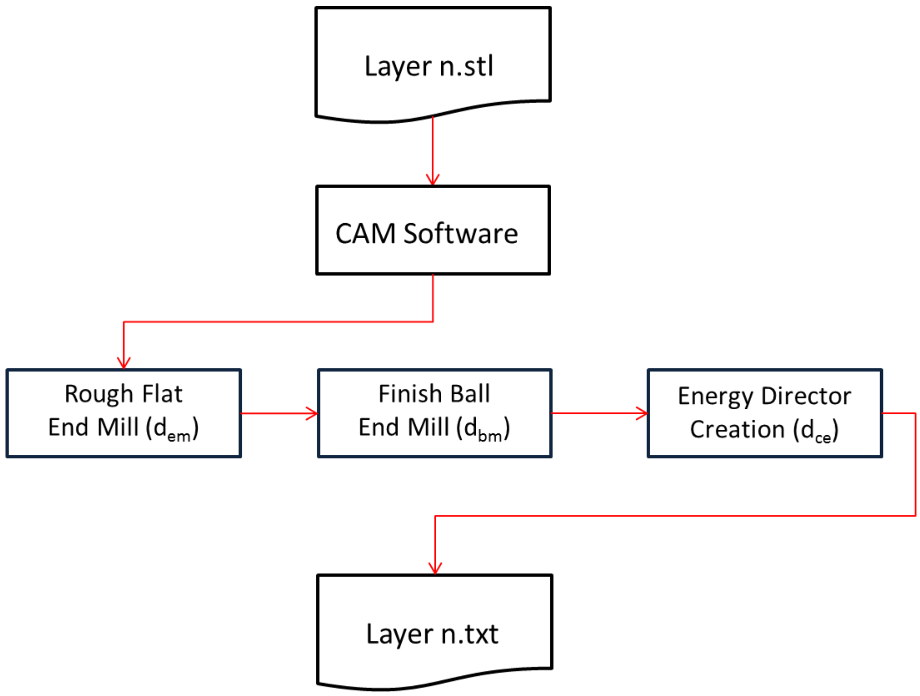

Figure 3.12: Tool path planning process steps

3.4.4 Support Walls

An outer wall will always be used to surround the pattern even if it is temporary (not needed as part of the tool). The width and length of the added layer will remain constant for the entire pattern build. Hence, the length and width will be chosen based on the largest required. The layer with the largest amount of area will always be at the bottom for pattern tooling, because there will never be undercuts. As the build moves towards the top surface of the pattern, supports will be needed to effectively stack layers (Figure 3.13). This is because the cross sectional area of the surfaces will decrease monotonically and the top section of pattern geometry will need to be suspended over the pattern for welding, as shown in Figure 3.13.

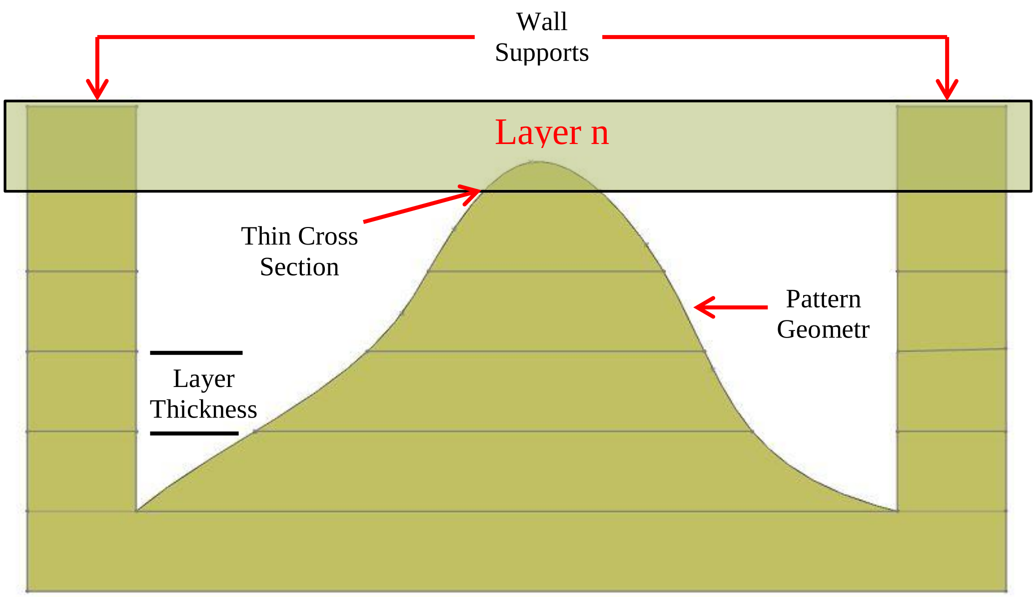

Figure 3.13: Side view of tool with support wall required for each layer

3.4.5 Layer Elevation

One of the issues of ultrasonically welding large layers is what is defined in this paper as the elevation factor. The layer elevation factor is when the ultrasonic welder engages with one edge of the slab and the opposite side is consequently warped upward (Figure 3.14).

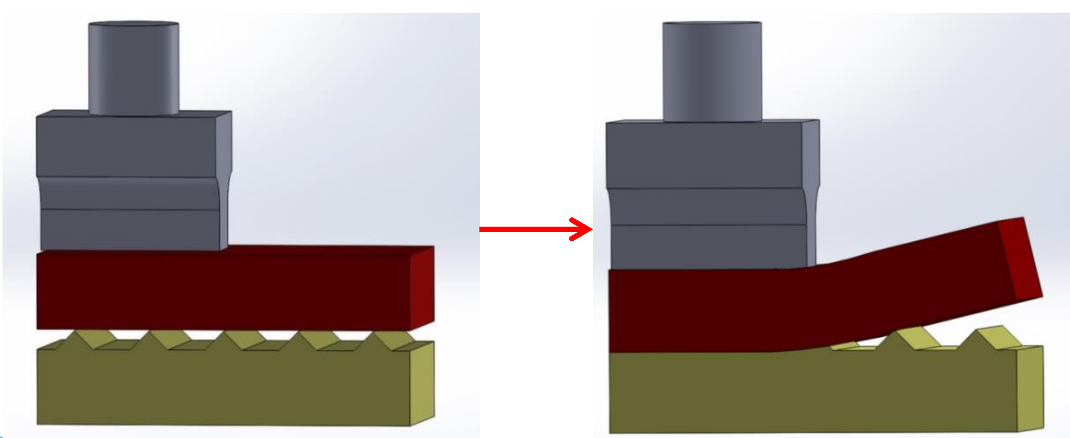

Figure 3.14: Illustration of layer warping opposite weld horn

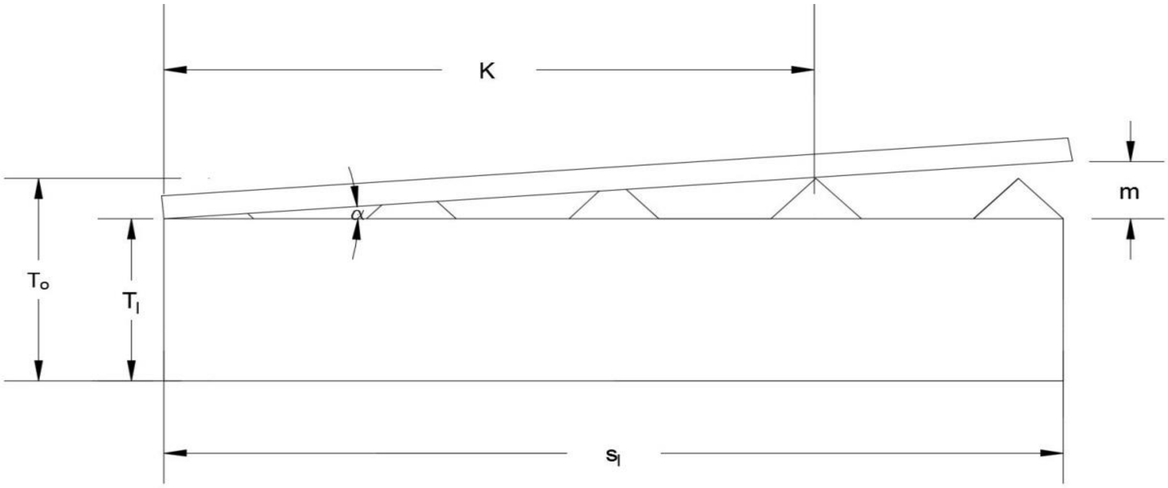

Figure 3.15: Idealized version of layer warping opposite weld horn

m=height of the elevation T_o=Overall thickness of the layer

α= angle of the elevation T_l= Thickness of the layer

k= Distance from the weld to the nearest unwelded energy director

This elevation factor is dependent on the size of the ultrasonic welding horn being used. When the horn is engaging with more surface area, the smaller the value for α is in turn reducing the value for m. In smaller patterns, the value for *m* will tend to be small. As the pattern size gets larger, m can become large. If force is applied to an unwelded area after previously welding a different area, the energy directors could act as fulcrum and the board as a lever subsequently causing the bond to be broken. One of the ways to counteract this issue is to keep the welder engaged with the work piece and gradually work the layer down while moving the weld bead across the pattern (Figure

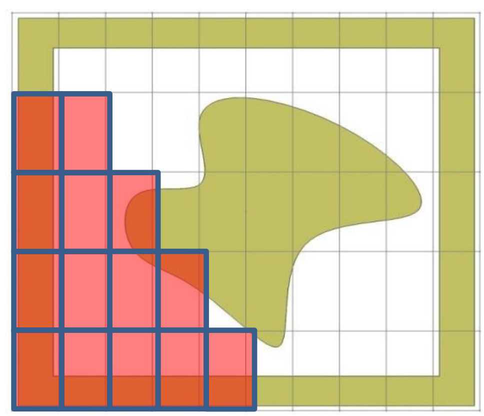

Figure 3.16: The travel of the ultrasonic welding horn

3.16). In order to maintain a good quality, strong bond this issue must be controlled. The actual path of the welder will need to be optimized for this process. This could be in terms of spot welding or scan welding, but is outside of the scope of this paper.

3.5 Implementation

To validate the process planning methods discussed in this paper, a part was designed in CAD, sliced, machined and ultrasonically welded. The CAD model of the part being created can be seen in Figure 3.17.

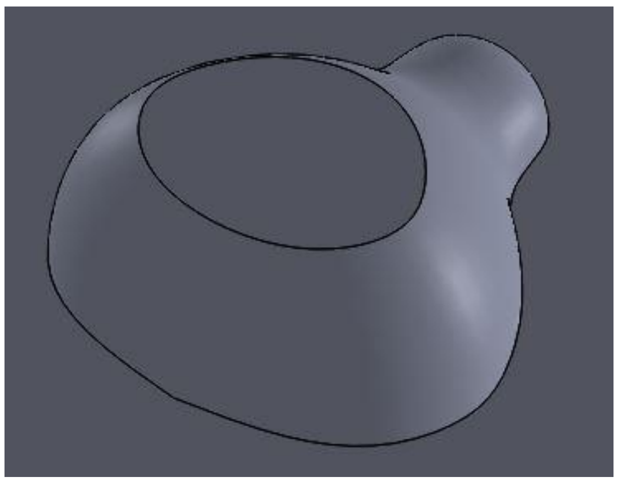

Figure 3.17: CAD model of sample tool

As described in the method section, the variables for the process (Figure 3.18) were defined by the material and the tools selected to make the sample tool. In the process, the overall the limitations were due to the ultrasonic welder.

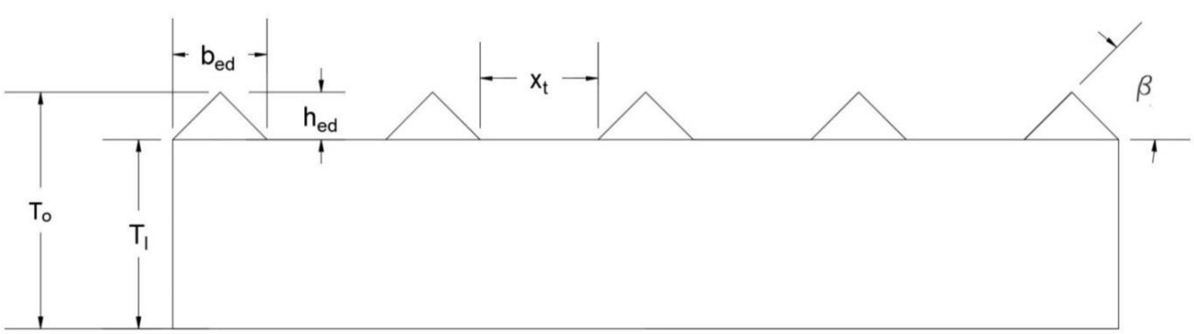

Figure 3.18: Parameters for sample tool energy directors

The parameters settings for the process were as follows: 1) the energy director height, h_{ed}, was .075”, 2) the overall all thickness of the slab, T_o, was .500”, 3) the base of the energy director, b_{ed}, was .086”, 4) the layer thickness, T_l, was .425”, 5) the distance between the energy director bases, x_t, was .250”, 6) the angle of energy directors, β, was 60°.

The material used for layer 1 was 1” ABS plastic, while layers 2 and 3 were 0.5”. A Branson 2000 series ultrasonic welder was used to weld the layers together. The settings for the welder were as follows:

- Trigger Pressure: 140 lb
- Weld Time: 5 seconds
- Dwell time: 2 seconds
- Horn width = 1.25”
- Horn length = 3.25”

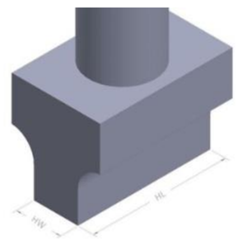

Figure 3.19: Shape of the ultrasonic welding horn used

To correctly mesh the contours of the new layer to the previous layer, the same coordinate system in the CNC machine needed to be used. A fixture for the ultrasonic welder doubled as the base plate in the CNC machine vise. The fixture featured a series of holes in the base plate in which screws attached the 1” plastic to the aluminum plate (Figure 3.20). This plate also served as the

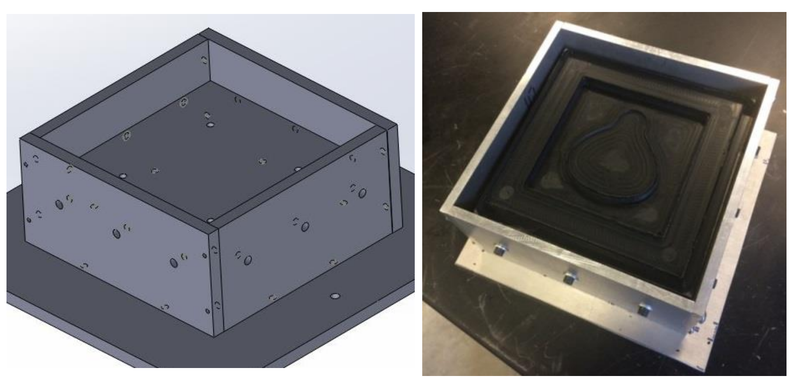

Figure 3.20: Fixture used for securing the pattern for machining and ultrasonic welding

fixture which held the workpiece to a height where the stroke could reach the workpiece, allowing the ultrasonic welding horn to weld the next layer onto the piece.

Since ultrasonic welding is based on small vibrations that generate friction with the bottom layer, it has a tendency to cause the item being welded to vibrate out of place. To counter this, the side walls of the fixture keep the slab of plastic in place during welding. When constraining the slab, if the new layer touched the side wall, the bond was negatively affected due to dampening of the energy.

A cross section of an ultrasonically welded sample coupon is shown in Figure 3.21. Notice, the layer with the energy directors is embedded into the layer being added. The greyed area around the energy director shows the mixing of the two different colored plastics. The two layers bonded together very well, with no noticeable seam between layers.

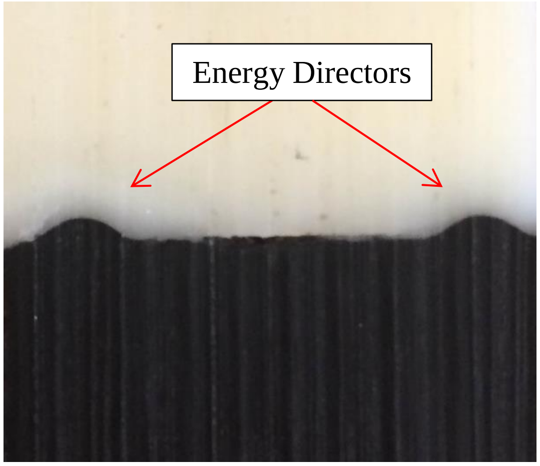

Figure 3.21: Cross section of the bond between layers

The proposed process successfully yielded a small sample tool with relatively smooth and homogeneous seams between layers (Figure 3.22). Multiple colors of plastic were used to show the laminating of the plastic to create the part. There are tool marks visible from the ball-end mill finishing passes; however this is common in any milling process and could be reduced by adjusting the speeds and feeds of the milling process.

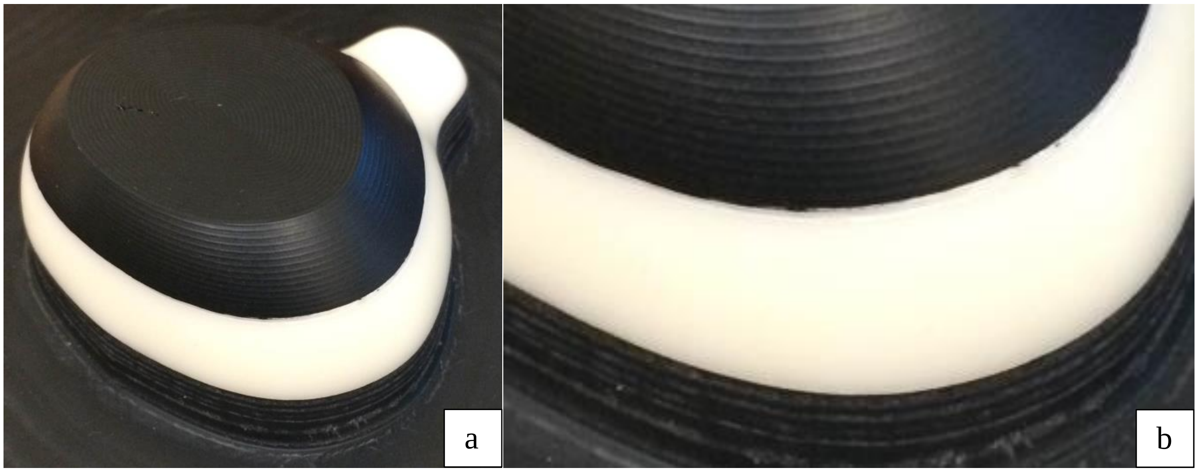

Figure 3.22: (a) The completed part by the process and (b) a close up of the layer interface

Finally, the overall process from CAD model to sand impression can be seen in Figure 3.23. One will note that the walls on the pattern were removed prior to molding since a separate flask was used deposit and pull the sand off of the pattern.

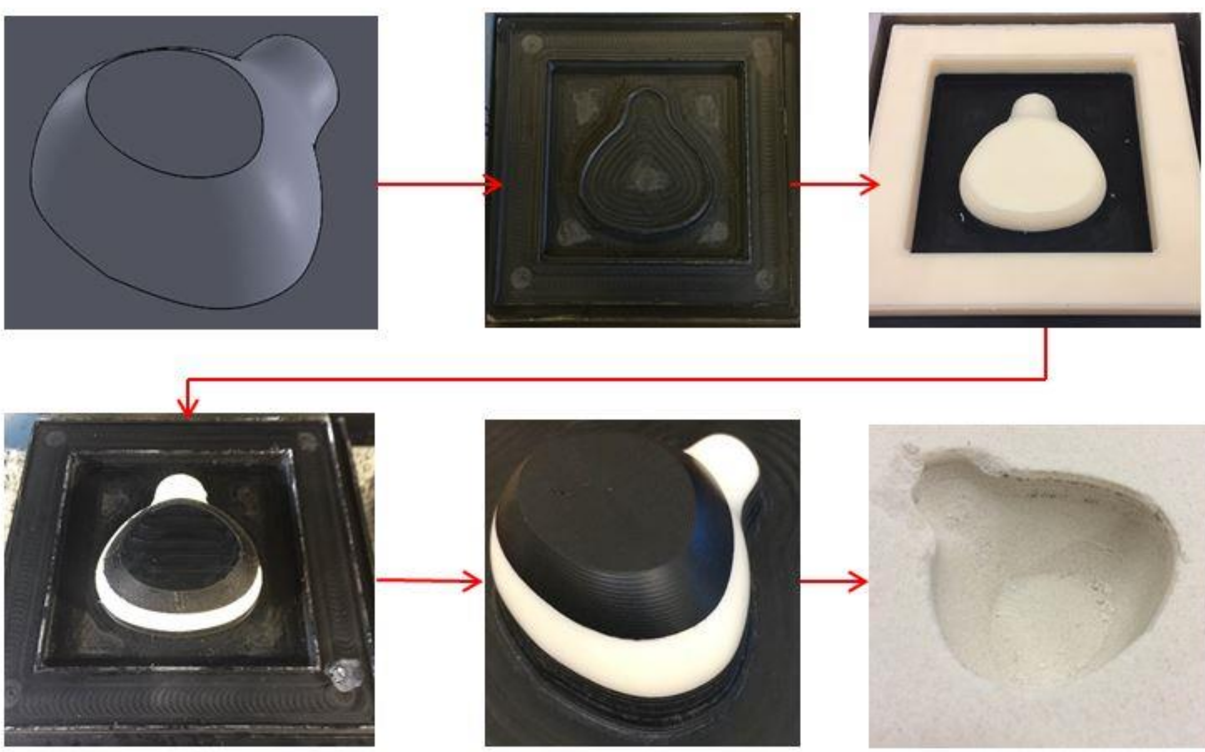

Figure 3.23: Progression of the part from CAD model to sand impression

3.6 Conclusion and Future Work

A method for rapidly manufacturing plastic pattern tooling has been presented. This process for rapid tooling utilizes a hybrid approach by ultrasonically welding slabs of plastic and machining the desired pattern geometry. A pattern for validation was created and sand was pulled from that pattern. A solution for the arrangement of energy directors and the formation of the energy directors using machining has been developed. This method could allow for rapid production of functional pattern tooling to be built by a layer based approach with a homogeneous interface between the layers.

There are numerous opportunities for further research directions. The proposed process is able to use a variety of plastics, but work needs to be done in order to establish the parameters for different types of polymers. A link should be formed between ultrasonic welder strength and the polymer type, slab thickness, energy director height, and energy director density. An optimization model could be formulated to take all process parameters plus the energy director location method presented in this paper, to make the entire process automated and reduce processing time.

3.7 References

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CHAPTER 4: FUTURE WORK AND CONCLUSIONS

4.1 Future Work

There are many directions the research of this thesis can continue. This process is able to use a variety of plastics, but work needs to be done in order to establish the parameters for different types of polymers. A link should be formed between ultrasonic welder strength and the polymer type, slab thickness, energy director height, and energy director density. An optimization model could be formed to take all these parameters plus the energy director location method in this paper, to make the entire process automated.

4.2 Conclusions

A method for rapidly manufacturing plastic pattern tooling has been presented. This process for rapid tooling utilizes a hybrid approach by ultrasonically welding slabs of plastic together and machining the desired features into the layers. A pattern for validation was created and sand was pulled from that pattern. A solution for the arrangement of energy directors and the formation of the energy directors using machining has been developed. This method allows for long term plastic pattern tooling to be built by a layer based approach with a homogeneous interface between the two layers. Using ultrasonic welding and machining to create pattern tooling not only serves as a way for prototyping but also long term tooling.

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