

Additive/Subtractive Rapid Pattern Manufacturing for Casting Patterns and Injection Mold Tooling

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Abstract

This paper presents a Rapid Pattern Manufacturing system that involves both additive and subtractive techniques whereby slabs are sequentially bonded and milled using layered toolpaths. Patterns are grown in a bottom-up fashion, both eliminating the need for multi-axis operations and allowing small features in deep cavities. Similar approaches exist in the literature; however, this system is able to provide a larger range of both materials and sizes, from smaller conventional injection mold tooling to very large wood or urethane sand casting patterns. This method introduces a novel sacrificial support structure approach by integrating a flask into the pattern build process. The system has been implemented in an automated machine capable of producing patterns in excess of several thousand pounds in a build envelope over 1m³. In this current research, a new layer bonding method using friction stir welding of aluminum plates is presented. In this manner, one can create seam-free laminated aluminum injection mold tooling using a unique combination of industrial adhesives and friction stir spot welding to secure the slab initially, then continuous friction stir welding of layer perimeters that are subsequently machined in a layer-wise process.

Introduction

Although most rapid prototyping systems are appropriate for testing form, fit and function, they usually require a long processing time; which is reasonable if only one or a few parts are required. When there is a need to make tens, hundreds or thousands of parts, RP systems are not always the best choice because of the cost and processing time for each part. The availability of rapid prototyping systems for the areas of mass production is limited, but is just starting to see some successes. One of the most commonly chosen manufacturing methods for the mass production of plastic parts is the injection molding process. A wide range of products that vary in their size, shape and complexity can be easily manufactured using injection molding. However, the process of manufacturing an injection mold tool is a complex and highly skilled task that is very costly. Once the design is confirmed it usually takes several weeks or months to actually manufacture and market the product. This is mainly due to the complexity involved in creating the mold tooling. There is a strong motivation to implement rapid manufacturing technology for the manufacture of plastic injection molds to reduce the product development time and reduce the cost of manufacturing.

Related Work

Different types of rapid prototyping and manufacturing methodologies have been developed in the past few decades. Some of the noteworthy methods are Stereolithography (SLA), Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), Selective Laser Sintering (SLS), Electron Beam Melting and other direct metal method, and 3-D Printing. These RP systems are excellent for testing the form, fit and sometimes function of a new design; however most are limited in terms of part accuracy, size and choice of materials. Hybrid RP process combines the advantage of conventional CNC machining process and a layered manufacturing process to find the solution to these problems [3].

Shape Deposition Manufacturing (SDM) was a hybrid process developed at Carnegie Mellon University that employed an additive process to deposit the part or support material using micro-casting process. The material is then machined to achieve the desired accuracy and finish [4]. Solvent welding freeform fabrication technique (SWIFT) creates short run tooling based on solvent welding and CNC machining [5]. For each layer a thin film of high-density polyethylene (HDPE) is printed through a laser printer. HDPE is the solvent mask that prevents unwanted bonding wherever it is applied. After masking, acetone solvent is applied to the bottom side of the sheet and then stacked to the previous layers and bonded under force. A three axis CNC machine is used to mill down the current sheet to the shape. Computer-aided manufacture (CAM) of laminated engineering materials (LEMs) is another hybrid RP process for fabricating laminated engineering components directly from sheet metal. A laser was used to cut the part slices from the stock of materials such as metals and ceramics. These slices are then assembled together using a selective area gripper [6]. However the part accuracy of this system was low due to unpredictable shrinkage which can be as high as 12 – 18 percent [7].

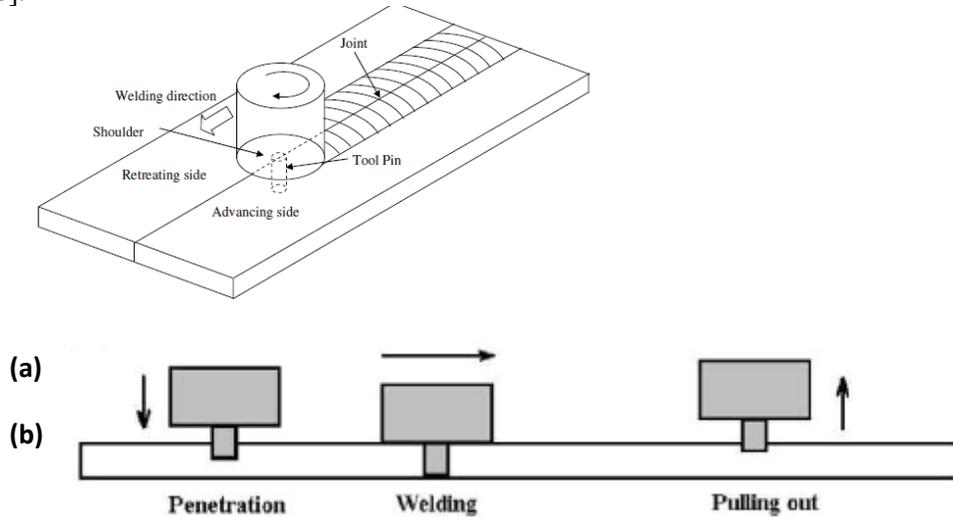
Rapid Tooling is an extension of rapid prototyping which is used to prototype mold tooling that can be used for early production. Rapid tooling (RT), allows manufacturing of production tools such as molds and dies rather than the final part itself which can reduce the lead time for the product to reach the market [2]. Rapid laminated tooling is similar to laminated object manufacturing (LOM), In the LOM process, each layer of the part is formed from an adhesive coated sheet of paper which were subsequently cut with a laser [10]. Instead of paper, other forms of laminated tooling used sheets of metals. These sheets of metals could be joined together by bolts, welding or brazing. Extensive research has been conducted on creating tooling for plastic and metal forming processes. Laminated tooling is not a new concept, where research and development in this field has been conducted since early researchers like Nakagawa back in 1980, who were creating blanking dies for sheet metal components by using bainite steel sheets for the tool face and cheaper steel as backing plates. The steel sheets were cut using a laser, stacked horizontally and joined together by using mechanical fasteners [11].

Most of these laminated tool manufacturing processes follow a build sequence of cut, stack and bond. First, the plates are cut to the required cross section using a laser or EDM process and then these laminates are cleaned and stacked in either horizontal or vertical orientation. Finally, the stacked plates are bonded together. Many researchers used different bonding methods, such as mechanical fasteners, laser welding, diffusion bonding and bonding by adhesives. The more popular joining method being the use of mechanical fasteners such as bolts and rivets to join the laminates together [11-14]. However, most of these processes do not provide a complete automated process planning solution. In addition, selecting the thickness of the laminates has always been an issue, where selecting thin laminate thickness of 0.5 and 2mm increased both the complexity and time in creating the tooling

The proposed process, Rapid Manufacturing of Plastic Injection Mold (RMPIM) uses a build sequence of *stacking-bonding-cutting* of aluminum plates as opposed to *cutting-stacking-bonding* cited in most of the literature. This approach should more readily enable completely automated process planning for creating injection mold tooling. The proposed process uses a new layer bonding method; a unique combination of industrial adhesives and friction stir welding. A hybrid Rapid Pattern Manufacturing system (RPM), previously developed by the authors, can create large wooden casting patterns [8-9]. The process combines depositing a thick slab of Medium-density fiberboard (MDF) and a three axis CNC machine to cut the board to a defined layer thickness and to create part geometry on the layer. The advantage of this system is that the patterns are built in the bottom-up fashion so a small tool can be used to mill deep cavities without the use of multi-axis (beyond three-axis) CNC machines.

Friction stir welding (FSW) is a solid-state joining process. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into the abutting edges of sheets or plates to be joined and traversed along the line of joint. Frictional heating is produced from rubbing of the rotating shoulder

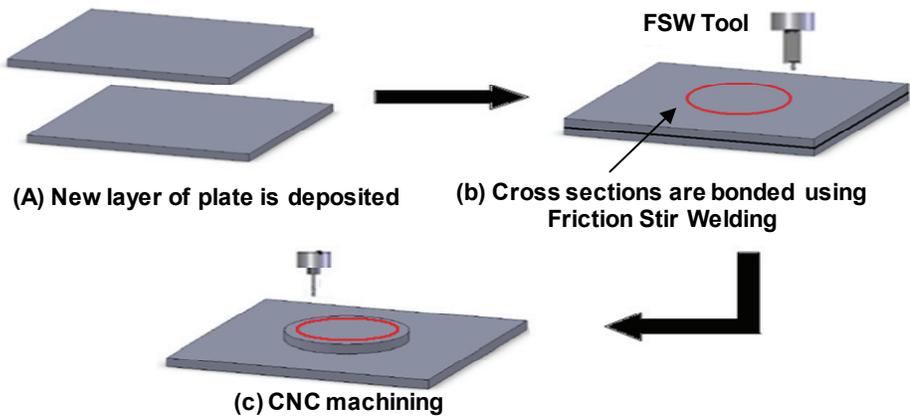
with the work pieces, while the rotating pin causes plastic deformation of work piece. The heating is accomplished by friction between the tool and the work piece and plastic deformation of work piece. The localized heating softens the material around the pin and the combination of tool rotation and translation leads to movement of material from the front of the pin to the back of the pin where it is forged into a joint [15-16].



Overview of Process

The proposed rapid mold manufacturing system uses a hybrid manufacturing method, a combination of additive and subtractive process to create plastic injection molds. The basic process involves adding a layer of aluminum plate, which is then subsequently machined to obtain the 3D shape of that particular layer. This process uses friction stir welding for layer bonding, which would enable the creation of seam-free laminated aluminum injection mold tooling. The fundamental additive and subtractive nature of the process is illustrated in figure 2 for simply two layers.

When a new plate is added to the base plate, it needs to be clamped for the subsequent welding and machining process, but the use of mechanical fixtures and clamps for machining in rapid manufacturing will create a potential problem for collision of the tool/spindle and the work piece setup. Therefore, the process proposed in this paper uses a combination of industrial adhesives and friction stir spot welding to secure the aluminum plates.



The adhesive is applied in the areas of both the boundary

wall cross section and the mold cross section. The boundary wall in this process acts as a sacrificial support structure which aids in orienting and fixturing of the deposited plate. The adhesively bonded plate is then spot welded using friction a stir spot welding process (FSSW). This is because the strength of the adhesives alone is assumed insufficient withstand the forces of the continuous friction stir welding process (FSW). Both the adhesives and the spot welding acts as a clamp so that the plates will not move or shear due to friction stir welding and generally keeps the plate flat and undistorted.

A face milling operation is performed on the deposited plate prior to friction stir spot welding to make sure that the plate is flat and parallel with the work table of the machine. The plate can then be pre-drilled in all the spot weld locations and at the entry point of the continuous friction stir welding process. The pre drilled holes will reduce the force acting on the mold work piece and the machine table from the friction stir spot welding and friction stir welding processes [19]. Next, the plates are bonded together using a continuous friction stir welding process so that the tooling can withstand the pressure of injection molding process and to create a seam-free tool.

Lastly, the plates are machined using ball and flat end mills to obtain the part geometry of that particular layer. The plate is once again face milled to remove burrs from the friction stir welding process so that the next plate can be stacked onto a known height flat surface. The process of stacking, bonding and machining of the plate is continued sequentially until the complete mold tooling defined by the CAD model is created. For previous work in sand casting patterns, the outer boundary wall would either be discarded or kept as the flask if draft was designed into the wall geometry. For aluminum tooling, the wall would simply be removed at the end. It should be noted that female mold tooling, having a boundary region already, would not necessarily **need** the boundary wall added to the CAD model. To illustrate the step by step process more clearly, Figure 3 illustrate a few layers of a hypothetical piece of tooling as the process steps through plate addition, Friction Stir spot and cross section welding, and then CNC machining.

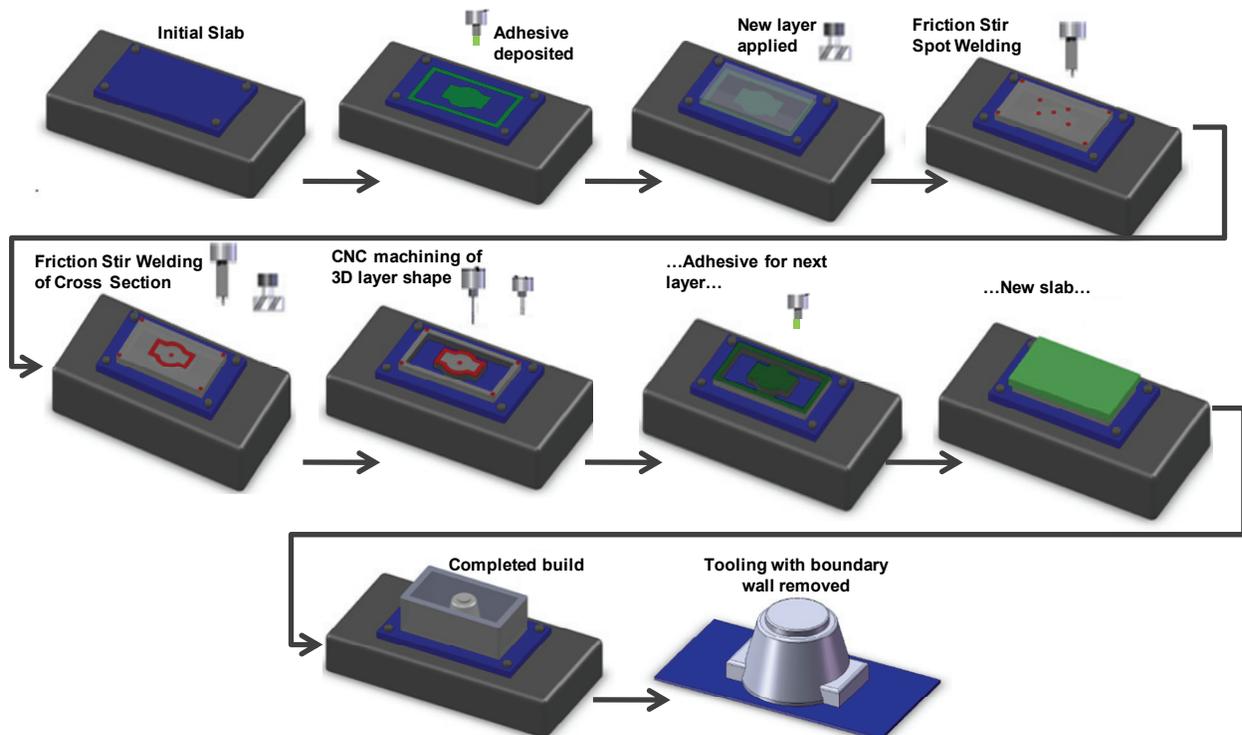


Figure 3 – Detailed process steps for the proposed rapid tooling system

Process Planning Method

A critical characteristic for any rapid prototyping and manufacturing system is completely automated process planning. That is, the process must be able to be executed from a CAD model, with little or no human intervention or skill required. The main problems that need to be addressed in order for this process to be completely automated are:

- Determining the boundary wall dimension
- Finding the *Number*, *Location* and *Sequence* of Friction Stir Spot Welds (FSSW)
- Toolpath planning for Friction Stir Welding (FSW)
- Toolpath planning for CNC machining

The following section presents methods that will enable the automated process planning for this system, using only a CAD model and basic system and processing parameters.

Determining the Boundary Wall Dimension

The aluminum plates that are added layer by layer to create the tooling need to be oriented and clamped together for friction stir welding and subsequent machining process. The use of fixtures and clamps for friction stir welding or machining in rapid manufacturing create a potential problem for collision of the tool/spindle and the work piece setup. Therefore, in this process a combination of industrial adhesives and friction stir spot welding is used to secure the aluminum plates for machining. Each pattern is enclosed by a boundary wall that serves as a sacrificial fixture to aid in the layer based addition of plates. When a new plate is added to the part, the plate can be positioned securely and repeatedly with the support of boundary wall. Initially, an adhesive will hold the plates together and be able withstand the forces from the subsequent FSSW process without the shearing of plates.

The intent is to secure the plate with enough adhesive strength to enable spot welding, which then enables continuous friction stir welding of the pattern geometry within the plate. Obviously, if the load acting on the adhesive during spot welding is more than the strength of the adhesive; the bond fails. Adhesive joint strength can be increased by increasing the area of the bond, (e.g. doubling the bond area approximately doubles the force required for failure stress). This paper presents a method to determine the dimension of the boundary wall (Figure 4a) based on size of the mold geometry, forces acting on the plate due to friction stir spot welding, mechanical properties of the adhesive used and the boundary wall clearance. The boundary wall clearance (dimension a in Figure 4b) is the required space between the boundary wall and mold geometry. The objective of adhesive bonding is such that it will transfer and distributes the stress so the plates will not shear due to the forces of the friction stir spot welding process.

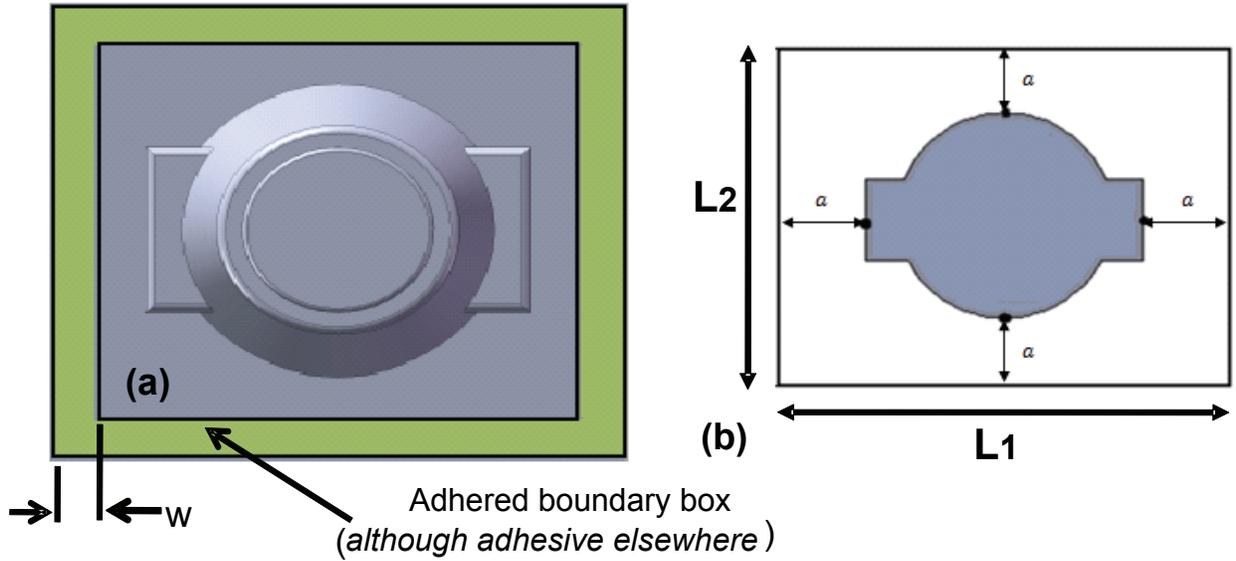


Figure 4 – Mold geometry showing lengths, $L_{1,2}$ and width, w of the boundary wall

The polygon cross section of the CAD model differs from slice to slice but the size of the boundary wall is constant throughout. Therefore, the dimension of the boundary wall is determined such that the area of adhesive applied to the boundary wall should be able to withstand the forces from the FSSW process. The boundary wall clearance will be with respect to the extreme points (x_{min}, y) , (x_{max}, y) , (x, y_{min}) , (x, y_{max}) of the polygon cross section obtained by the union of all the slices of the mold. The length of the boundary wall, L will be a constant and it is determined based on the boundary wall clearance value, a . The magnitude of the shear force that the plate can withstand will depend on the bond area, as length being constant the width of the wall; w is calculated such that the bond area is sufficient to prevent the movement of the plates. The dimension of the boundary wall will be the same throughout the mold. The area of the bond to withstand the forces will depend on the mechanical properties of the adhesives and the stress acting on it. The stresses in adhesives arising from the differential shear strain were analyzed by Volkersen [20]. The maximum shear stress, $\tau_{12}(max)$, in the adhesive is related to the applied shear stress, τ_0 , by:

$$\eta_c(max) = \frac{\tau_{12}(max)}{\tau_0} \quad (1)$$

where η_c is the stress concentration and the value of τ_0 is given by:

$$\tau_0 = \frac{F}{(bonded\ area)} = \frac{F}{bl} \quad (2)$$

where,
 F - Applied load
 l - Length of the bonded area
 b - Width of the bonded area

$$\eta_c(max) = \left(\frac{\phi}{\omega}\right)^{1/2} \left[\frac{\omega - 1 + \cosh \phi \omega}{\sinh(\phi \omega)^{1/2}} \right] \quad (3)$$

where ϕ is a dimensionless coefficient,

$$\phi = \frac{G_a l_a^2}{E_{s2} d_2 h_a} \quad (4)$$

and ω is defined by,

$$\omega = \frac{(E_{s1} d_1 + E_{s2} d_2)}{E_{s1} d_1} \quad (5)$$

where,
 E_{s1} - Tensile modulus of substrate 1
 E_{s2} - Tensile modulus of substrate 2
 d_1 - Thickness of substrate 1
 d_2 - Thickness of substrate 2
 G_a - Shear modulus of adhesive
 h_a - Thickness of adhesive layer

When $E_{s1} d_1$ and $E_{s2} d_2$ are equal ω reduces to a value of 2 and the equation (3) becomes:

$$\eta_c(max) = \sqrt{\frac{\phi}{2}} \cot h \sqrt{\frac{\phi}{2}} \quad (6)$$

The maximum adhesive shear stress occurs at the corner of the joint and it is given by $\eta_c(max)$.

$$\tau_{12}(max) = \eta_c(max) \times \frac{F}{bl} \quad (7)$$

In the above equation, the length of the boundary wall is constant; therefore the width of the boundary wall can be calculated such that the maximum shear stress in the adhesive is less than the shear strength of the adhesive, τ_{adh} . The minimum width of the boundary wall will depend on the smallest diameter FSW tool available in the tool library.

The length and width of the required plate is:

$$L_p = (x_{max} - x_{min}) + (2 * w) + (2 * a) \quad (8)$$

$$W_p = (y_{max} - y_{min}) + (2 * w) + (2 * a) \quad (9)$$

where,
 w - Width of boundary wall
 a - Boundary wall clearance

Sequence, Number and Location of Friction Stir Spot Welds

The plates that are fastened together using adhesives will not be able to initially withstand the forces from a continuous FSW pass. Therefore the plates are subsequently bonded together using a Friction Stir Spot Welding process. The load acting on the spot welds due to FSW process will not be uniform and if the load acting on a particular spot weld is greater than the failure load, f_f , the spot weld will fail. Therefore, an algorithm will determine the location and number of spot welds needed so that load acting on each of the spot welds is less than the failure load. The algorithm will consider inter layer dependency; when any spot weld location is same as the location of a spot weld or exit hole location of a previous layer, then the spot weld location must change. The location will be moved on the offset curve by a distance $2r$, where r is the radius of the FSW tool. This is because the friction stir welding process will leave a hole at the retracting point of the tool; previously mentioned as the *exit hole*. The shear force f_s acting on the plate will cause mode II type failure (sliding mode), in plane overlap shear failure. The failure rule for the spot weld for mode II is given by the equation,

$$(f_s/F_s)^\alpha \leq 1 \quad (10)$$

The denominator F_s represents the shear strength of the spot weld. The value of α is an unknown that will define the failure relation between independent modes. For any single loading, regardless of the value of α , the equation will satisfy the failure condition. It means that when the applied load reaches the strength of the spot weld, the spot weld will fail for each single load [21]. The value of α can be determined by experiments; for example, tests conducted by Wang [22] gave the value of α to be 2 for small thickness to radius ratio (thickness of plates to radius of the weld). In this thesis, the t/r ratio is small so the value of α is taken as 2. In future work, when this process uses thick plates the value of α should be determined by experiments.

Friction Stir Spot Welding in the boundary wall cross section:

For each layer to be spot welded to the previous layer, the possible regions for the location of the spot are the boundary wall and the cross section area of the polygon of that slice. This is because in the previous layer all the regions of the plate except for the polygon cross section of the slice and the boundary wall will be machined. There will be one spot weld in each of the boundary wall sides which will act as a clamp to hold the current plate to the previous plates. The boundary wall used in this thesis will only be in rectangular shape (four sided), therefore there will be four spot welds in each layer which will be either in the corners of the boundary wall or in the mid span of the boundary walls. The location of the spot welds is alternated for subsequent layers as in figure this is because of the exit hole in the previous layer.

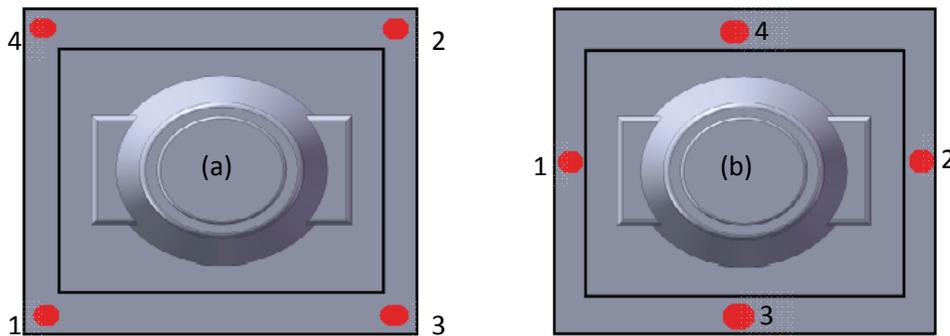


Figure 5 – Friction stir spot welding (a) on layer_n (b) on layer_{n+1}

The sequence of spot welds for the rectangular boundary wall is as shown in Figure 5. In figure 5a, the location of the first spot weld will be on the bottom most point of the left boundary wall side and the second spot is the point diagonal to the first spot weld. The location of the second spot weld is selected such that it increases the moment arm from the first spot weld so the force acting on the spot weld is reduced. The location of the third and fourth spot weld is as shown in the figure. Similarly in figure 5b, the location of the second spot weld is selected such that it has increased moment arm from the first spot weld. This alternating pattern should generally provide a robust and flat outer wall boundary to ensure repeatable placement of each new plate, not affected by build height.

Friction Stir Spot Welding in the mold cross section:

The four spot welds on the boundary wall are to clamp the plates firmly so that it can withstand the forces from friction stir welding process without the shearing of plates, but the forces involved in

friction stir welding are generally of high magnitude therefore spot welds are also needed in the polygon of mold cross section. In addition, it is imperative that the plate is in intimate contact with the layer below before continuous FSW of the layer boundary; therefore spot welds are needed in the mold cross section. The four spot welds on the boundary wall cross section will be same throughout the mold but the number of spot welds on the mold cross section polygon will depend on the size of the mold. The location of the spot welds in mold cross section polygon will depend on the critical number of welds, $n_{critical}$. $n_{critical}$ for a mold cross section polygon is determined such that it prevents the plate from shearing during friction stir welding and also the load acting on each of the spot weld f_s is less than the failure load f_f . One of the main objectives in determining the location of the spot weld is that the welds should be well distributed within the mold cross section polygon. Figure 6 illustrates the layout of spot welds on a hypothetical cross section, in this case, where $n_{critical}$ is equal to six.

When, $n_{critical} = 1$, the location of the spot weld will be on the center of the mold cross section polygon, $(x_c, y_c) = (x_{s1}, y_{s1})$. When the load acting on this spot weld is more than the failure load, the locations of the spot welds will be calculated with $n_{critical}$ as three spot welds. When, $n_{critical} = 3$, the location of the first spot weld will be on the center of mold cross section polygon $(x_c, y_c) = (x_{s1}, y_{s1})$. The location of the second, (x_{s2}, y_{s2}) and third, (x_{s3}, y_{s3}) spot weld will be the two farthest points on the offset curve of the mold cross section polygon. This is due to the need to have the locations of the spot welds in the mold cross section well distributed. In this case, the point that is farthest from the centroid will be the second spot weld, where: $\overline{(x_{s2}, y_{s2})(x_{s3}, y_{s3})} = d_{max}$. When, $n_{critical} = 4, 5$, the location of the first three spot welds will be same as in the previous case. The location of the fourth and fifth spot welds will be determined based on angle of $(x_{s1}, y_{s1}) (x_{s2}, y_{s2}) (x_{s3}, y_{s3})$ with respect to the center of the polygon cross section, (x_c, y_c) . The angle bisector will intersect the offset curve at (x_a, y_a) and (x_b, y_b) , where $a \equiv \overline{(x_a, y_a)(x_{s1}, y_{s1})}$ and $b \equiv \overline{(x_b, y_b)(x_{s1}, y_{s1})}$. If $a > b$, then $(x_a, y_a) = (x_{s4}, y_{s4})$, fourth spot weld and $(x_b, y_b) = (x_{s5}, y_{s5})$, fifth spot weld. Else, $(x_b, y_b) = (x_{s4}, y_{s4})$ and $(x_a, y_a) = (x_{s5}, y_{s5})$. Finally, when, $n_{critical} = 6$ to n , the location of first five spot welds will be the same as in figure. The location of the sixth and subsequent spot welds will depend on the region analysis of the previous spot welds. The regions will be determined based on the angle between the neighbor spot welds.

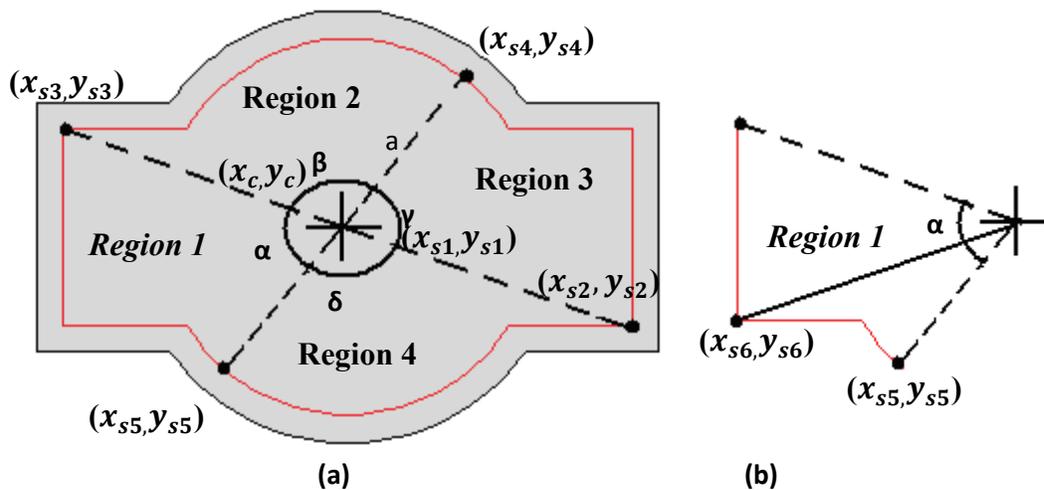


Figure 6 – Location of the spot welding when $n_{critical} = 6$ to n

To determine the location of sixth spot weld, the region with largest swept angle will be selected. Within that region the midpoint of the polygon section, M will be determined as the location of sixth spot weld. This region-based analysis will continue until the loading condition is satisfied. The minimum distance between two spot welds should be at least $2r$, where r is the radius of the smallest friction stir welding tool available in the machine tool library. When a particular mold cross section polygon does not have sufficient space to accommodate all the spot welds required to with stand the forces from FSW process, then FSW cannot be performed in that layer. This problem could occur at the peaks of tall thin structures, but will not be formally addressed in this paper.

Tool Path Planning for Friction Stir Welding

The aluminum plates are oriented, fixtured and clamped using adhesives and friction stir spot welding. The plates are then welded together using continuous friction stir welding process. The FSW process welds the two plates together which is the **additive** process then it is subsequently machined in a **subtractive** process for creating the final 3D shape of the mold tooling. The FSW path is generated such that it moves along the perimeter of the layer polygon so it creates seam-free laminated aluminum injection mold tooling. The FSW tool path on each layer will simply depend on the polygon profile on $slice_{n+1}$ as shown in the figure. This is because if the tool path is based on any other polygon profile then the FSW tool will affect the previously machined layer. An offset loop is generated at an offset distance of at least the radius of FSW tool.

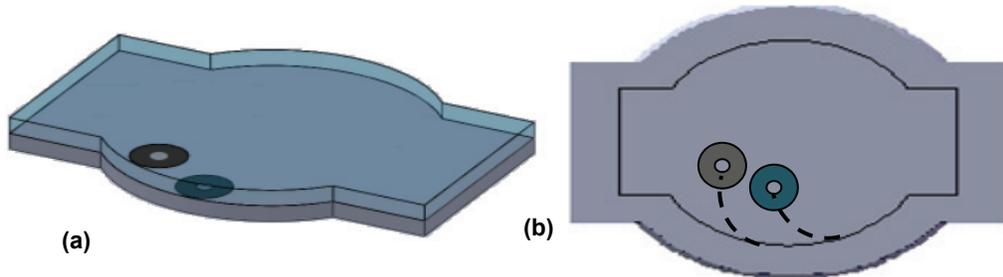


Figure 7 – (a) $layer_n$ of mold geometry (b) FSW tool path on $layer_n$ showing exit holes

The entry point for the FSW tool starts in an arbitrary point assumed to be (x, y_{min}) , the bottom most point of that particular cross section. The direction of the FSW tool will not affect the strength of the friction stir welding, therefore the tool will move either in clock wise or anti clockwise direction along the offset polygon to weld the plates together. The friction stir welding process will leave a hole at the exit point it is called *exit hole* so the exit point of the FSW cannot be same for all the layers (or at least cannot repeat in the same x-y location on the immediate next layer. Therefore the exit point of the subsequent layers will be offset from the entry points of the previous layers at least by the diameter of the FSW tool. In addition it is advantageous to move the exit hole toward the cross section interior, as shown in Figure 7, thereby burying the void inside the aluminum mold geometry.

The last step in process planning is the 3D CNC machining toolpath planning. This step is exceedingly straightforward and will not be presented in this paper. Essentially, each layer is face milled to a flat surface, then executed upon by waterline toolpaths using a flat and ball end mill for roughing and finishing, respectively.

Preliminary Results

Experiments with relatively thin aluminum layer bonding have been conducted in order to evaluate the possibility of using Friction Stir Welding as the bonding method for a rapid tooling system. A tool was created from H13 tool steel, based on the design of a Flared-Triflute developed by The

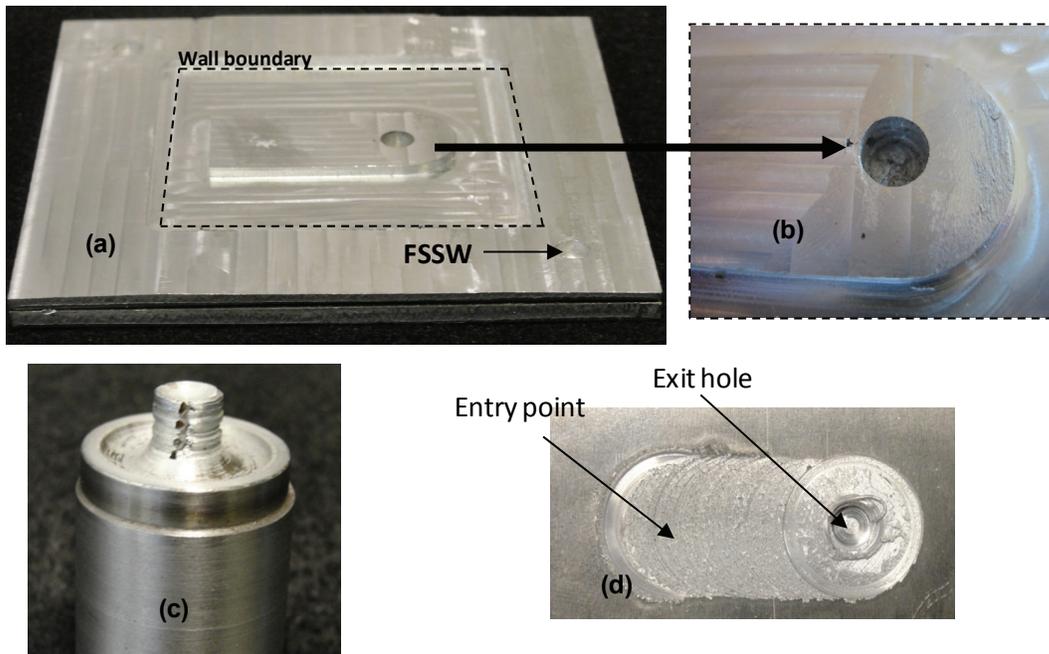


Figure 8 – Test sample (a) layer sample after all steps, (b) close up of cross section geometry and exit hole, (c) FSW tool geometry and (d) example FSW from entry to exit hole

Welding Institute (TWI), UK. The tool had a pin diameter and length of 6mm and 4.7mm, respectively, and a shoulder diameter of 18mm. Aluminum plates at 1/8" thick were bonded using Friction Stir Spot Welding and then continuous Friction Stir Welding. The plunge and retract federates were 7 and 11 inches per minute, while the continuous stirring was conducted at 1800rpm and 25 inches per minute. Lastly, the cross sectional geometry of the layer was machined using a face mill and flat-end mill. Images of the tooling, sample layers and a friction stir weld are shown in Figure 8.

Conclusion and Future Work

This work illustrates a new method for bonding aluminum layers for rapid tooling, which could enable high performing rapid tooling based on a hybrid approach. The work is a further step from a previously developed system called RPM, or *Rapid Pattern Manufacturing*. The RPM system was developed for the rapid construction of mainly wood patterns for steel casting sand-mold making. RPM automatically generates process plans from a CAD file alone, and then sequentially stacks, bonds and machines layers of wood to create very large patterns. In order to use aluminum as a possible material, enabling tooling such as injection molds, a new method for bonding layers needs to be developed. This work showed preliminary studies using a combination of industrial adhesives, Friction Stir Spot Welding and Friction Stir Welding. The system is intended to use adhesives to initially secure the aluminum plates for spot welding, which in turn, enables continuous friction stir welding of the tooling cross sectional contours. Once bonded, the RPM system using a 3-axis milling apparatus to create accurate 3D

contoured shapes. The future of this work is envisaged as seam-free, quasi monolithic aluminum tooling. The concept of *quasi-monolithic* is based on the idea that the friction stir welding on the cross sectional contours could be executed near the edge of each lamination; hence, the subsequent CNC machining would actually mill through this welded boundary. Viewed from above, the stack of aluminum plates created by the RPM system would appear to be one continuous aluminum “shell” surface (Figure 9). Within the tooling, one could bury all exit and entry holes from welding, the interlaminar spaces where adhesive remains, and perhaps even integrated cooling channels. Moreover, this approach would allow for extremely deep cavity machining of complex geometry with no collision conditions. Not only could tooling be created in a rapid fashion, but this process could enable revolutionary capabilities and performance, along with the accuracy of a CNC machined surface. The efficacy of this approach will require extensive continued testing and research to evaluate weld capabilities, strength, geometric limitations, etc.

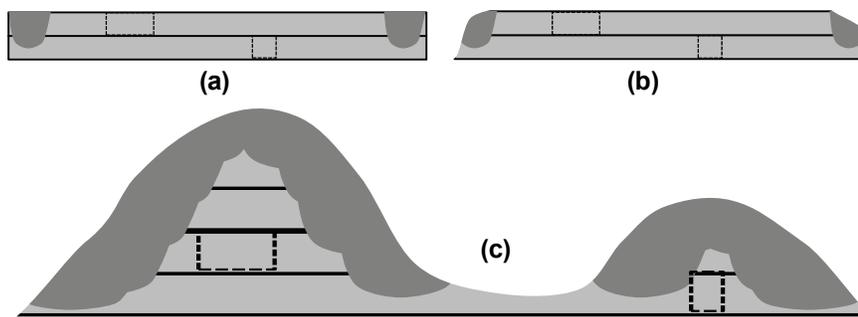


Figure 9 – Proposed Seam Free Laminated tooling (a) two layers Friction Stir Welded, (b) layers after machining through profile welds, and (c) illustration of a seam-free tooling stack up, with laminations, exit holes, cooling channels, etc contained within the tool surface

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