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Process planning for rapid manufacturing of plastic injection mold for short run production

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**Process planning for rapid manufacturing of plastic injection mold for
short run production**

by

Rajesh Kumar Karthikeyan

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Industrial Engineering

Program of Study Committee:
Matthew Frank, Major Professor
Frank Peters
Scott Chumbley

Iowa State University

Ames, Iowa

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ABSTRACT

This thesis presents a process planning methodology for a rapid injection mold tool manufacturing system that involves additive and subtractive techniques, whereby slabs are sequentially bonded and milled using layered tool paths. Mold tools are grown in a bottom up fashion, eliminating the need for multi-axis machining operations (beyond three axes) and allowing small features in deep cavities. In this 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 initially secure the slab, then continuous friction stir welding of layer perimeters that are sequentially machined in a layer wise process. The original research is presented as a journal article. This research includes three areas of interest that will enable highly automated process planning.

The first research area focuses on determining the process plan for applying adhesives on the laminated plates that will be sufficient to resist the forces acting on the plate due to subsequent friction stir spot welding. The use of fixtures and clamps for machining in rapid manufacturing create a potential problem for collision of the tool/spindle and the workpiece setup. Therefore, the process proposed in this thesis uses a combination of industrial adhesives and friction stir spot welding to secure the aluminum plates for machining.

The second area focuses on determining the number, location and sequence of friction stir spot welds sufficient to secure the plate prior to continuous friction stir welding. The use of

adhesive alone is assumed to be not sufficient to withstand the high forces involved in the friction stir welding process. Therefore, there is need to friction stir spot weld the plates to hold them against the previously formed stack. The location and the number depend on the geometry of that particular layer.

The final research area focuses on creating a toolpath planning method for the friction stir welding and CNC machining of each laminated plate. The FSW toolpath is generated based on a predetermined offset distance from the boundary of the polygon representing each cross sectional slice of the mold, while the CNC machining uses a basic waterline toolpath strategy.

The impact of this research is that it will provide a completely automated process planning approach for rapid tool manufacturing that is currently not possible using existing additive- or subtractive- only approaches.

CHAPTER 1: GENERAL INTRODUCTION

This thesis proposes a new additive/subtractive process for the rapid manufacturing of aluminum injection mold tooling. This chapter presents the background and motivation for this new rapid tool manufacturing process and the research objectives to overcome the challenges in achieving completely automated planning of the process.

1.1 Background

In the past few decades there has been a revolution in the field of design and manufacturing. The advent of rapid prototyping has enabled engineers to create parts directly from the CAD model to test its form, fit and function. The advantage of rapid prototyping systems is that they do not require any part specific tooling and process planning is simple so it requires little or no human intervention. Whatever the complexity of the part, most RP systems build the part layer-by-layer.

Most of the rapid prototyping processes have been developed on the idea of *additive* manufacturing; the main difference among these RP processes are in the way layers are built and the materials used to create parts. For example, some of the processes such as Fused Deposition Modeling (FDM) and Selective Layer Sintering (SLS) create parts by melting, sintering or softening of materials, whereas the Stereolithography (SLA) process creates parts by curing of photopolymers. In the case of lamination systems such as Laminated Object Manufacturing (LOM) thin layers of materials are cut to desired shape and joined together to create parts. These RP systems create parts using materials such as

plastics, ceramics and few limited metals. This limitation in materials usually keeps RP technology from being used for the manufacturing of actual functional parts [Gibson (2005)].

Although most rapid prototyping systems are appropriate for testing form, fit and function, they usually require a long processing times; 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 the best choice because of the cost and processing time for each part. The availability of rapid prototyping systems in the areas of mass production is very 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 and shape can be easily manufactured using injection molding. The injection molding process requires the use of an injection molding machine, raw plastic material, and a mold. The plastic is melted in the injection molding machine and then injected into the mold, where it cools and solidifies into the final part. The complexity of the part manufactured in this process is limited mainly to mold manufacturability [Dominick et al. (2000)].

The plastic injection molding process uses mold tooling, usually made of steel or aluminum. The mold component consists of two halves. Both halves are attached to the plastic injection molding machine, the rear half is movable so that the mold can be opened and closed along the mold's parting line. The mold tooling consists of a mold core and

mold cavity. When the mold is closed, the space between the mold core and the mold cavity forms the part cavity, which will be filled with molten plastic to create the desired part. When there is need to make several identical parts multiple-cavity molds can be used.
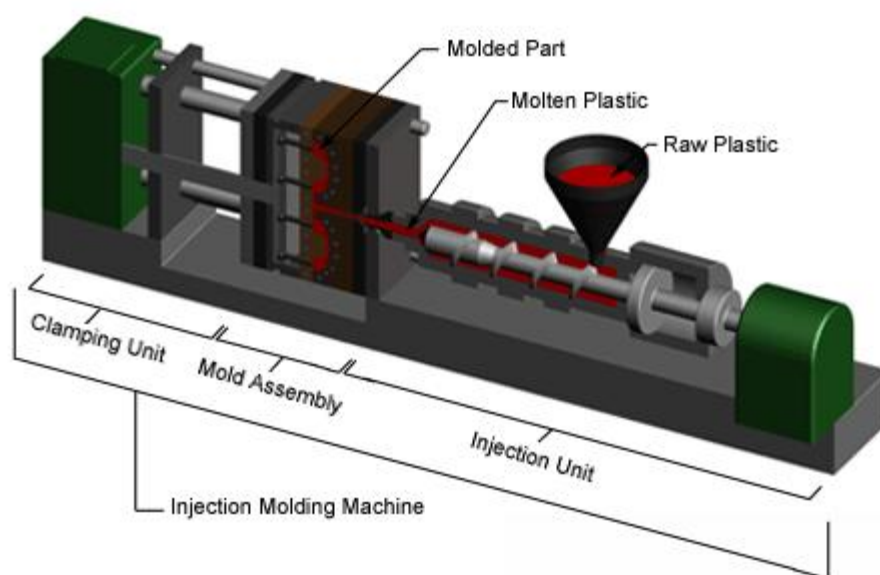
Figure 1.1- Plastic injection molding process overview [www.custompartnet.com (2009)]

The mold core and mold cavity are each mounted to the mold base, which is then fixed to the platens inside the injection molding machine. The front half of the mold base includes a support plate, to which the mold cavity is attached. This half also consists of a sprue bushing into which the material will flow from the nozzle. The rear half of the mold base includes the ejection system to which the mold core is attached, and a support plate.
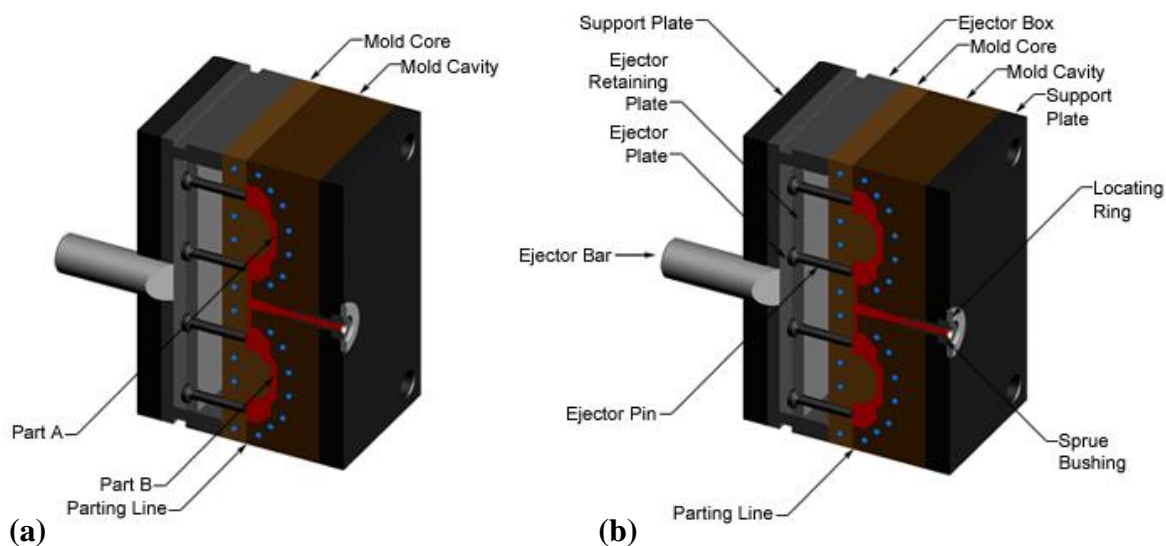
Figure 1.2- (a) Mold overview (b) Mold base (c) Sample aluminum mold created from machining process [www.custompartnet.com (2009)]

When the clamping unit separates the mold halves, the ejector bar actuates the ejection system. The ejector bar pushes the ejector plate forward inside the ejector box, which in turn pushes the ejector pins into the molded part. The ejector pins push the solidified part out of the open mold cavity. The mold is closed within the platen arrangement and clamped using necessary force to hold the mold shut during the plastic injection cycle, thus preventing plastic leakage over the face of the mold. Overall, the plastic injection molding

process has several advantages for mass production of plastic parts at very high design flexibility [Dominick et al. (2000); Dym (1987); www.custompartnet.com (2009)].

Even though the injection molding process enables the production of quality plastic parts at high, repeatable production rates, there needs to be a strong justification to select this process because of high cost and time involved in creating the tooling. Often times, it cannot be justified especially in the market of *mass customization*.

1.2 Motivation

Despite several advantages of plastic injection molding, the process of manufacturing an injection mold tool is still 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. Traditional injection molding is less expensive for manufacturing polymer products in high quantities; in contrast, RP processes are faster and less expensive when producing relatively small quantities of parts. However, there exists a niche area where neither the use of injection molding or traditional rapid prototyping process can be justified. This thesis proposes a technology to fill this gap by providing rapid tooling for injection molding.

Rapid tooling (RT) techniques, an extension of rapid prototyping processes, allows the manufacture of production tools rather than the actual part itself, offering a high potential for a faster response to market needs [Karapatis et al. (1998)]. The advantages of RT is that

apart from reducing the time taken to create the tool, the entire process itself is a turnkey operation which means that the entire tool can be created with little to no human intervention.
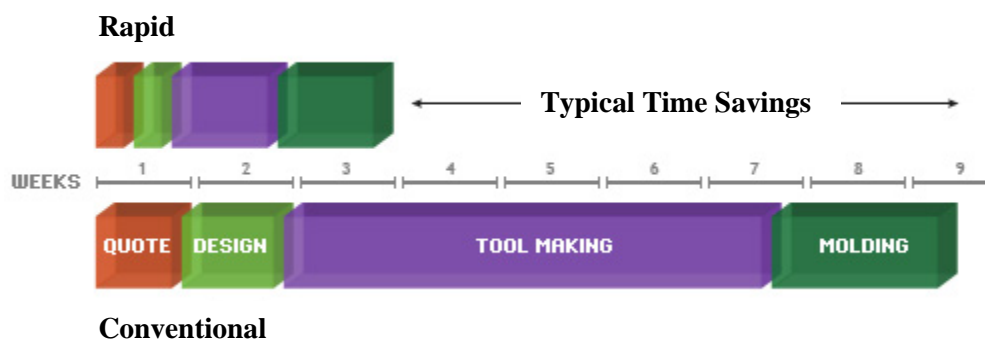
Figure 1.3- Rapid vs conventional injection molding process [www.protomold.com (2010)]

There are several existing choices for rapid tooling available from purely additive, purely subtractive and hybrid systems. The hybrid approaches using additive and subtractive processes are starting to evolve into rapid manufacturing techniques for mass customized products. Rapid tool manufacturing is not a new concept, research and development has been conducted in this area since 1980's. However most of these processes failed to offer completely automated process planning for the manufacturing of tools, which is the most critical criterion for any rapid manufacturing system.

There is a strong motivation to implement rapid manufacturing technology for the manufacture of aluminum injection mold tooling with completely automated process planning solution. A hybrid Rapid Pattern Manufacturing system (RPM) previously

developed in the Rapid Manufacturing and Prototyping Lab at Iowa State University has been demonstrated for large wooden casting patterns [Luo (2009)]. The process combines depositing thick slabs 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.

Figure 1.4- Pattern created from the Rapid Pattern Manufacturing process [Luo (2009)]

The proposed process is an extension of the RPM process where aluminum mold tooling is created using a new layer bonding method, a unique combination of industrial adhesives and friction stir welding processes. The advantage of this system is that the patterns are built in a 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. The fundamental additive and subtractive nature of the process is illustrated in Figure 1.5, whereby the aluminum plates are bonded using industrial adhesives, friction stir spot welding and continuous friction stir

welding, and then the bonded plates are subsequently machined using a simple 3-axis CNC machine.

Initial slab   **Adhesive applied**   **New layer deposited**

Friction stir welding plates   **CNC machining of 3D layer shape**
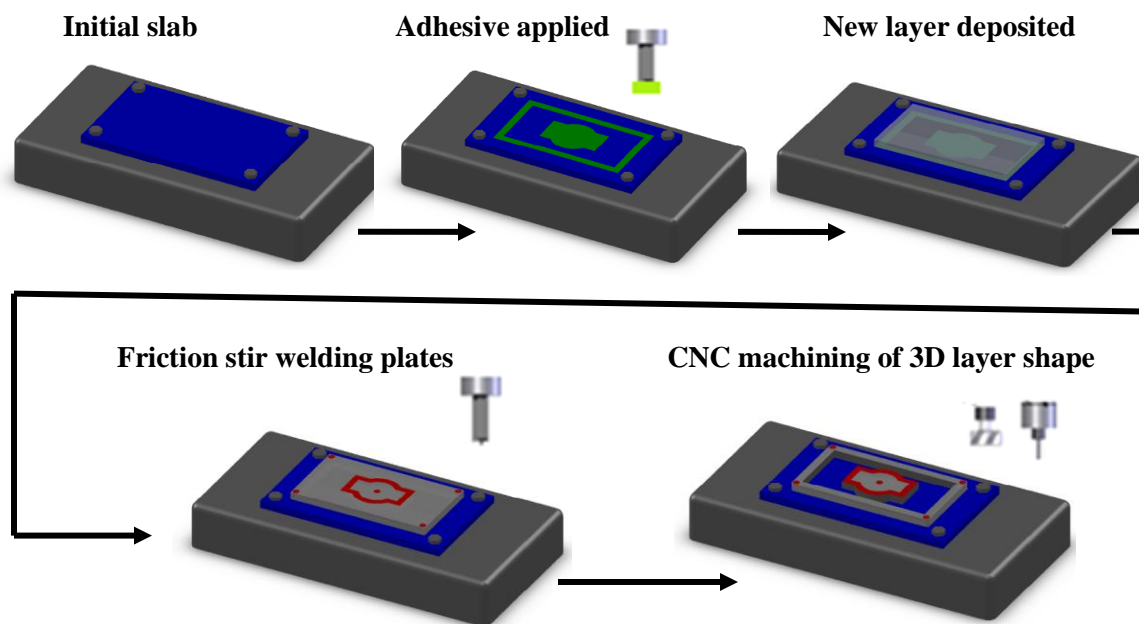
Figure 1.5- Fundamental process steps of the proposed methodology using friction stir welding for layer bonding (additive) and CNC machining (subtractive) for 3D layer shaping

1.3 Research Objectives

The primary objective of this research is to develop an automated process planning method for the rapid manufacturing of injection mold tooling for short run production. To achieve this objective the following sub-objectives are presented.

The first sub-objective is to determine the process plan for applying adhesives on the laminated plates that will be sufficient to resist the forces acting on the plate due to subsequent friction stir spot welding. The use of fixtures and clamps for machining in rapid

manufacturing create a potential problem for collision of the tool/spindle and the workpiece setup. Therefore, the process proposed in this thesis uses a combination of industrial adhesives and friction stir spot welding to secure the aluminum plates for machining. The adhesive in this process is applied on the boundary wall, a flask enclosing the mold tool. Therefore, based on adhesive properties, the *dimension of the boundary wall* is determined such that the maximum shear stress acting on the adhesives is less than its shear strength.

The second sub-objective is to determine the *number*, *location* and *sequence* of friction stir spot welds. The use of adhesive alone is assumed to be not sufficient to withstand the high forces involved in the friction stir welding process. It is evident that the load distribution on the spot weld will not be uniform and it could cause the spot weld to fail. Therefore, the number, location and sequence of spot welds will be determined such that load acting on these spot welds is less than the failure load. The location and the number depend on the geometry of that particular layer.

The third sub-objective is to create a toolpath planning method for the friction stir welding and CNC machining of each laminated plate. The toolpath of FSW will depend on the polygon representing each cross sectional slice of the mold and the diameter of the FSW tool. An offset algorithm will be used to generate toolpaths based on a pre-determined offset distance from the boundary of the polygon, while the CNC machining uses a basic waterline toolpath strategy.

1.4 Thesis Organization

The remainder of the thesis is organized as follows: A detailed review of literature related to rapid prototyping and manufacturing is presented in Chapter 2. This review demonstrates the need for a new process planning for a rapid tool manufacturing system. The original work providing solution methodology to research problems in automating the process plan is presented in journal paper format in Chapter 3. The final chapter of this thesis provides general conclusions and future research directions of the presented work.

CHAPTER 2: LITERATURE REVIEW

In this chapter, research in the area of rapid prototyping applications, laminated tooling in mold and pattern manufacturing and friction stir welding are reviewed.

2.1 Rapid Prototyping and Applications

In the past few decades, rapid prototyping and manufacturing systems have made a great revolution in the field of product design and manufacturing, where the physical models can be directly created from the CAD model. Rapid prototyping is mostly an additive manufacturing process in which the RP systems reads CAD data and creates successive layers of liquid, powder or sheet material and in this way the entire model is built with many layers in it.

Different types of rapid prototyping and manufacturing methodologies have been developed. As most are additive processes, the main differences in these RP systems are in the way layers are created and the materials used to create the part.

Stereolithography (SLA), patented in 1986 is an early technology which started the rapid prototyping revolution [Jacobs (1992)]. In this process, solid models are created from liquid photopolymer. The part is created on an elevator platform that is submerged in a vat of UV curable photopolymer resin. A low power UV laser light is focused at the liquid surface and the laser scans the part cross-section on the liquid resin. The resin exposed to the UV light will be partially cured to create the layer. The elevator is lowered into the vat

to create the next layer. The process will be repeated until all the layers are cured to create the final part. The partially cured part is then removed from the elevator and is again cured under UV light to solidify any uncured resin.

Fused Deposition Modeling (FDM) is another additive based RP technology in which the models are created from thermoplastic materials [Walters (1992)]. In this process filaments of heated thermoplastic are extruded from the nozzle that moves in the x-y plane. The extruded material is deposited on a z platform layer by layer to create the part.

In Laminated Object Manufacturing (LOM) layers of heat sensitive adhesive coated sheet material are bonded together to create the part [Faygin et al. (1991)]. In this process, a new layer is glued to the previous layer by a hot roller and a laser is used to cut the outline of the part in each sheet layer. Parts are created by stacking, cutting and bonding of layers of adhesive coated sheet material.

Selective Laser Sintering (SLS) [Deckard et al. (1987)] was developed by The University of Texas at Austin and DTM Corporation. This process is very similar to SLA but in this case, powders of thermoplastic polymers, elastomers and metals are used instead of liquid photopolymer. A high power laser is used to selectively fuse powdered materials. The laser scans the cross-section of the layer. When a layer is created the bed containing the power is lowered to create the next layer, and the process is repeated until all the layers are created.

Three-Dimensional printing (3DP) is a powder based technology developed by the Massachusetts Institute of Technology (MIT) [Sachs et al. (1990)]. In this process parts are built by repetitively laying down a thin layer of powered material. An ink-jet printing head selectively deposits adhesive binder to fuse the powder together in desired areas. The platform containing the part is lowered and a new layer of powder is deposited, leveled and bonded. Unbonded powder will act as passive support structures. The process creates a green part, which can be infiltrated with epoxy or wax to improve its strength properties [Kawola (2003)]. Metal parts formed by this process using metal powders can be infiltrated with low melting point alloy; which can enable the creation of plastic injection molds [Michaels et al. (1992)].

These RP systems are great for testing the form, fit and some basic function of the design; however most are limited in terms of part accuracy, size and choice of materials. Hybrid RP processes combine the advantage of conventional CNC machining and a layered manufacturing process in order to find the solution to these problems [Hur et al. (2002)].
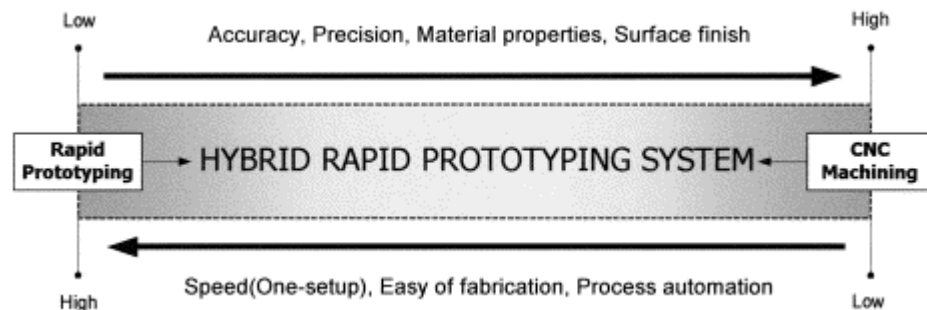
Figure 2.1- Positions of RP and CNC processes in terms of their characteristics [Hur et al. (2002)]

Shape Deposition Manufacturing (SDM) [Merz (1994); Ramaswami (1997)] is a hybrid process developed at Carnegie Mellon University that employs an additive process to deposit the part or support material using micro-casting. The material is then machined to get desired accuracy and finish. The basic methodology is to deposit individual segments of part and support material as near net shapes, and then the deposited material is machined to net shape before depositing and shaping additional material. The overall finish and part accuracy of the part is better compared to layer by layer deposition methods only. However, material deposition in SDM is a time consuming process and only materials that can be easily deposited can be used for SDM [Kelkar et al. (2008)].

Solvent welding freeform fabrication technique (SWIFT) creates short run tooling based on solvent welding and CNC machining [Cormier et al. (2001)]. This process uses solvent weldable thermoplastic materials that are available in sheet form. 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. In this process, a laser is used to cut part slices from the stock materials such

as metals and ceramics. These slices are then assembled together using a selective area gripper [Wyatt et al. (1996)]

Song et al. (2002) presented a direct approach for freeform fabrication of metallic prototypes by 3D welding and milling. The principle methodology of this process is based on layer based deposition of molten wire using GMAW which is subsequently milled using CNC machining.

Research in hybrid systems has been conducted in order to overcome the challenges of conventional additive RP systems. However due to constraints in materials used, build time, part precision etc., the current rapid prototyping and manufacturing technology cannot be effectively used for rapid tool manufacturing for plastic injection molds.

2.2 Laminated Tooling in Mold and Pattern Manufacturing

Rapid Tooling is an extension of rapid prototyping which is used to prototype mold tooling that can be used for early production. Rapid tooling techniques (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 [Karapatis et al. (1998)].

Tooling is often classified as *hard* and *soft* tooling and again as *direct* and *indirect* tooling. Tooling that is created for short run productions is often called soft tooling, usually made of materials such as epoxy resins or low melting point alloys. Tooling that is made for long run production use materials such as tool steel and are classified as hard tooling. In direct

tooling, the tool is created directly form a RP process, whereas in indirect tooling, only the master is created from the RP process and the moulds will be created from this master [Chua et al. (1999)].

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 is subsequently cut with a laser. 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.
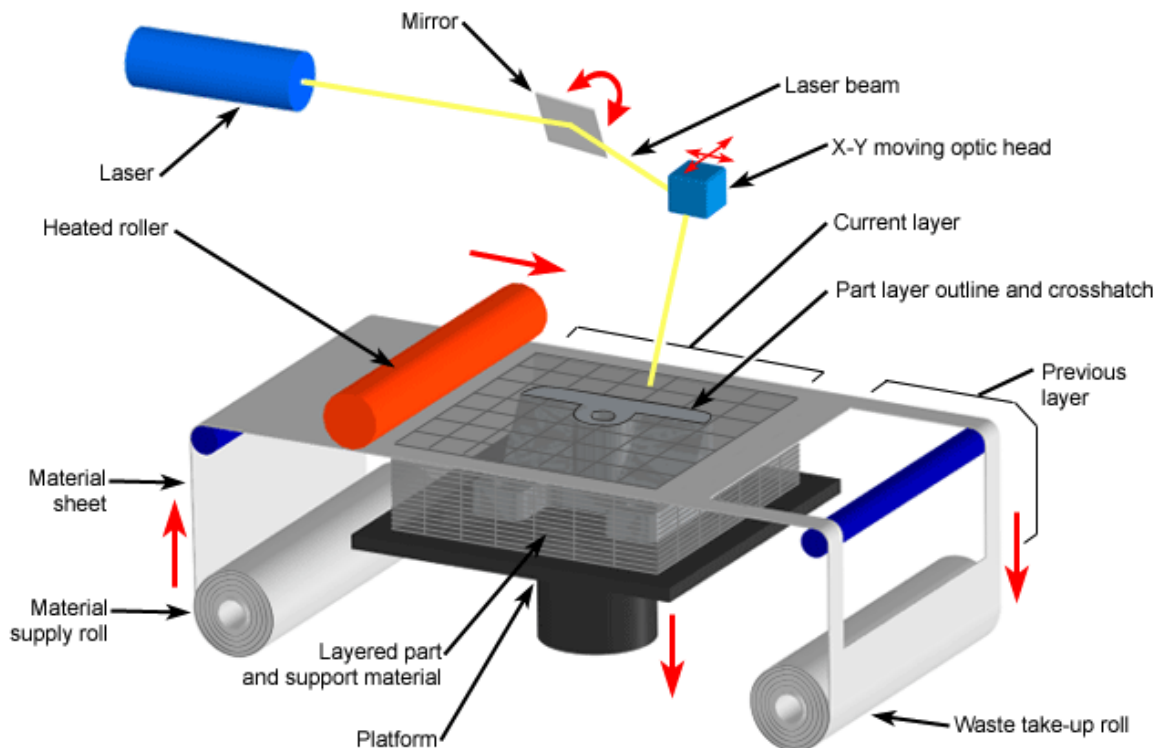
Figure 2.2- Laminated Object Manufacturing [www.custompartnet.com (2009)]

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 laser, stacked horizontally and joined together by using mechanical fasteners [Nakagawa (1980)].

Walczyk and Hardt (1994, 1998) proposed a Profiled Edge Lamination (PEL) method to create tooling for manufacturing processes such as sheet metal forming, thermoforming and injection molding. In this process thick laminates are profiled using abrasive water jet or laser provided by a CNC cutting trajectory. The array of cut PEL's are then clamped together vertically by diffusion brazing to form a rigid tool.

Himmer et al. (1999) described a manufacturing process to produce injection molding tools by lamination of aluminum alloy sheets. This process involves laser beam cutting of 2 mm flux coated aluminum alloy sheets into 2D profiles. These sheets are then assembled and bonded together using bolted joints followed by finishing process using high speed milling operation.

Soar and Dickens (1996, 2001) proposed a method for creating unbonded laminated tooling for pressure die casting. The tools in this process are created by clamping the laser cut profiles of H13 tool steel sheet using studs. The sections and internal features created in this laminated tool can be modified by exchange of laminates giving an advantage for multiple design iterations. Although this process can create low cost, flexible and robust

tooling, there is a constraint in choosing the thickness of the sheet and many issues are encountered with respect to the flatness of the sheet material.

Bryden and Pashby (2001) used hot platen brazing as the bonding method to produce laminated steel tooling. In this process profile cut steel sheets are sequentially joined using high strength brazing. Braze such as silver based alloys or nickel based alloys are supplied in the form of paste or evenly sprayed on the laminates which is then followed by a hot platen brazing process comprising heating and compressing of the joint between two platens.

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 laser or EDM, 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 has been the use of mechanical fasteners such as bolts and rivets to join the laminates together [Nakagawa (1980); Dickens (1996); Glozer et al. (1993); Walczyk and Hardt (1998)]. 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 2 mm 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 process.

2.3 Friction Stir Welding

Friction stir welding (FSW) is a solid-state joining process invented at The Welding Institute (TWI) in 1991 [Mishra et al. (2005)]. A non-consumable rotating tool with a specially designed pin and shoulder is inserted into sheets or plates to be joined and traversed along the line of joint. Frictional heating is produced from rubbing of the rotating shoulder on the workpiece, while the rotating pin causes plastic deformation of workpiece material. The heating is accomplished by friction between the tool and the workpiece and plastic deformation of the workpiece. The localized heating softens the material around the pin and 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 [Mishra et al. (2005); Adamowski et al. (2007)]. This process allows one to continuously weld a wide range metals such as aluminum, lead, magnesium, steel, titanium, zinc, copper etc. [Wayne et al. (2003)].

(a)

(b)

(c)
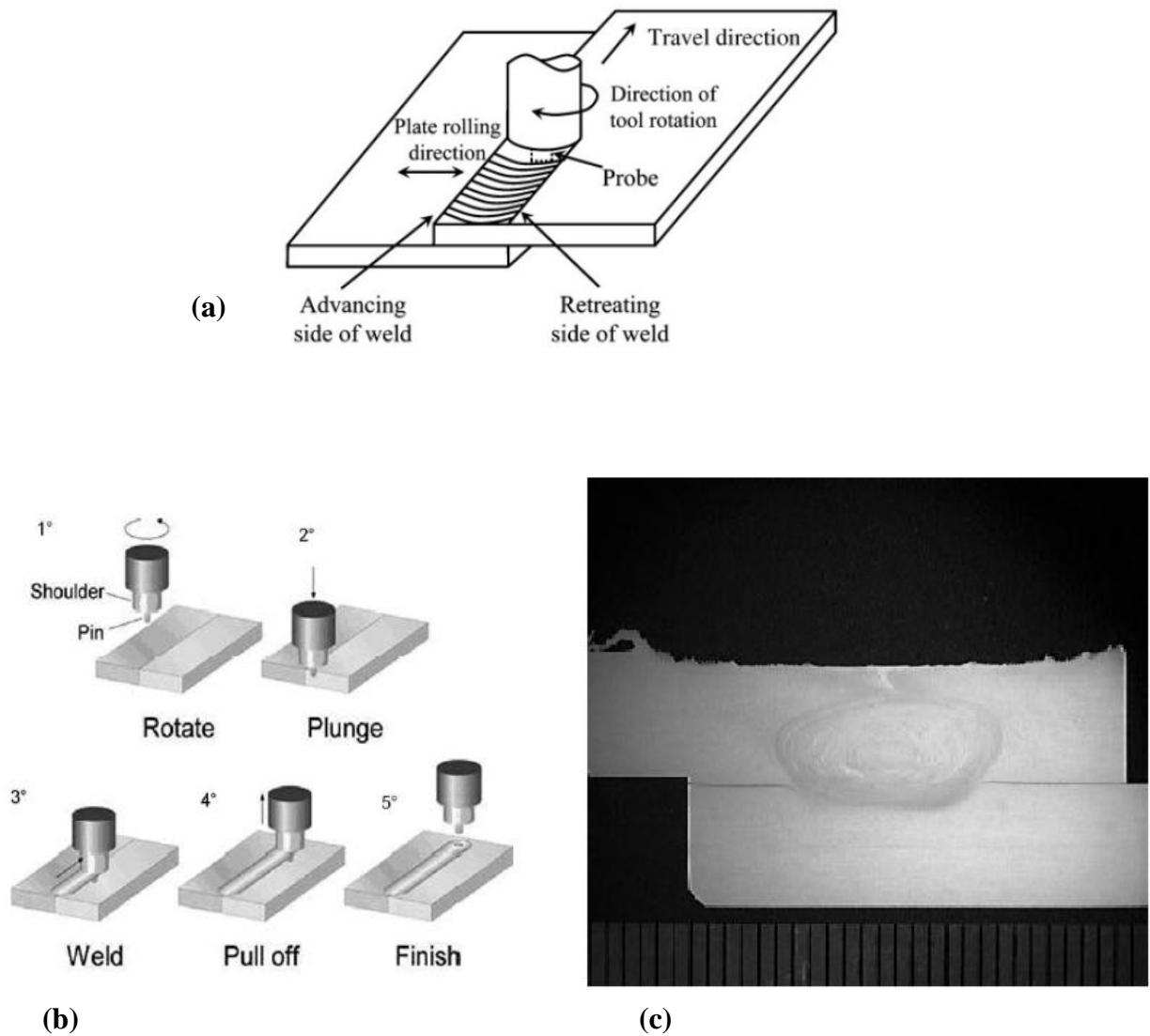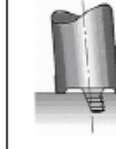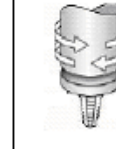
Figure 2.3- (a) Friction stir lap welding [Cantin et al. (2005)] (b) Schematic representation of FSW process [Adamowski et al. (2007)] (c) Metallurgical section of a Re-stir™ lap weld made with an A-skew™ probe in combination with a skew motion [Wayne et al. (2003)]

One of the main advantages of friction stir welding over fusion welding process is that it can be easily automated on a simple milling machine at lower set up costs. However, friction stir welding is a complex process; there are several factors and parameters that will

affect the strength and quality of the weld. Some of the most critical factors are the tool design, plunge depth, welding speed and tool rotational speed.

Tool design has a major influence on the uniformity of the weld. The flow of material during the welding process mainly depends on the geometry of the tool pin and shoulder, therefore selecting the right tool geometry is a critical factor in achieving a good quality weld. Several tool designs have been proposed by researchers; a list of tools designed at the welding institute (TWI) is shown in Tale 2.1.

Table 2.1- A selection of tools designed at TWI [Nandan et al. (2008)]

Tool	Cylindrical	Whorl™	MX triflute™	Flared triflute™	A-skew™	Re-stir™
Schematics						
Tool pin shape	Cylindrical with threads	Tapered with threads	Threaded, tapered with three flutes	Tri-flute with flute ends flared out	Inclined cylindrical with threads	Tapered with threads
Ratio of pin volume to cylindrical pin volume	1	0.4	0.3	0.3	1	0.4
Swept volume to pin volume ratio	1.1	1.8	2.6	2.6	depends on pin angle	1.8
Rotary reversal	No	No	No	No	No	Yes
Application	Butt welding; fails in lap welding	Butt welding with lower welding torque	Butt welding with further lower welding torque	Lap welding with lower thinning of upper plate	Lap welding with lower thinning of upper plate	When minimum asymmetry in weld property is desired

The plunge depth is the depth to which the shoulder of the tool sinks into the material; it is a critical parameter for ensuring weld quality. The plunge depth needs to be correctly

determined to ensure that the tool completely penetrates into the plate. Welding speed and tool rotational speed has a considerable importance in attaining the peak temperature to soften the material. If the rotational speed is not sufficient enough to generate frictional heat to plasticize the material then the metal in the weld will not diffuse and recrystallize, which will result in holes in the weld. This hole is called a *worm hole*, the void will exist completely below the weld surface along the weld line and this void will severely weaken the integrity of the weld [Fleming et al. (2008)]. On the other hand if the rotational speed is high and the weld speed is too small, then it will generate excessive frictional heat which will create fluidification cracks in the weld [Zhi-Hong et al. (2004)]. Therefore finding the proper parameter value for the rotational speed and the weld speed is very crucial for a good quality weld.

Although several researchers have conducted experimental studies to determine the relation between these factors to achieve good welds, the parameters depend on the material properties, thickness of sheet and the machine used to create the friction stir weld. Therefore there is strong need to determine the optimum welding parameters and appropriate tool design for this rapid tool manufacturing process.

Friction stir welding has several advantages when compared to fusion welding process. FSW does not require any filler for welding purposes and also distortion of workpiece is very much lower than fusion welding giving good dimensional stability and repeatable metallurgical properties [Mishra et al. (2005)].

Friction stir spot welding (FSSW) is a variant to the continuous friction stir welding process. FSSW is very similar to friction stir welding, in this process a rotating tool with a probe pin is simply plunged into the plate. The rotating tool generates sufficient frictional heat to soften the material and create a bond between the upper and lower sheets as shown in the Figure 2.4. Similar to the friction stir welding process, the weld quality of friction stir spot welding also depends on various process parameters.

Plunging   **Stirring**   **Drawing out**
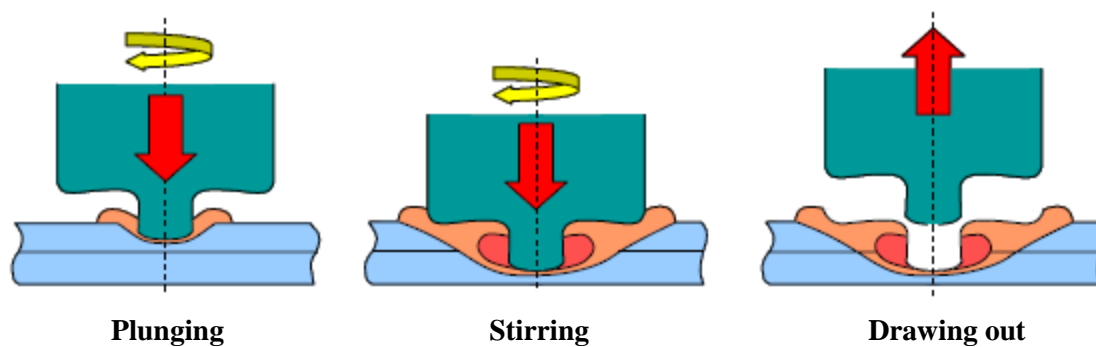
Figure 2.4- Visual schematic of the three step friction spot welding process [Hovanski et al. (2007)]

CHAPTER 3:PROCESS PLANNING FOR RAPID MANUFACTURING OF PLASTIC INJECTION MOLD FOR SHORT RUN PRODUCTION

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Abstract

Purpose – The purpose of this paper is to present a new process planning method for the rapid manufacturing of plastic injection mold tooling. The proposed process is intended to automatically create aluminum mold tooling for short run production and prototyping.

Design/methodology/approach – This paper proposes a new process methodology for the rapid manufacturing of injection mold tooling using a unique combination of adhesives and friction stir spot welding for sacrificial supports, friction stir welding for layer addition and then CNC machining for 3D shaping.

Findings – Algorithms to determine boundary wall dimension, number, location and sequence of friction stir spot welds, and tool path planning for friction stir welding and CNC machining have been presented. The proposed process with the aid of these algorithms will provide a complete automated process planning solution compared to the previous processes available in the literature.

Originality/value – A new approach of additive and subtractive manufacturing process has been presented for layer based manufacturing of seam-free aluminum injection mold tooling.

Keywords – Rapid Manufacturing, Rapid Tooling, Plastic injection molds, Friction Stir Welding, Process planning

Paper Type – Research paper

3.1 Introduction

In the past few decades there has been a revolution in the field of design and manufacturing. The advent of rapid prototyping has enabled engineers to create parts directly from CAD model in order to test its form, fit and/or function. The advantage of rapid prototyping systems is that they do not require any part-specific tooling and process planning is simple so it requires little to no human intervention. Whatever the complexity of the part, RP systems build the part layer-by-layer.

Most rapid prototyping systems are appropriate for testing form, sometimes fit and rarely function; however, they most always require a long processing time. This last characteristic 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 the best choice because of the cost and processing time for each part. The availability of rapid prototyping systems in the areas of mass production is very 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.

Traditional injection molding is less expensive for manufacturing polymer products in high quantities whereas RP processes are generally faster and less expensive when producing relatively small quantities of parts. However, there exists a niche area where the use of either injection molding or rapid prototyping process cannot be justified. 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.

In this paper, a layer based additive and subtractive manufacturing process has been proposed which can create aluminum injection mold tooling in a very short lead time compared to convention mold tool manufacturing process.

A hybrid Rapid Pattern Manufacturing system (RPM) previously developed in the Rapid Manufacturing and Prototyping Lab at Iowa State University has been demonstrated for large wooden casting patterns [Luo (2009)]. 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 process proposed in this paper is an extension of the RPM process where aluminum mold tooling is created using a new layer bonding method, a unique combination of industrial adhesives and friction stir welding process. The advantage of this system is that the patterns are built in a 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.

The fundamental additive and subtractive nature of the process is illustrated in Figure 3.1 for simply two layers, whereby the aluminum plates are bonded together by a combination of structural adhesives, friction stir spot welding and continuous friction stir welding process. After lamination, the bonded plates are subsequently machined using a simple three axis milling process.

FSW Tool

(c) New layer of plate is deposited **(b) Cross sections are bonded using friction stir welding**
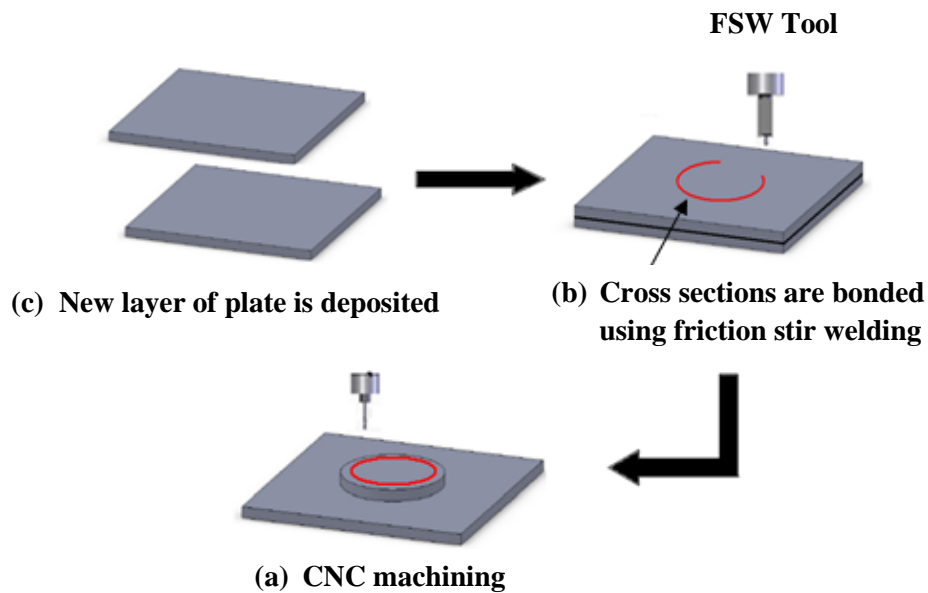
(a) CNC machining

Figure 3.1- Basic process steps using friction stir welding for layer bonding (additive) and CNC machining (subtractive) for 3D layer shaping

3.2 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) and 3-D Printing. These RP systems are highly automated

and simple to use; however most are limited in terms of part accuracy, size and choice of materials. A Hybrid RP process combines the advantage of conventional CNC machining process and the layered manufacturing process to find the solution to these problems [Zhu Hu et al. (2002)]. A few researchers have developed more hybrid systems that enable an expanded set of materials and higher accuracy.

Shape Deposition Manufacturing (SDM) is 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 desired accuracy and finish [Merz et al. (1994)]. Solvent welding freeform fabrication technique (SWIFT) creates short run tooling based on solvent welding and CNC machining. 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 [Cormier et al. (2001)]. 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 is used to cut the part slices from stock materials such as metals and ceramics. These slices are then assembled using a selective area gripper. However the part accuracy of these systems is low due to unpredictable shrinkage that can be as high as 12-18 percent [Wyatt et al. (1996); Yang et al. (2002)].

Rapid Tooling (RT) is an extension of rapid prototyping; methods used to prototype mold tooling that can be used for early or short run production. Rapid tooling techniques 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 [Karapatis et al. (1998)]. Laminated tooling is a direct rapid tooling process and is similar to laminated object manufacturing (LOM), In the LOM process, each layer of the part is formed from adhesive coated sheets of paper which are subsequently cut with a laser [Mueller et al. (1999)]. 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 laser, stacked horizontally and joined together by using mechanical fasteners [Nakagawa (1980)].

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 laser or EDM, 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 has been the use of mechanical fasteners such

as bolts and rivets to join the laminates together [Nakagawa (1980); Dickens (1996); Glozer et al. (1993); Walczyk and Hardt (1998)]. 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 increases 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 process uses a unique combination of industrial adhesives and friction stir welding process for bonding of plates.

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 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 [Mishra et al. (2005); Adamowski et al. (2007)].
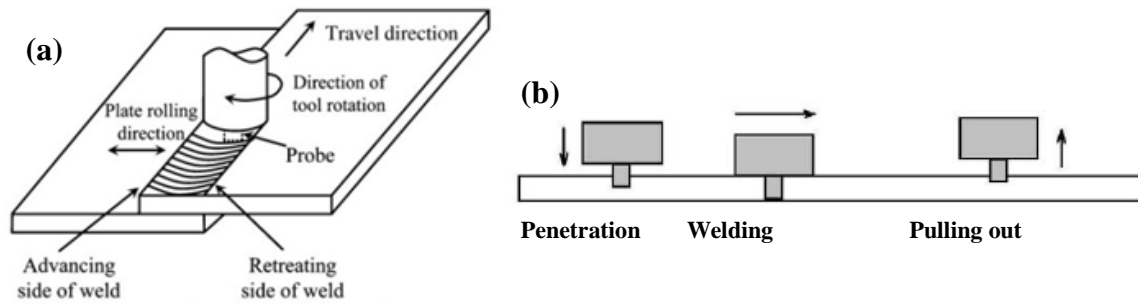
Figure 3.2- (a) Friction stir lap welding [Cantin et al. (2005)] (b) FSW process [Song et al. (2003)]

3.3 Overview of Process

The proposed rapid tool manufacturing system uses a hybrid manufacturing method, a combination of additive and subtractive processes to create plastic injection molds. The basic process involves adding a layer of plate metal, which is then subsequently machined to obtain the 3D shape of that particular layer. This process uses friction stir welding for layer bonding, which could enable the creation of seam-free laminated injection mold tooling. The fundamental additive and subtractive nature of the process is illustrated in Figure 3.1 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. However, the use of mechanical fixtures and clamps will create a potential problem for collision of the tool/spindle and the workpiece setup. Therefore, the proposed process uses a combination of industrial adhesives and friction stir spot welding to automatically secure the aluminum plates.

The adhesive is applied in the areas of the boundary wall cross section and mold cross section. The boundary wall is a flask around the mold which acts as a sacrificial support

structure that aids in orienting and fixturing of the deposited plate. The adhesively bonded plate is then spot welded using friction stir spot welding (FSSW). This is because the strength of the adhesives alone is assumed insufficient to 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 ensure that the plate is flat and parallel with the work table of the machine. The plate could optionally 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 would reduce the force acting on the mold workpiece and the machine table from the friction stir spot welding and friction stir welding processes [Khaled (2005)]. 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 flat- and ball- 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. Finally after creating the mold tool, the boundary wall support structures would simply be removed by machining/cutting. It should be noted that female mold tooling, having a boundary region already, would not necessarily require the boundary wall added to the

CAD model. To illustrate the step by step process more clearly, Figure 3.3 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.

Initial slab

Adhesive applied

New layer deposited

Friction stir spot welding

Friction stir welding of cross section

CNC machining of 3D layer shape

…Adhesive applied for next layer…

…New layer…

Complete build

Tooling with boundary wall removed
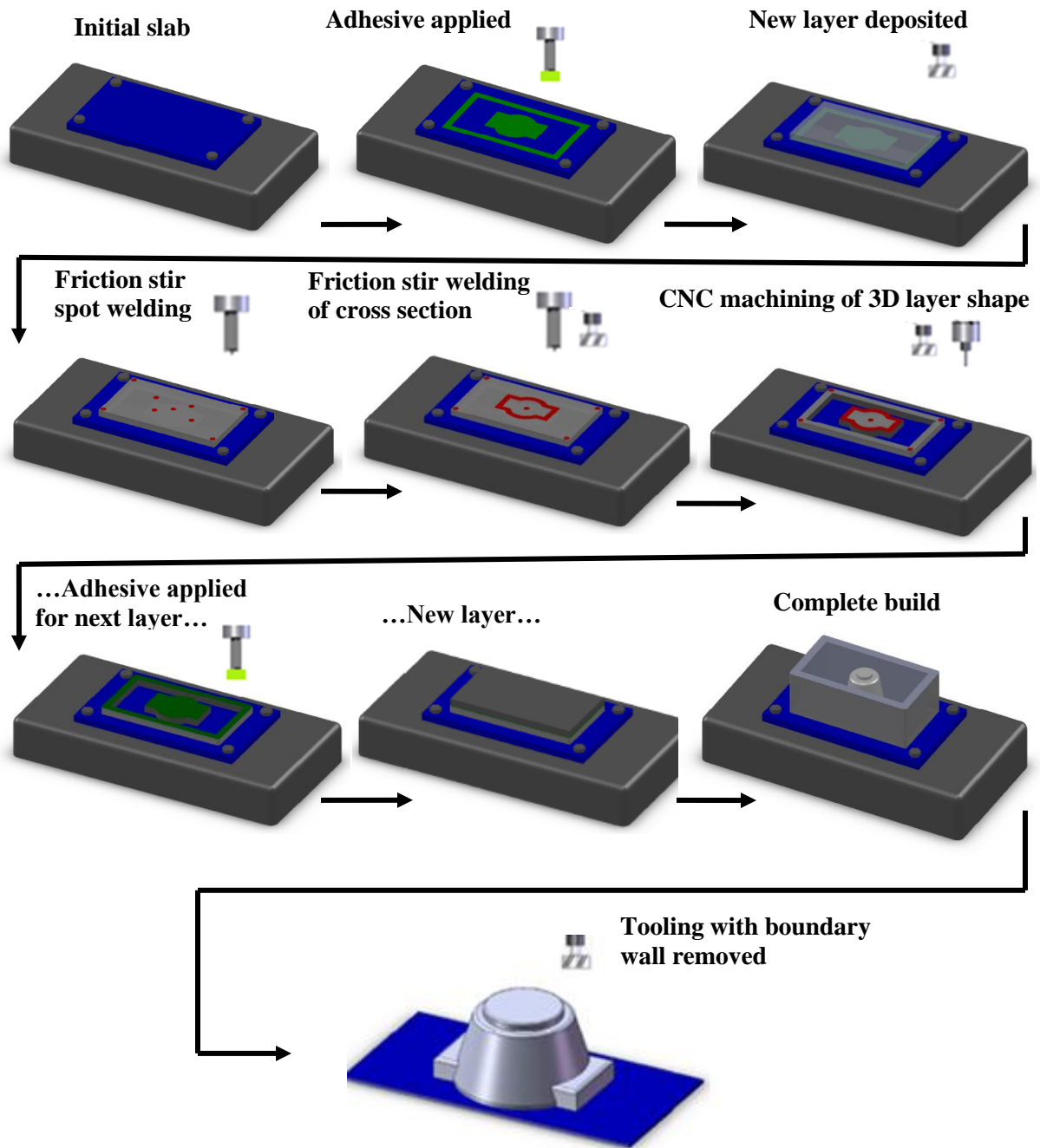
Figure 3.3- Detailed process steps for the proposed rapid tooling system

3.4 Process Planning Method

A critical characteristic for any rapid prototyping and manufacturing system is to have completely automated process planning. That is, the process must be able to execute directly 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
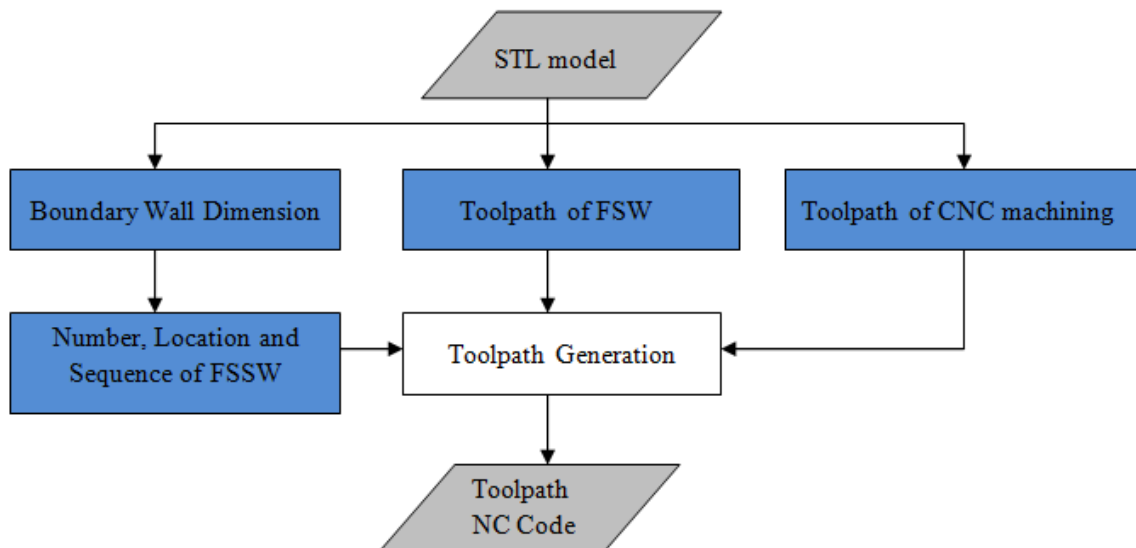
Figure 3.4 - Process planning operation in RMPIM process

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

3.4.1 Determining the Boundary Wall Dimension

The aluminum plates that are added layer by layer to create the tooling needs to be oriented and clamped together for friction stir welding and subsequent machining process. Initially, an adhesive will hold the plates together and be able withstand the forces from the subsequent FSSW process without the shearing of plates.
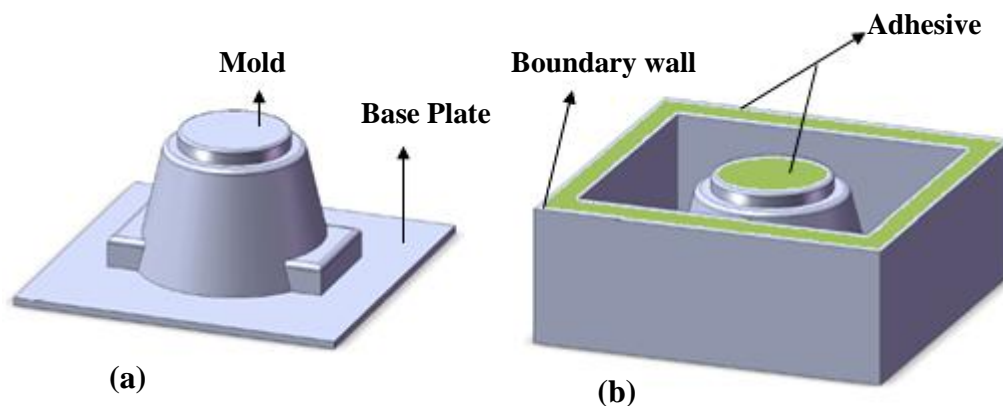
Figure 3.5- (a) Mold geometry (b) Mold with boundary wall enclosed

The intent is to secure the plate with enough adhesive strength to enable spot welding, which then enables continuous friction stir welding of the mold tool geometry within the plate. Obviously, if the load acting on the adhesive during spot welding is more than the strength of the adhesive then 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 based on size of the mold tool geometry, forces acting on the plate due to friction stir spot welding

process, mechanical properties of the adhesive used and the boundary wall clearance. The boundary wall clearance is the required space between the boundary wall and mold geometry. The dimension of the boundary wall is determined such that the adhesive applied on the boundary wall is sufficient enough to with stand the FSSW force without the shearing of plates.
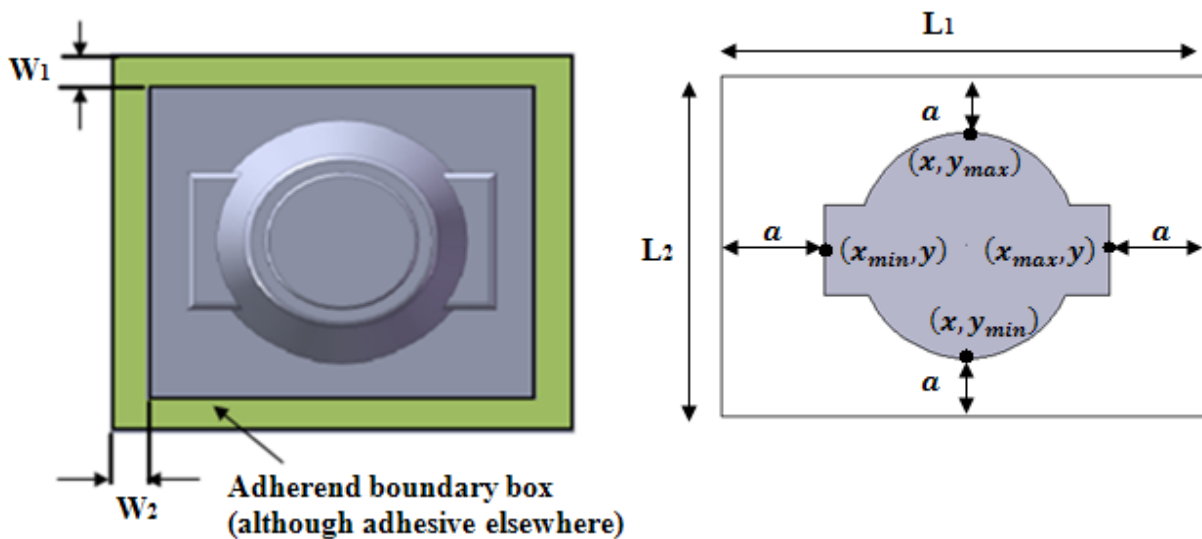
Figure 3.6- (a) Mold geometry showing length, $L_{1,2}$ and width, $W_{1,2}$ of the boundary wall (b) Extreme points, $(x_{min}, y), (x_{max}, y), (x, y_{min}), (x, y_{max})$ and boundary wall clearance value, a of the polygon slice

Figure 3.7- (a) Slicing of mold geometry (b) Union of all slices

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 slices of the mold (Figure 3.7). The length of the boundary wall, L_1 and L_2 will be a constant and are determined based on the boundary wall clearance value, *a*. The magnitude of shear force that the plate can withstand will depend on the bond area, as length being a constant equal to the width of the wall; W_1 and W_2 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 the adhesive arising from the differential shear strain were analyzed by Volkersen (1965). The maximum shear stress, $\tau(max)$, in the adhesive is related to the average shear stress, τ_0, by

$$\eta_c(max) = = \frac{\tau(max)}{\tau_0} \tag{1}$$

where $\eta_c(max)$ is the stress concentration and the value of τ_0 is given by,

$$\tau_0 = \frac{F}{(bonded\ area)} = \frac{F}{LW} \tag{2}$$

where,   F - Applied load

L - Length of the bonded area

W - Width of the bonded area

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

where $\emptyset$ is a dimensionless coefficient,

$$\emptyset = \frac{G_a l_a^2}{E_{s2} d_2 h_a} \tag{4}$$

and ω is defined by,

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

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,

$$\eta_c(max) = \sqrt{\frac{\emptyset}{2}} \cot h \sqrt{\frac{\emptyset}{2}} \tag{6}$$

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

$$\tau(max) = \eta_c(max) \times \frac{F}{LW} \tag{7}$$

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 minimum length and width of the plate required to create a particular mold tooling is,

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

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

where, $W_{1,2}$ - Width of boundary wall

a - Boundary wall clearance

3.4.2 Number, Location and Sequence of Friction Stir Spot Welds

The plates that are fastened together using adhesives alone are assumed unable to withstand the direct forces from the friction stir welding process. Therefore the plates are subsequently bonded using friction stir spot welding. 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 shear strength, F_s, the spot weld will fail. Therefore, an algorithm is used to determine the number and location of spot welds needed such that load acting on each of the spot welds is less than failure load.

The algorithm considers the inter layer dependency between two layers; when any of the 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 offset 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* [Fuller (2007)].
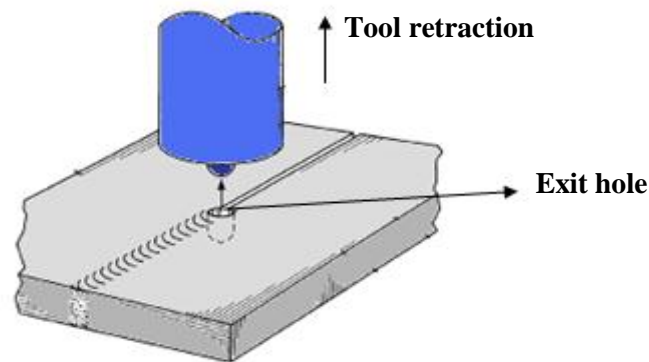
Figure 3.8- Friction stir welding: Exit hole during tool retraction

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,

$$(f_s/F_s)^{\propto} \leq 1 \qquad (10)$$

The denominator F_s represents the shear strength of the spot weld. The value of $\propto$ is an unknown that will define the failure relation between independent modes. For any single loading, regardless of the value of $\propto$, 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 [Wung (2001)]. The value of $\propto$ can be determined by experiments, for example, from the tests conducted by Wung (2001) the value of $\propto$ is found to be 2 for

small thickness to radius ratio (thickness of plates to radius of the weld). In this paper, the t/r ratio is small so the value of $\propto$ is taken as 2. In future work, when this process uses thick plates the value of $\propto$ 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 layer. 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 side of the boundary wall, which will act as a clamp to hold the current plate to the previous plates. The boundary wall used in this process will only be of 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 3.9; this is because of the exit hole in the previous layer.
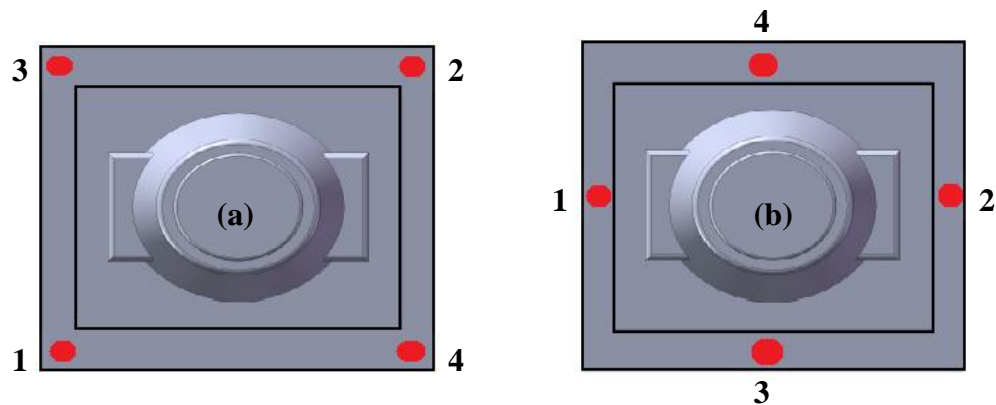

Figure 3.9- Friction stir spot welding (a) on $layer_n$ (b) on $layer_{n+1}$

The sequence of spot welds for the rectangular boundary wall is as shown in the Figure 3.9. In Figure 3.9a, 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 3.9b, the location of the second spot weld is selected such that it has increased moment arm from the first spot weld. The alternating pattern should generally provide a robust and flat outer wall boundary to ensure repeatable placement of each new plate, unaffected by build height.

Friction Stir Spot Welding in the mold cross section:

The four spot welds on the boundary wall are simply intended to clamp the plates firmly so that it can withstand the forces from the continuous friction stir welding process without the shearing of plates. Forces involved in continuous friction stir welding are generally of high magnitude; therefore, spot welds are also needed within 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 the same throughout the mold but the number of spot welds on the mold cross section polygon will depend on the size of the polygon of that particular layer. The location of the spot welds in mold cross section polygon will depend on the critical number of welds, $n_{critical}$.

In this work, $n_{critical}$ for a mold cross section polygon is determined such that it prevents the plate from shearing during friction stir welding and that the load acting on each of the spot weld f_s is less than the strength of the spot weld, F_s . The proposed algorithm is a heuristic method in which the number and location of spot weld is determined such that welds should be well distributed within the mold cross section polygon and the load acting on it is less than the failure load. Figure 3.10a illustrates the layout of spot welds on a hypothetical cross section, in this case, where $n_{critical}$ is equal to three.

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 two spot welds.

When, $n_{critical} = 2, 3$, 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, $\overline{(x_{s2}, y_{s2})(x_{s3}, y_{s3})} = d_{max}$. This is done so that the spot welds in the mold cross section are well distributed, avoiding concentrated load on a few particular spot welds. The point that is farthest from the center of the mold cross section polygon will be the second spot weld and the other point will be the third spot weld location.

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 weld will be determined based on angle of (x_{s2}, y_{s2}), (x_{s3}, y_{s3}) with respect to the center of the polygon cross section, (x_c, y_c). This is because, forming an angle between first three spot welds will divide the polygon to two regions, which will aid in better distribution of spot welds. 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 $(x_a, y_a) = (x_{s5}, y_{s5})$.
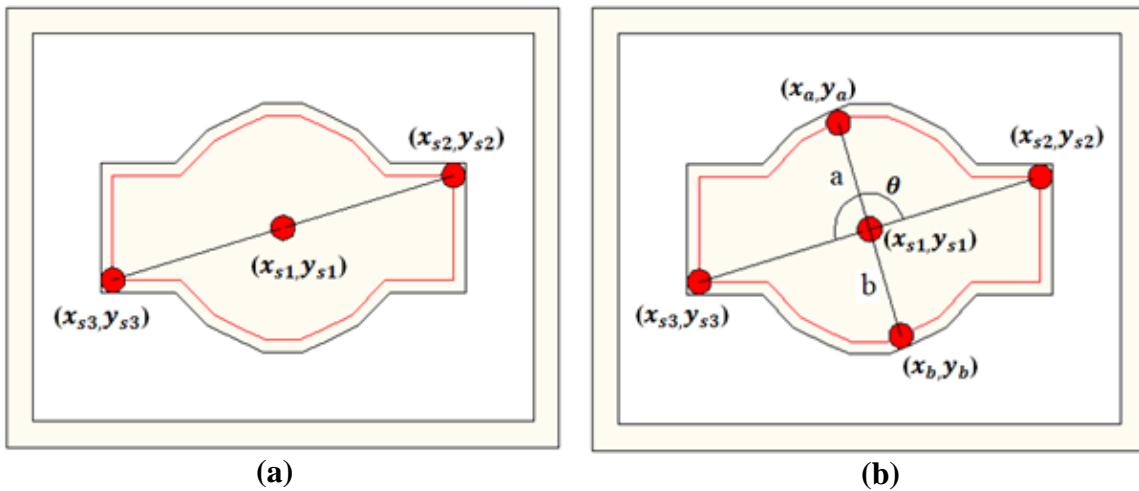
Figure 3.10- Location of spot welds (a) when $n_{critical} = 2, 3$ (b) $n_{critical} = 4, 5$

When, $n_{critical} = 6\ to\ n$, The location of first five spot welds will be the same as in Figure 3.10(b). The location of the sixth and subsequent spot welds will be similar to the case where $n_{critical} = 4, 5$, but for $n_{critical} = 6\ to\ n$ the mold cross section polygon will be further sub divided and each region will be analyzed separately for midpoints instead of

angle bisectors. The regions will be determined based on the swept angle between the neighbor spot welds. 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. In this case midpoint of the polygon section is calculated instead of angle bisector is because for any irregular polygon the location of angle bisector may be close to the first spot weld (center of the polygon). Therefore, calculating the midpoint for each region will assist in better distribution of spot weld within that region. 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 tool library.
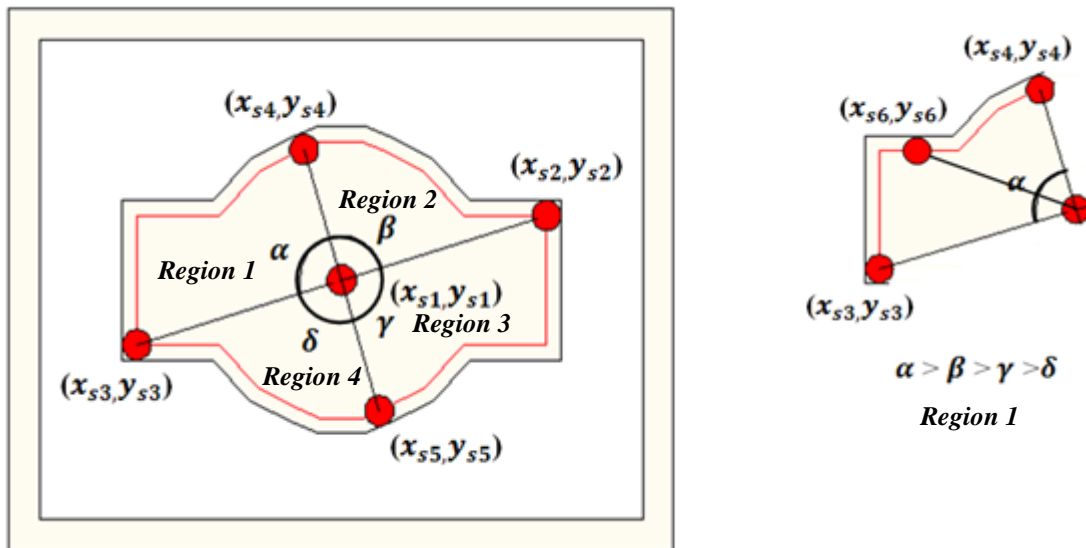
Figure 3.11- Location of the spot welds when $n_{critical} = 6 \ to \ n$

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. The assumption is that most mold designers will avoid such small diameter protruding sections for a mold, or that one would simply choose not to use the rapid tooling method for such mold. When there is more than one polygon in any of the mold cross section as shown in Figure 3.12. The whole procedure of finding $n_{critical}$ and the locations of spot weld will be applied to both the polygons.
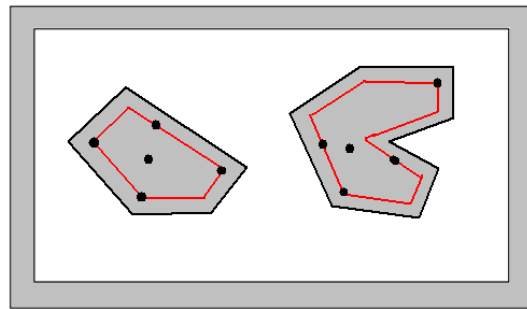
Figure 3.12- Friction stir spot welds based on $n_{critical}$ for two polygon cross section

When there is a pocket in the mold as shown in the Figure 3.13. The procedure of finding the location and number of spot welds will be applied to both the exterior mold cross section and interior mold cross section polygons.

Exterior mold cross-section polygon

Interior mold cross-section polygon
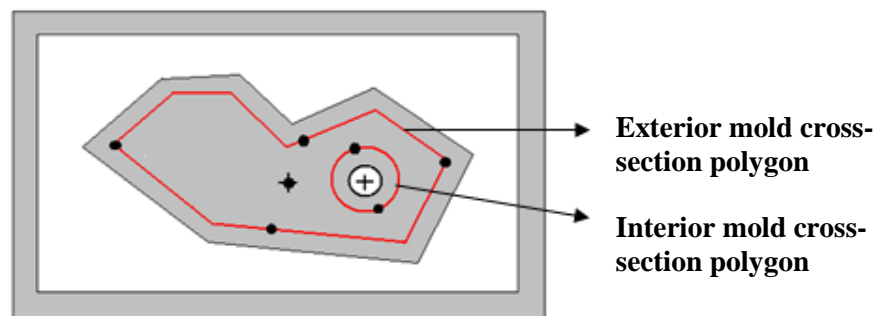
Figure 3.13- Friction stir spot welding location for mold cross section with pocket

The load acting on each spot weld can be determined as follows [Case (1925)],

Load distribution of spot welds:
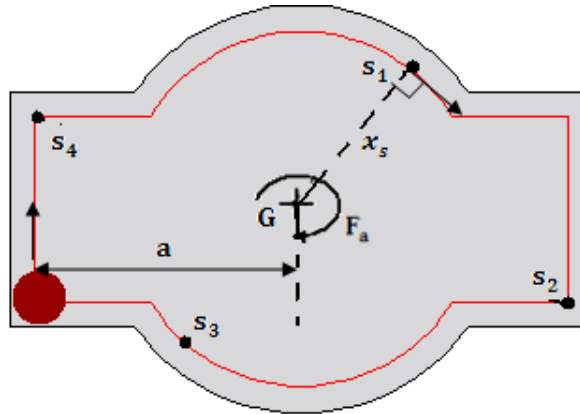
Figure 3.14- Load acting on the spot welds

In the above figure,

G - Centroid of the plate

S - Spot weld

GS- Distance between G and S

F - Force acting due to FSW process

a - Perpendicular distance between G and the line of action of force F

F_a- Couple acting at G due to force F

$s_1 s_1 s_1..,s_n$ - Spot welds

w_s - Load on the spot weld

Load acting on the spot weld due to force F and couple F_a will be considered separately,

(i) Due to force F, each spot weld will carry a load F/n, where n is the number of spot welds.

(ii) Due to couple F_a, the loading on spot weld is proportional to the distance GS and the direction of force is perpendicular to GS.

$$GS = x_s \tag{11}$$

$$w_s = k \, x_s \tag{12}$$

where,　　　k - Constant

w_s - Load on the spot weld

Then,

$$F_a = \sum_{s=1}^{s=n} w_s x_s \tag{13}$$

$$F_a = \sum_{s=1}^{s=n} k x_s^2 = k \sum_{s=1}^{s=n} x_s^2 \tag{14}$$

$$k = \frac{F_a}{\sum_{s=1}^{s=n} x_s^2} \tag{15}$$

$$w_s = F_a \frac{x_s}{\sum_{s=1}^{s=n} x_s^2} \tag{16}$$

w_s is the load acting n each spot due to couple F_a.

Therefore for finding load at spot weld 2, (x_{s2}, y_{s2})

$$w_{s2} = F_a \frac{x_{s1}}{\sum_{s=1}^{s=n} x_s^2} \qquad (17)$$

The total load on each spot weld is,

$$R_s = \sqrt{w_s^2 + (F/n)^2 + \left(2 \times w_s \times \left(\frac{F}{n}\right) \times Cos\ \theta\right)} \qquad (18)$$

where, R_s - Total load acting on one spot weld

θ – Angle between the line of action of force w_s and (F/n)

Algorithm 1:

Determining the number, location and sequence of FSSW

Input: FSW tool path, Force due to friction stir welding (F), Diameter of FSW tool (D),

Boundary wall dimension and Slice file data

Output: n - Number of spot welds

S - Location of spot welds, $[(x_{s1}, y_{s1}), (x_{s2}, y_{s2}), \ldots, (x_{sn}, y_{sn})]$
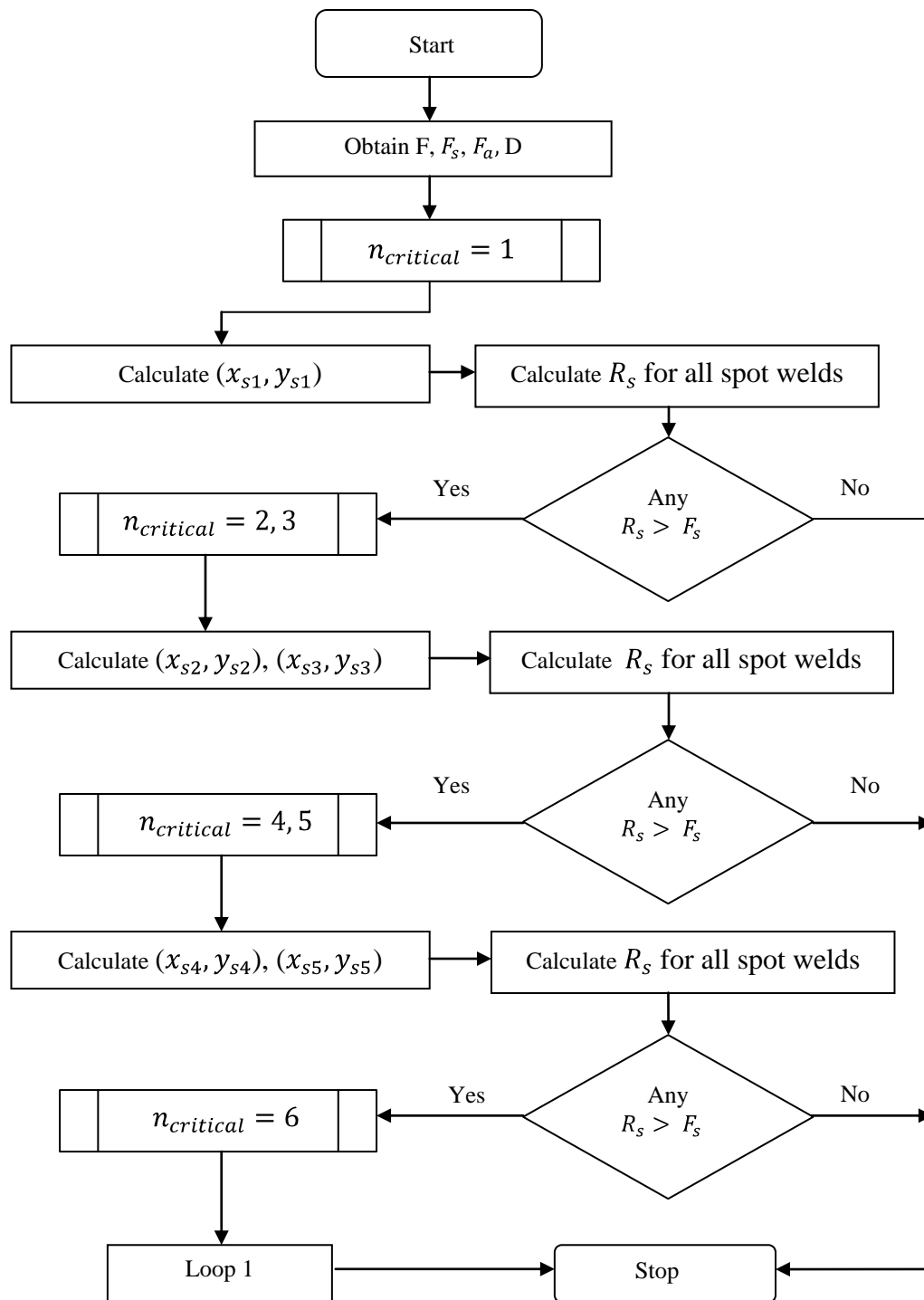
Figure 3.15- (a) Determining number and location of spot weld algorithm flow chart
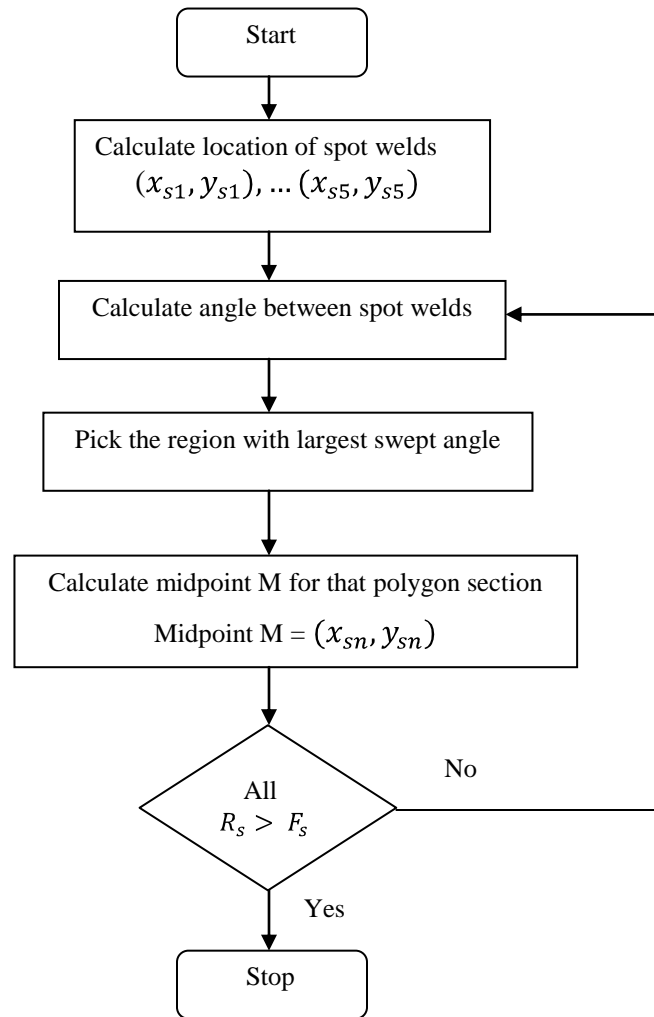
Figure 3.15- (b) Determining number and location of spot weld algorithm, $n_{critical} = 6 \ to \ n$

3.4.3 Toolpath 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 process proposed in this paper is for creating the tooling for single pull up mold, therefore there are no undercuts. The FSW toolpath on each layer will simply depend on the intersection of polygon profiles $slice_n$ and $slice_{n+1}$ as shown in the Figure 3.16. This is because if the toolpath 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.
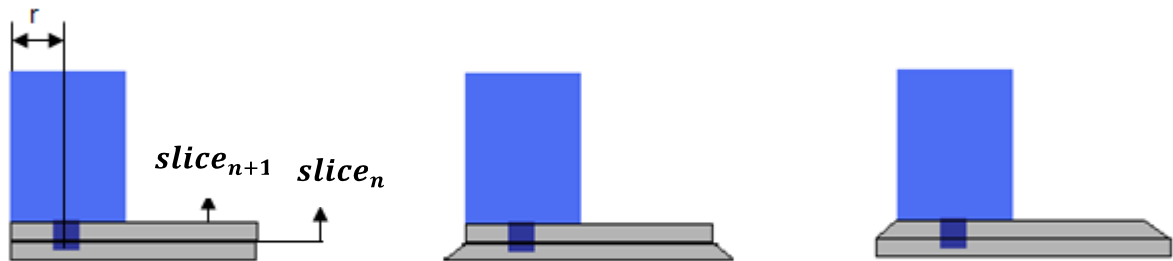
Figure 3.16- FSW toolpath based on the polygon profile of $slice_{n+1}$

The entry point for the FSW tool starts in an arbitrary point assumed to be (x, y_{min}), bottom most point of that particular cross section. The direction of the FSW toolpath and the tool rotation direction is determined such that the advancing side of the weld is facing outside the mold, this is because material properties of advancing side of FSW is better than retreating side [Mishra et al. (2005)] . The friction stir welding process will leave a hole at the exit point it is called *exit hole* so the entry and 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 entry 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 3.17, thereby burying the void inside the metal mold geometry.
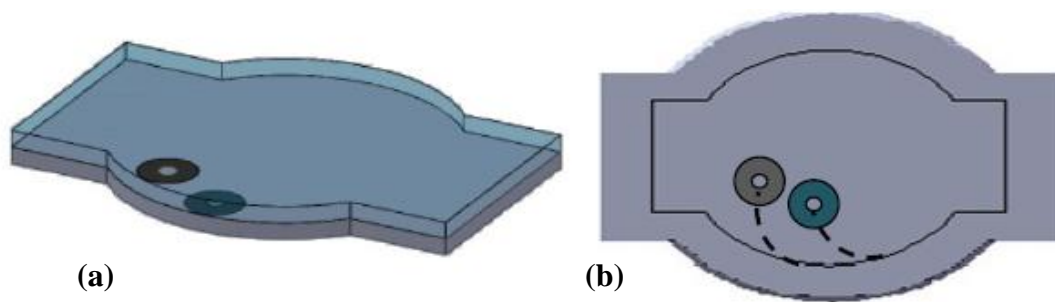
Figure 3.17- (a) Entry point of two subsequent layers (b) Exit holes moved towards the cross section interior

Different possibilities of polygon cross section for mold tooling are as shown in the Figure 3.18. If there is any pocket in the mold, the offset direction will be different, which depends on the orientation of the cross section polygon. The orientation of the exterior polygon will be counter clockwise and interior polygon will be clockwise. Three cases of offset loop intersection are possible as illustrated in Figure 3.18, self-intersection of offset loops, intersection of offset loops between two pockets, intersection of offset loop of the pocket with the offset loop of the island. All the intersections are detected and eliminated to give a valid offset loop for the toolpath of friction stir welding.
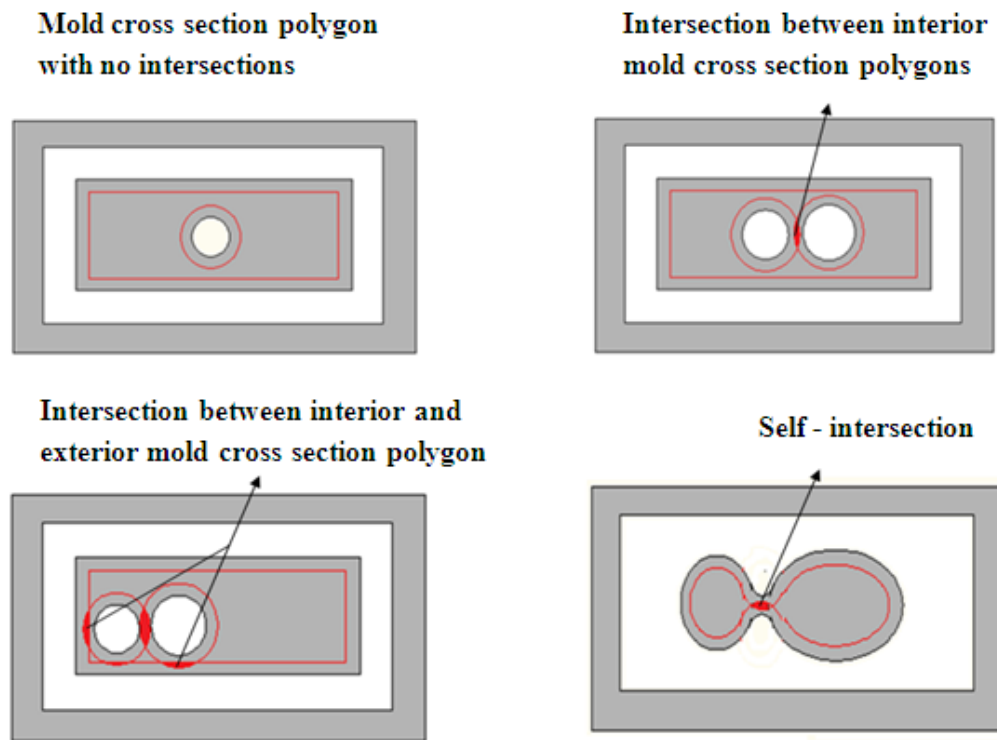
Figure 3.18- Different possible cases of intersection between mold cross section polygons

When the geometry of the cross section is as shown in Figure 3.19(a), post processing of the offset loop is required. When the self-intersection is eliminated, the two separate loops will be connected using a medial axis transformation method.
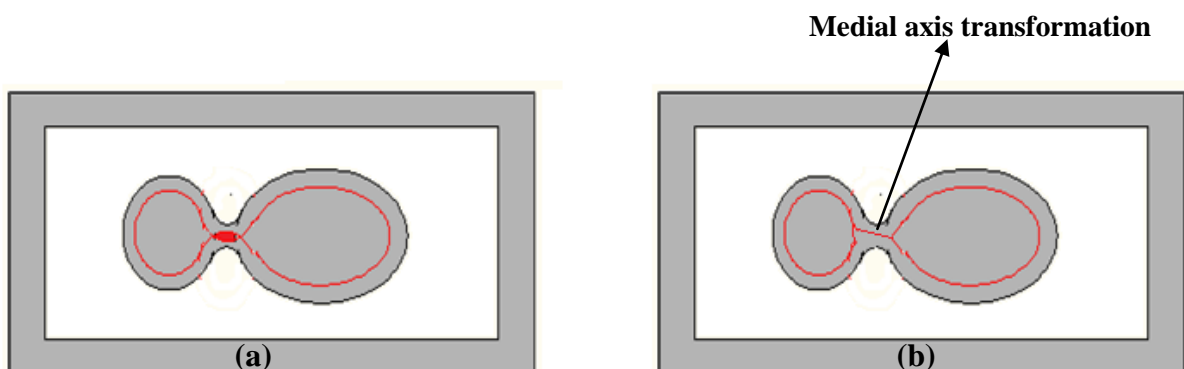
Figure 3.19- (a) Identifying and eliminating the intersections (b) Connecting the separate offset loops using medial axis transformation

Algorithm 2:

Determining the Toolpath for Friction Stir Welding

Input: Slice data with Exterior polygon points P = $[(x_1\ y_1), (x_2\ y_2), ..., (x_i y_i)]$

Interior polygon points $Q_1, Q_2, ..., Q_n = [(x_1\ y_1), (x_2\ y_2), ..., (x_i y_i)]$

n- Number of interior polygon

r- Radius of the Friction Stir Welding Tool

Output: Offset polygon loop points for exterior polygon R = $[(x_1\ y_1), (x_2\ y_2), ..., (x_i y_i)]$

Offset loop for interior polygon $S_1, S_2, ..., S_n = [(x_1\ y_1), (x_2\ y_2), ..., (x_i y_i)]$

Step 1: Create offset for the exterior contour polygon

Step 2: Detect the self-intersection of the exterior polygon offset loop and remove it

Step 3: Connect the separated offset loop using medial axis transformation

Step 4: Create offset for interior contour polygon

Step 5: Check for inter intersection

     (i)   intersection between offset loop of two interior polygon

     (ii)   intersection between offset loop of exterior and interior polygon

Step 8: Remove all intersections

Step 9: Determine entry and exit point for all the offset loops

Obtain r, P, $Q_1, Q_2, \ldots, Q_n$

Offset exterior polygon P = $[(x_1\ y_1), (x_2\ y_2), \ldots, (x_i y_i)]$ to
R = $[(x_1\ y_1), (x_2\ y_2), \ldots, (x_i y_i)]$

Self intersection in offset polygon R

Yes → Remove invalid loops

Connect separated offset loops using Medial Axis Transformation

No

Valid exterior polygon offset loop

Offset interior polygon $Q_1, Q_2, \ldots, Q_n$ to
$S_1, S_2, \ldots, S_n$

Intersection between $S_1, S_2, \ldots, S_n$ & Intersection between $S_1, S_2, \ldots, S_n$ with R

Yes → Remove invalid loops

No

Valid interior polygon offset loop

Create NC code for the polygon loops with entry and exit points for all loops

Stop

Figure 3.20- FSW tool path generation flow chart

3.4.4 Toolpath Planning for CNC machining

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 mill for roughing and finishing, respectively.

3.5 Case Study

This case study discusses the complete process planning methodologies for rapid tool manufacturing. The results of the previously designed process plans are applied to a specific layer in injection mold tooling. The geometry and dimensions of the layer considered for this case study is shown in Figure 3.21.
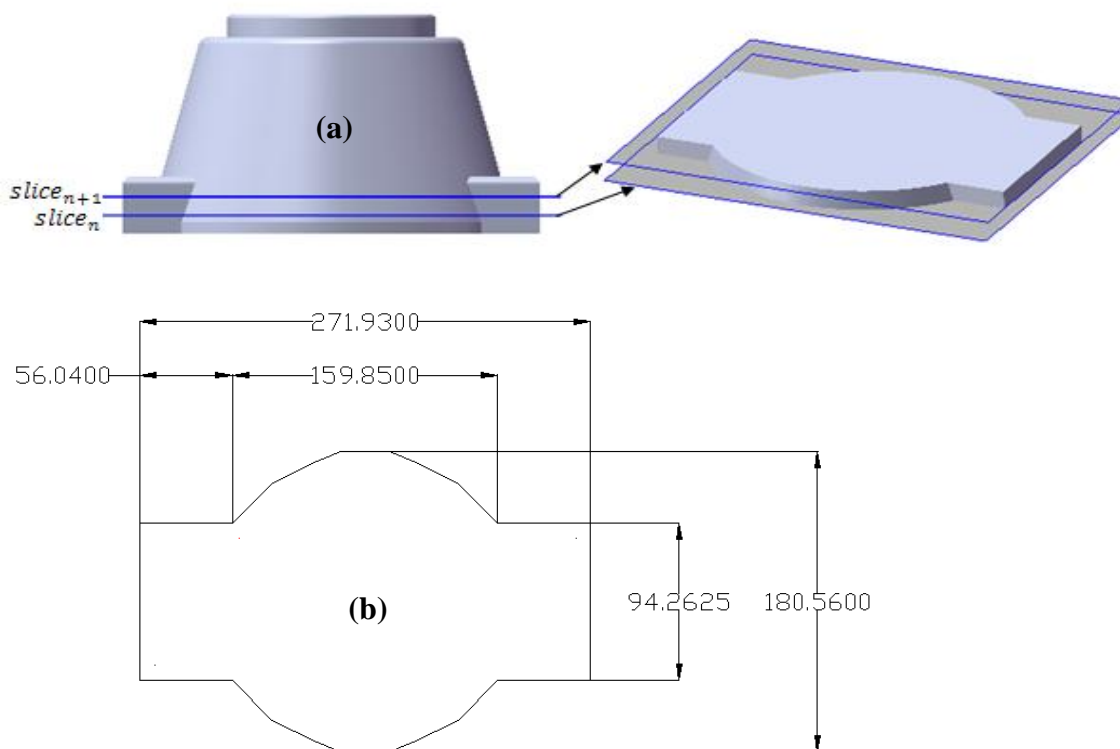
Figure 3.21- (a) Mold slicing (b) Union of all slices to determine boundary wall dimensions (all units are in mm)

The following are the specifications that are assumed for this case study,

- 6061-T6 Aluminum plate with 6.35 mm thickness is used as layers

- Araldite 2014 is the industrial adhesive with 0.5 mm thickness is used for temporary bonding of plates

The design specifications of the Friction Stir Welding tool used in this case study is as shown in the Figure 3.22.

Pin length, L (mm)	4.7
Tool shoulder diameter, D (mm)	18.0
Pin diameter, d (mm)	6.0
D/d ratio of tool	3.0
Tool pin geometry	Threaded with flutes
Tool inclined angle (deg)	0
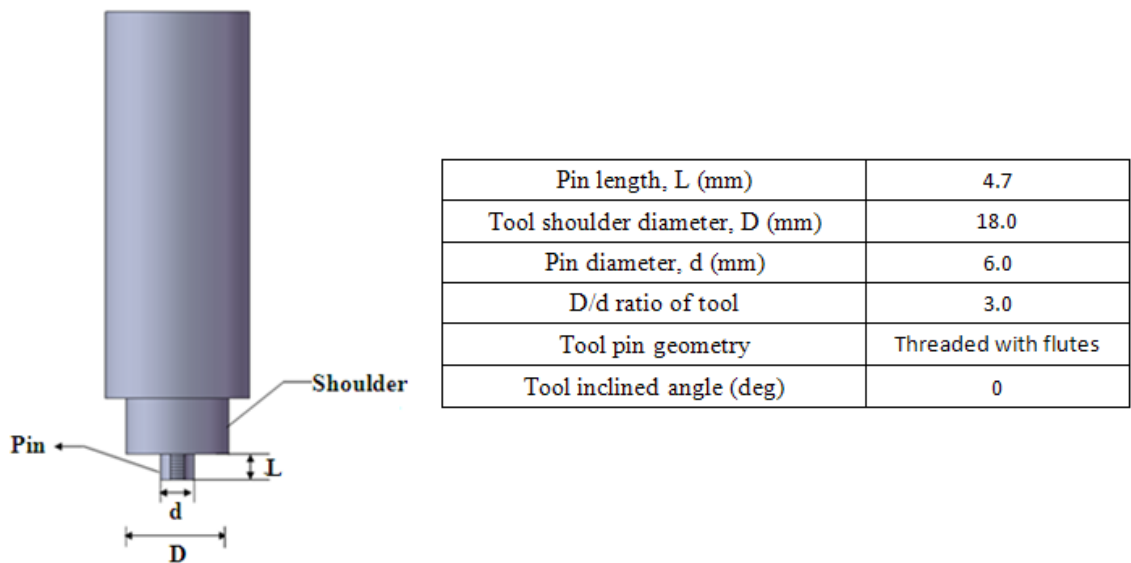
Figure 3.22- FSW tool with design specifications

The first step in the process methodology is determining the dimension of the boundary wall as discussed in section 3.4.1. From literature, the force acting on a plate due to FSSW is assumed to be 6 KN. The boundary wall clearance is assumed as 50.80 mm; therefore the length of the boundary wall L_1 and L_2 are 373.59 mm and 282.16 mm as in Figure 3.23. The properties of the adherend (aluminum) and araldite 2014 are summarized in Table 3.1.
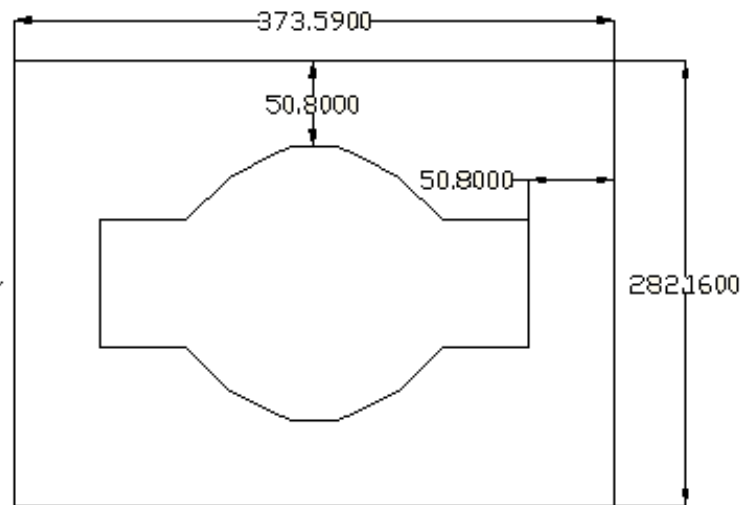
Figure 3.23- Mold cross section with boundary wall clearance value, *a*= 50.80 mm

Table 3.1- Properties of adherend and adhesive used in the case study

Adherend - 6061-T6 Aluminum Plate	Properties
Shear Modulus, G	26.0 GPa
Young's Modulus, E	68.1 GPa
Adhesive – Araldite 2014	
Shear Modulus, G	400 MPa
Young's Modulus, E	4.0 GPa
Average lap shear strength for aluminum	10 MPa

From section 3.4.1, the W_1 of the boundary wall for length $L_1 = 373.59$ mm is calculated as follows,

The maximum adhesive shear stress factor, $\eta_c(max)$, given in equation 6 is shown below

$$\emptyset = \frac{400 \, X \, 373.59^2}{68100 \, X \, 6.35 \, X \, 0.5} \tag{19}$$

$$\eta_c(max) = \sqrt{\frac{258.20}{2}} \cot h \sqrt{\frac{258.20}{2}} \tag{20}$$

$$\eta_c(max) = 11.36$$

Therefore the width, W_1 can be obtained from equation 7

$$W_1 = 6000 \, X \, \frac{11.36}{10} \, X \frac{1}{373.59} \tag{21}$$

$$W_1 = 18.24 \approx 19.00 \text{ mm}$$

For length $L_2 = 282.16$ mm, the width, W_2 is calculated similarly as W_1 which is given as,

$$W_2 = 19.00 \text{ mm}$$

From length $L_{1,2}$ and width $W_{1,2}$ the minimum dimensions of the aluminum plate required to create this specific tool is given in equation 8 and 9 is shown below,

$$L_p = (341.81 - 69.82) + (2*19) + (2*50.80) = 411.59 \text{ mm} \tag{22}$$

$$W_p = (250.36 - 69.80) + (2*19) + (2*50.80) = 320.16 \text{ mm} \tag{23}$$

Therefore a minimum plate dimension of 411.59 x 320.16 mm should be used in the system to create this specific mold tooling. The boundary wall enclosure for this specified mold will be as shown in Figure 3.24.
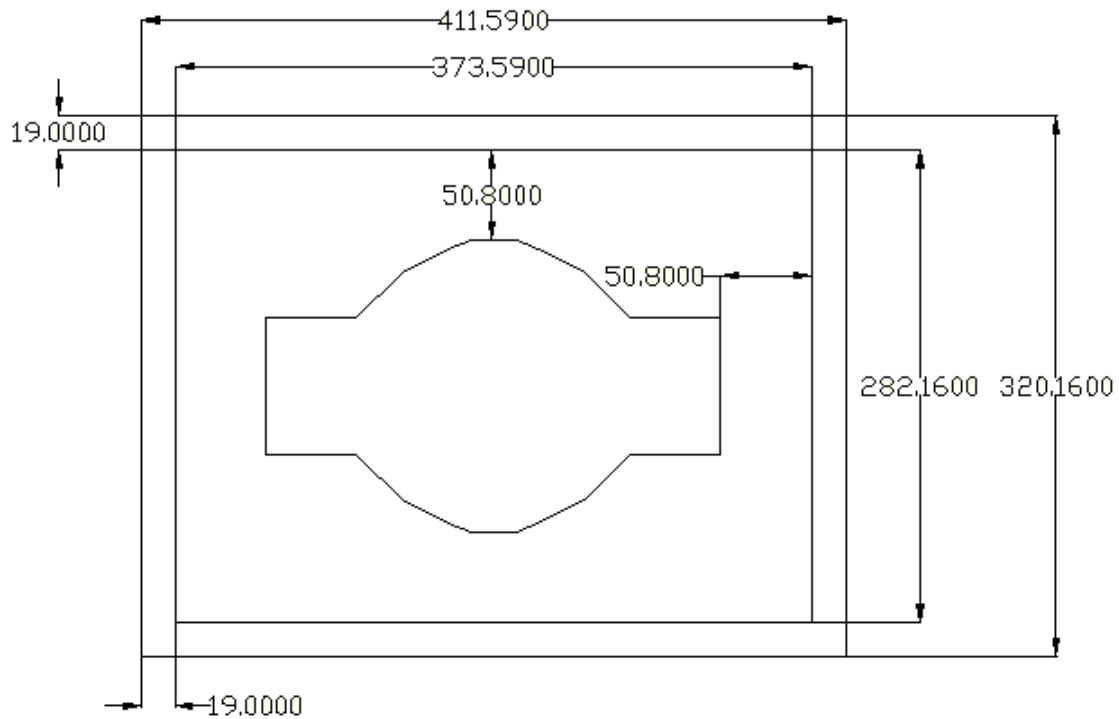
Figure 3.24- Length L$_{1, 2}$ and Width W$_{1, 2}$ of the boundary wall in mm

A two dimensional finite element study has been conducted to verify the stresses acting on the adhesives of calculated boundary wall area. Analyses were performed using ANSYS 12.0 finite element program. The adhesive and adherend were assumed to behave as linear elastic and isotropic. A finite element mesh was generated using 'PLANE 183', elements as an eight-noded, two dimensional quadrilateral with two degrees of freedom in translation: U$_x$ and U$_y$.

The basic joint configuration and finite element mesh used in these analyses are shown in Figure 3.25 and 3.26. Material properties of adhesive and adherend are listed in Table 3.1. Thickness of adhesive is small compared with adherend thickness and high stress gradients will occur at the adhesive area, so to achieve reliable results three elements were used along the thickness of the adhesive (0.50 mm) and a total of 463 elements were used on the bond line region.

(a)

(b)

Load

← 19 mm →　　　　19 mm →

411.59 mm

y

x
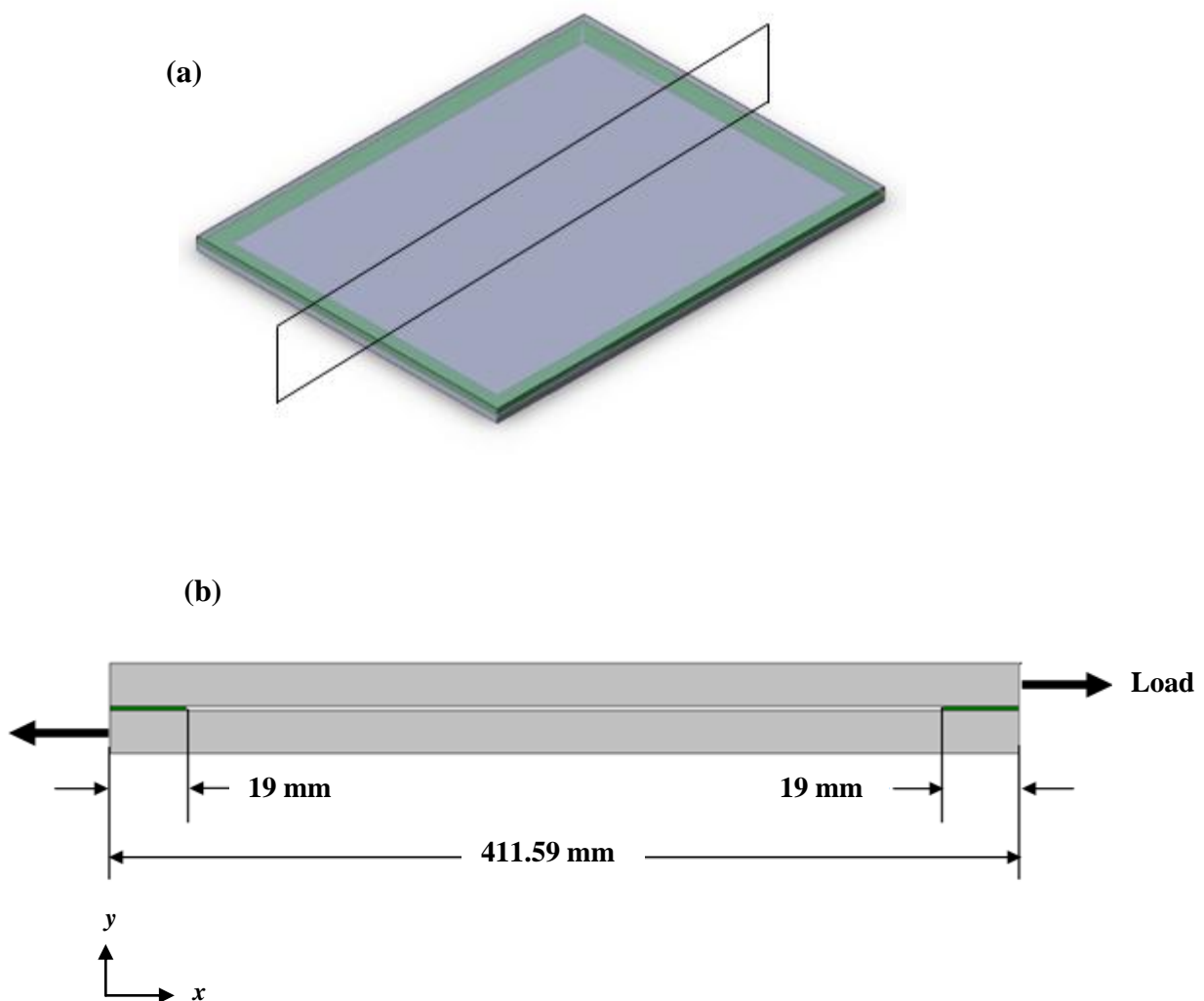
Figure 3.25- (a) Isometric view of two aluminum plates bonded together by adhesives (b) Geometry of the joint configuration

Left bond line

Right bond line

0 mm   19 mm   0 mm   19 mm
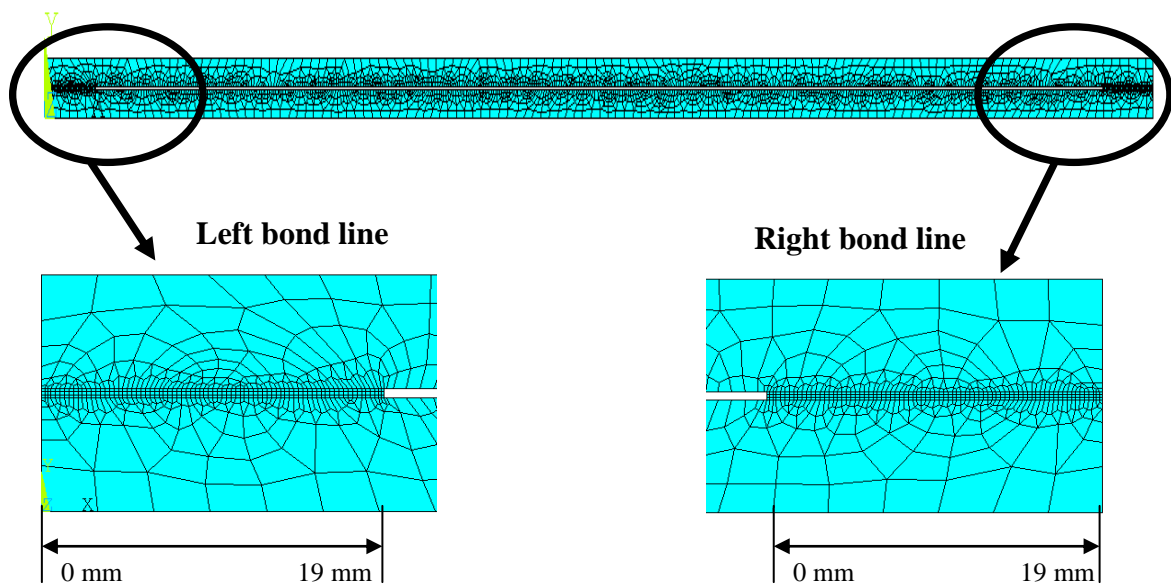
Figure 3.26- Finite element mesh pattern of the joint

The left and right bond lines are analyzed for shear, peel, axial and Von Mises stress distribution and the results are plotted in Figure 3.27-3.29. Figure 3.27 shows that the shear and Von Mises stresses are very high at the edges than at the center of the bond length as expected. However it is not symmetric as cited in literatures this is because of change in the joint geometry. Similarly, peel stresses were also high at the edges of the joint as shown in Figure 3.28.

This trend of high stresses at the edges of the bond is found true not only for the length of the joint but also across the adhesive thickness. Figure 3.28 shows that shear and peel stresses increases across the thickness to a maximum value at the adherend/adhesive interface.
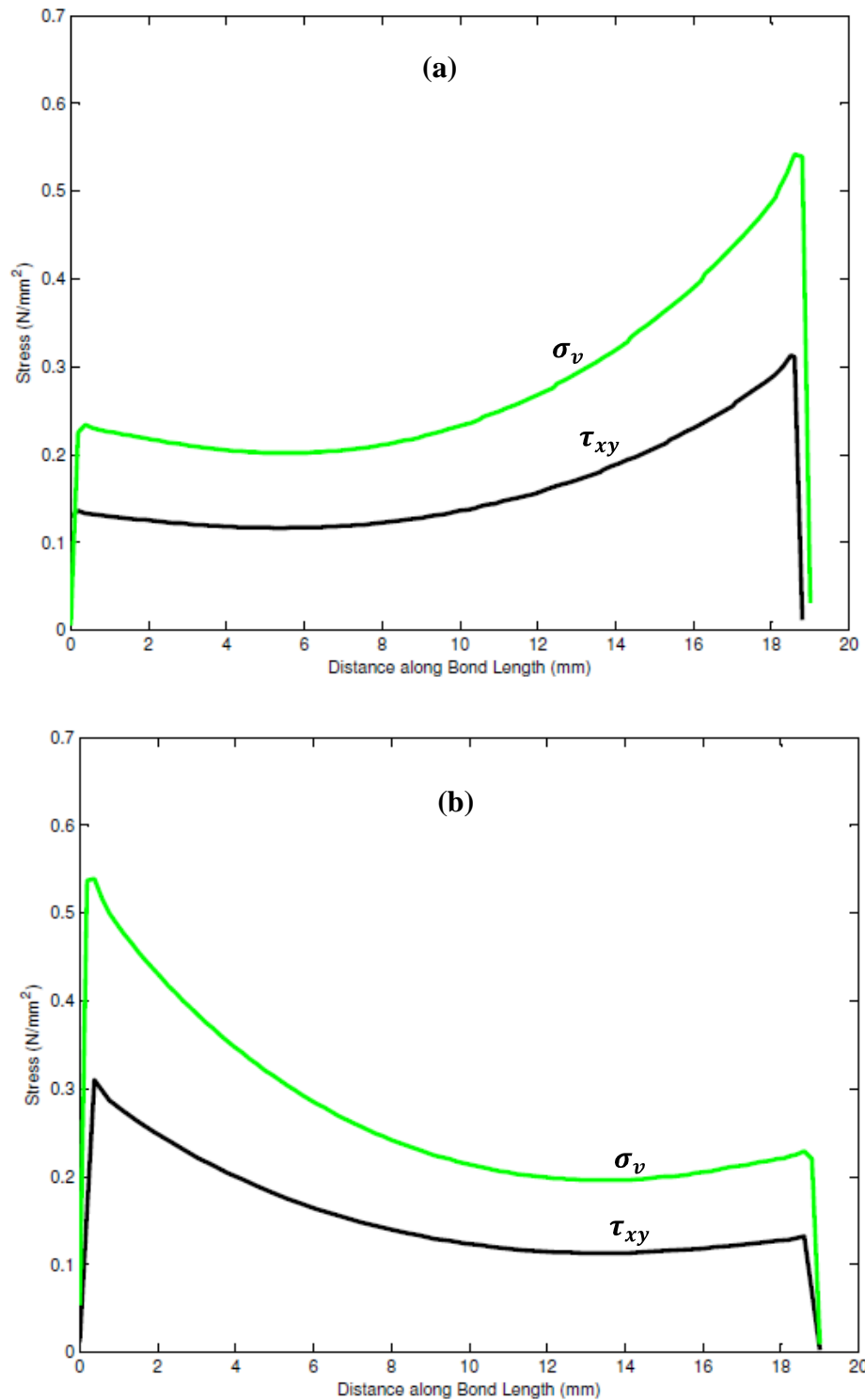
Figure 3.27- Shear (τ_{xy}) and von mises (σ_v) stress distribution along the bond length at the adhesive midthickness for 6KN load; (a) for left bond line (b) for right bond line
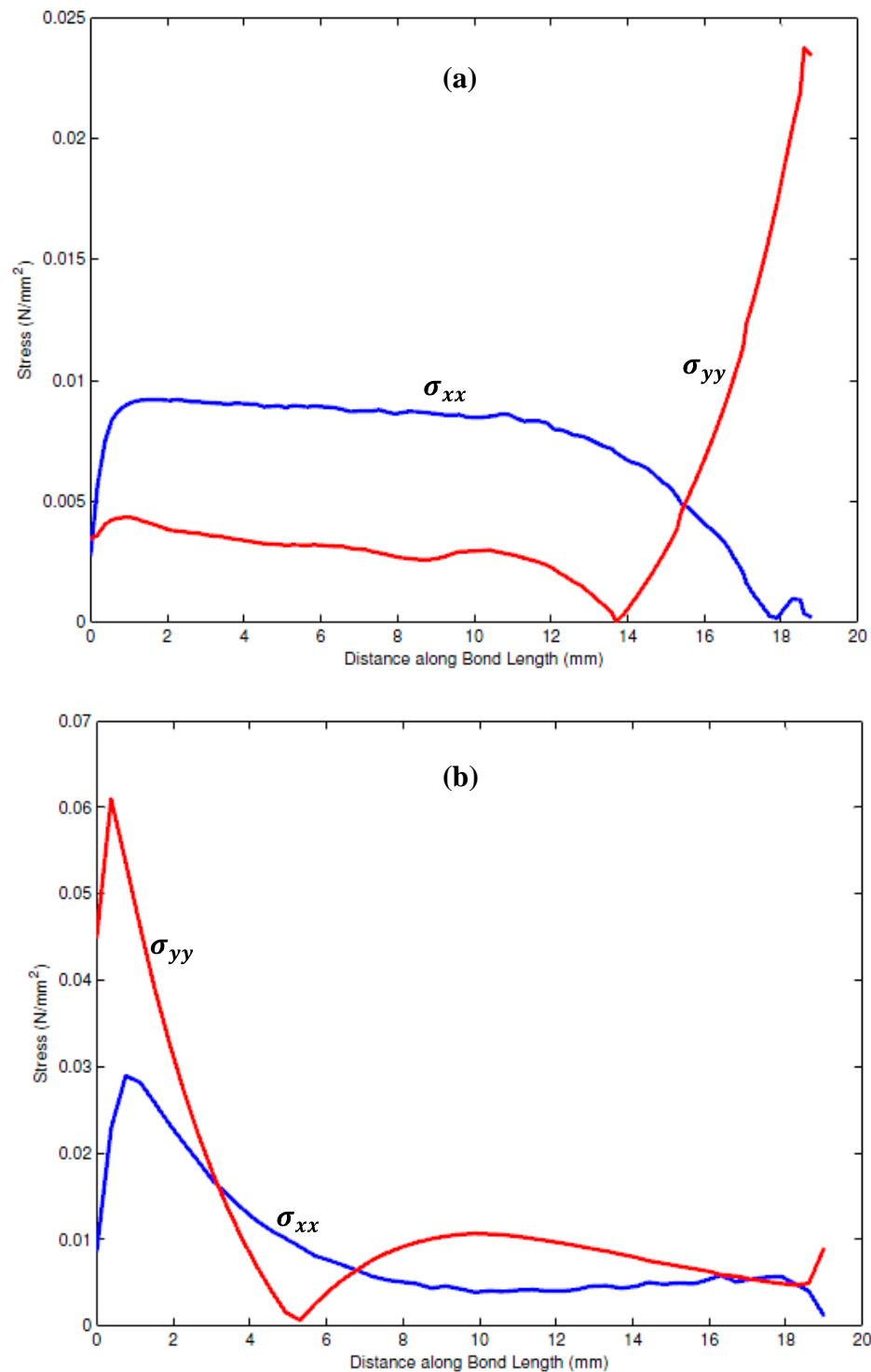
Figure 3.28- Peel (σ_{yy}) and axial (σ_{xx}) stress distribution along the bond length at the adhesive midthickness for 6KN load; (a) for left bond line (b) for right bond line
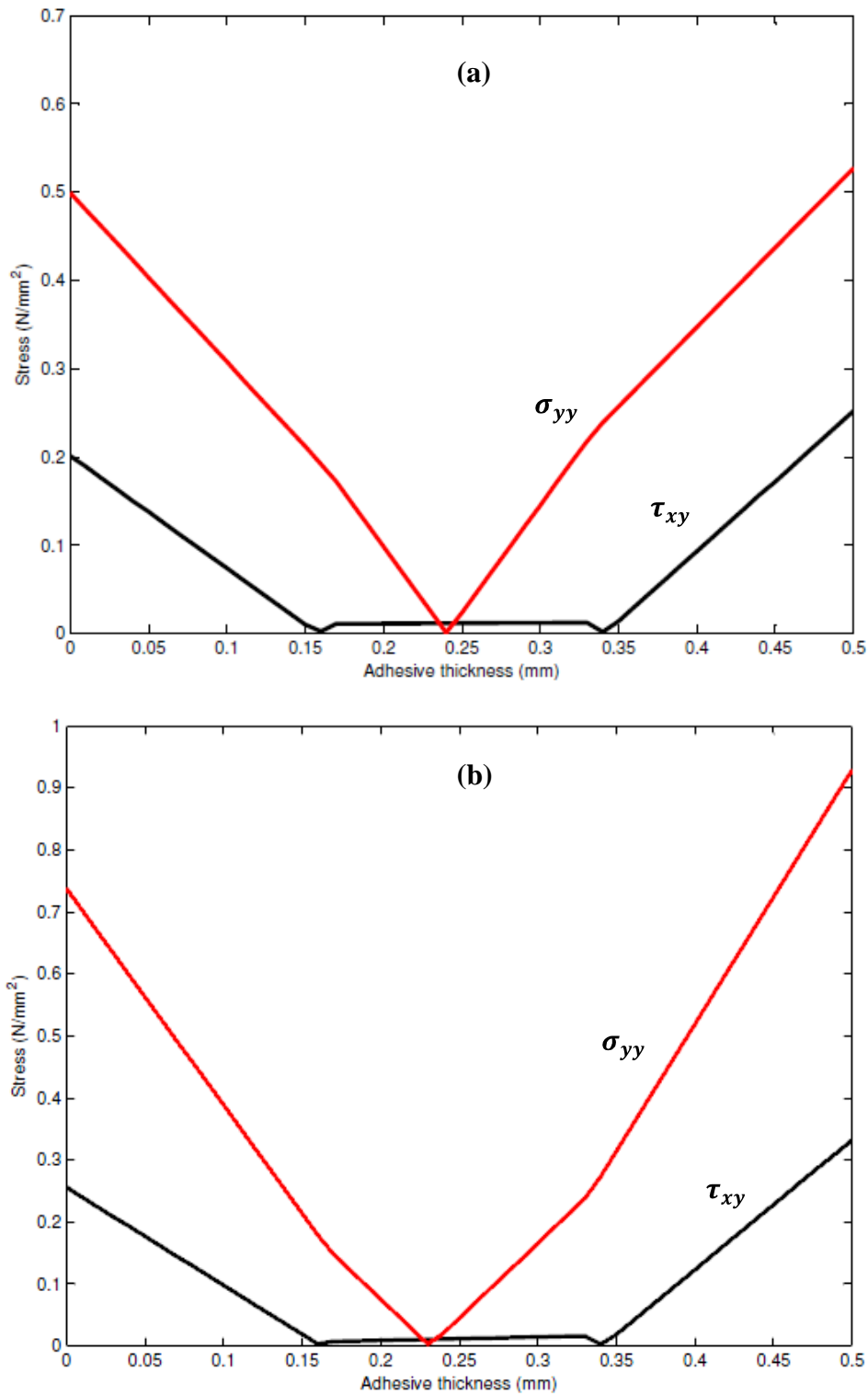
Figure 3.29- Shear (τ_{xy}) and peel (σ_{yy}) stress distribution across adhesive thickness at 19 mm for left bond line and at 0 mm for right bond line; (a) left bond line, (b) right bond line

The next step in this automated process planning is determining the *number, location* and *sequence* of the friction stir spot welds on the boundary wall cross section and in the mold cross section. The number, location and sequence for boundary wall will be the same irrespective of the mold tool size as explained in section 3.4.2. However, it is different for each layer of mold cross section area and is calculated as follows:

From the literature on friction stir spot welding and continuous friction stir welding, the shear strength for friction stir spot welding is assumed to be 3 KN and the inplane forces acting on the layer due to friction stir welding is assumed to be 11.31 KN. The minimal number of spot welds required for the particular layer is determined by assuming that only direct shear load is acting on the spot welds.

Min ($n_{critical}$) = Shear force acting on the plate / Shear strength of the spot weld

$$\text{Min } (n_{critical}) = \frac{11.31}{3} = 3.77 \approx 4 \text{ Spot welds} \tag{24}$$

However, apart from this direct shear load there is a secondary shear load acting on the spot welds due to the turning moment acting on the plate due to the friction stir welding force.

When ($n_{critical}$) = 4, the location of the spot welds in the mold cross section area is determined as discussed in section 3.4.2 and is shown in Figure 3.30. The resultant load acting on the spot welds due to direct and secondary shear is calculated in equation 18.

When $n_{critical}$=4, the resultant load acting on spot weld s_2 is 5.70 KN which will fail, but it is obvious because Min ($n_{critical}$) is calculated without considering the secondary shear force.
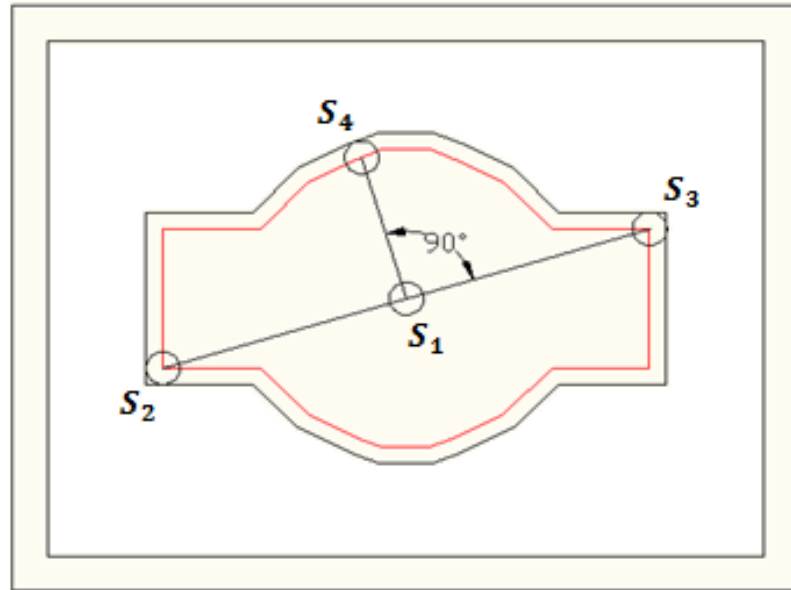
Figure 3.30- Location of spot weld when $n_{critical}$ = 4

The value of $n_{critical}$ will be incremented until it reaches a value such that the resultant load acting on each of the spot welds is less than 3 KN (failure load of spot weld). In this case study, when $n_{critical}$= 8, the load acting on all the spot welds is less than its failure load. The location of spot welds when $n_{critical}$= 8 is shown in Figure 3.31.
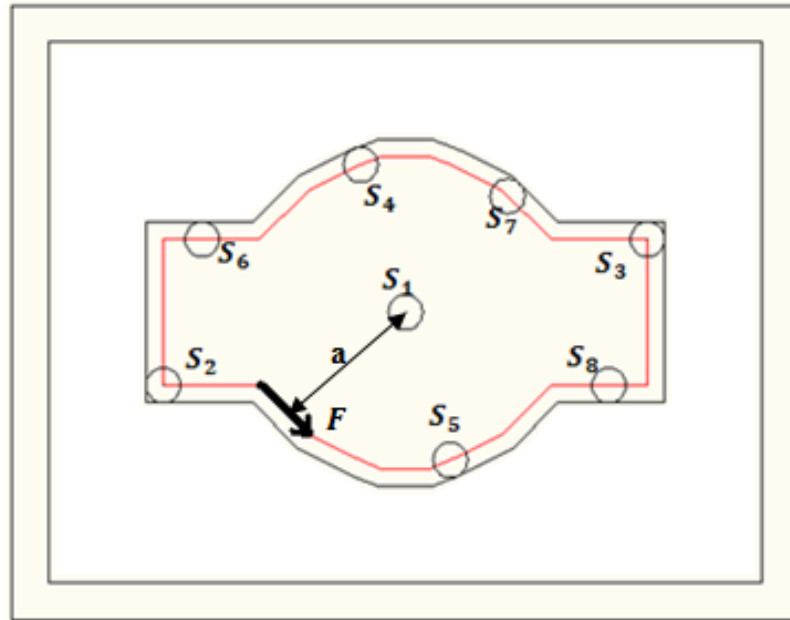
Figure 3.31- Location of spot weld when $n_{critical}$ = 8
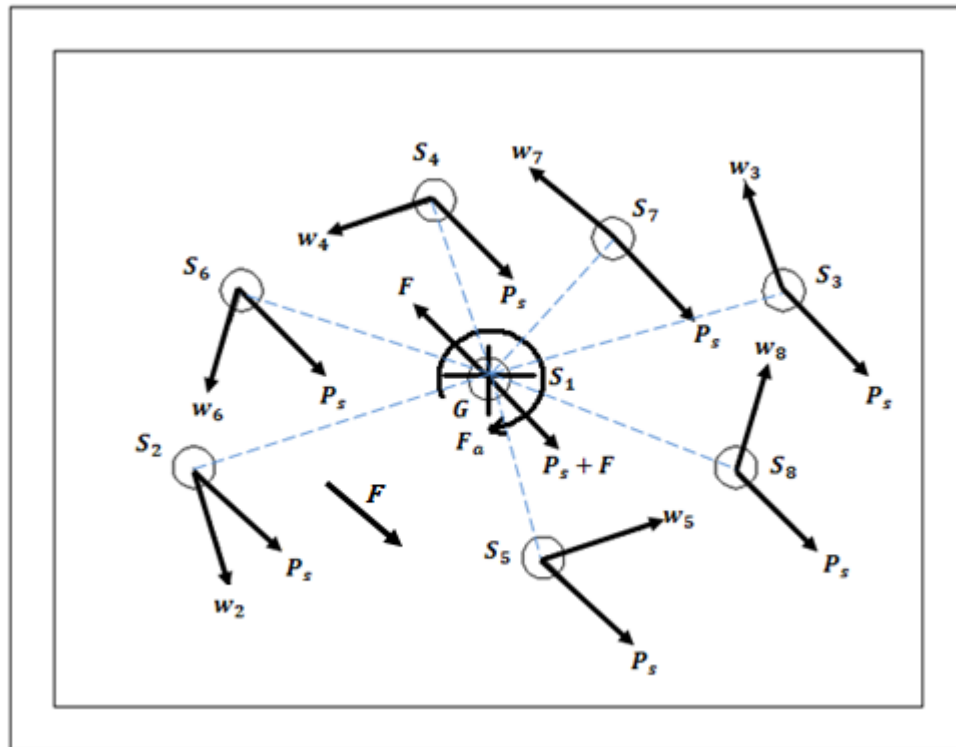
Figure 3.32- Line of action of forces due to direct and secondary shear load acting on spot welds, when $n_{critical}$ = 8

The direct shear load acting on each spot weld is given by,

$$P_s = \frac{F}{n} = \frac{11.31}{8} = 1.41 \text{ KN} \tag{25}$$

The magnitude of the turning moment acting on the center of the plate which tends to rotate the plate is calculated as 963.95 KN-mm. The resultant load acting on each of the spot weld due to direct shear and secondary shear caused by the turning moment is given in equation 18 and is summarized in the Table 3.2.

Table 3.2- Location and resultant load acting on spot welds when $n_{critical}$ = 8

Spot Weld	Location (x, y)	Resultant load acting (KN)
1	(205.84, 160.00)	1.41
2	(78.82, 121.98)	2.91
3	(332.79, 198.07)	0.69
4	(182.45, 237.07)	1.28
5	(229.27, 83.10)	2.04
6	(99.31, 198.18)	2.34
7	(259.37, 220.72)	0.45
8	(312.34, 121.98)	1.46

A tool was created from H13 tool steel, based on the design of a Flared-Triflute developed by The Welding Institute (TWI), UK. The dimensional specification of the tool is shown in Figure 3.22. The aluminum plates were bonded using friction stir spot welding and then

continuous friction stir welding process. The plunge and retract feed rates were 177 and 279mm per minute, while the continuous stirring was conducted at 1800rpm and 635mm 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 3.33.
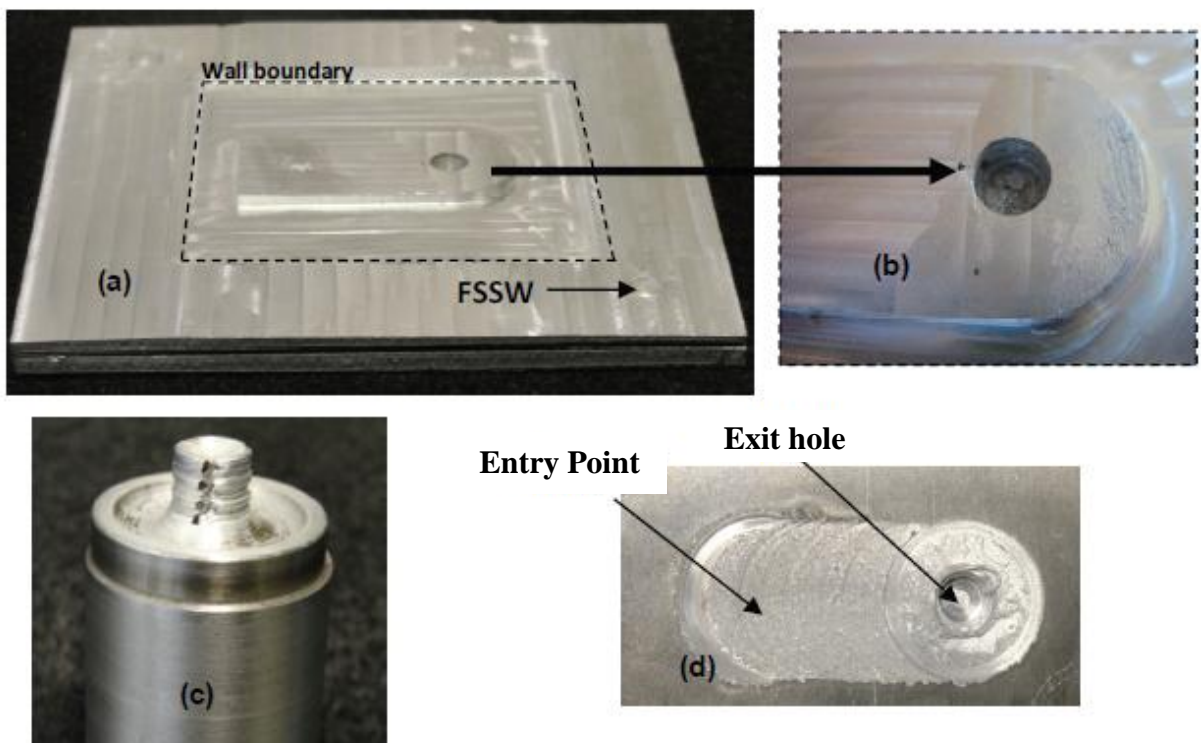
Figure 3.33- Test sample (a) layer sample after all steps, (b) close up of cross section geometry and exit hole, (c) FSW tool and (d) example FSW from entry to exit hole

3.6 Conclusion and Future Work

This paper presented a Rapid Tool Manufacturing system that involves both additive and subtractive techniques whereby slabs are sequentially bonded and milled using layered

toolpaths. This work illustrated a new method for bonding aluminum layers, which could enable high performing rapid tooling process based on a hybrid approach.

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 rapid tool manufacturing system uses a three-axis milling machine 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 rapid tool manufacturing system would appear to be one continuous aluminum "shell" surface (Figure 3.34).

Within the tooling, one could bury all exit and entry holes from welding, the interlaminate 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.
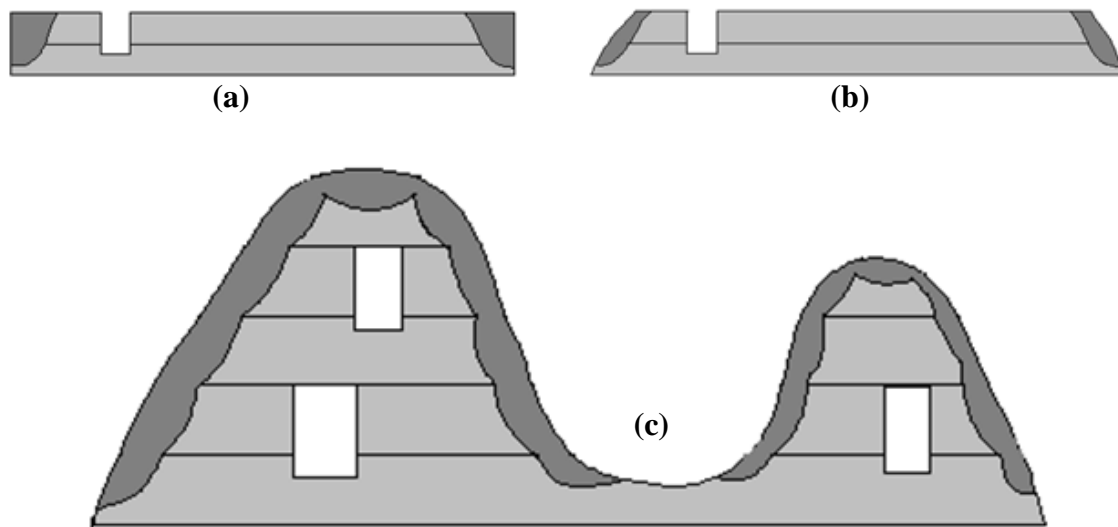
Figure 3.34- Seam free laminated tooling (a) Two layers Friction Stir Welded, (b) Two layers after machining through profile welds, and (c) Illustration of a seam-free tooling stack up, with laminations, exit holes, etc contained within the tool surface

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CHAPTER 4: GENERAL CONCLUSION

Plastic injection molding is one of the most commonly chosen processes for manufacturing quality plastic products at high production rate. However, the cost and time involved in creating the mold tooling cannot be justified for low volume production. From the review of literature there has been lot of research conducted to reduce the cost and lead time to create mold tooling. Several processes have been studied and proposed for rapid tool manufacturing systems. However, most of these systems failed to address the problem of automating the process planning which is very critical for any rapid manufacturing system.

In this thesis, a rapid manufacturing process for creating plastic injection mold tool was proposed where aluminum plates of definite thickness are sequentially deposited, bonded and milled to create 3D shapes.

4.1 Review of Contribution

This thesis provides a unique solution for automating the process planning for a rapid tool manufacturing system. Three research issues are studied in this thesis for the automated process planning system. When a new plate is deposited, it is friction stir spot welded and continuous friction stir welding as an **additive** process and the plates are subsequently machined as a **subtractive** process to create the 3D shape. The first area focused on determining the area of the adhesive applied so that it can withstand the forces from the friction stir spot welding process without shearing. The second area focused on

determining the number, location and sequence of friction stir spot welds on the boundary wall and mold cross section polygons for each layer. The purpose of spot welding is to prevent the shearing of plates during continuous friction stir welding. Therefore spot welds must be able to withstand the forces from the subsequent FSW process. The final research area focused on developing a toolpath planning for the friction stir welding process. The toolpath of FSW will depend on the polygons representing each cross sectional slice of the mold and the diameter of the FSW tool. A case study described the process planning methodology of RMPIM system. Application of these solutions will highly enable a completely automated process planning method for rapid tool manufacturing.

4.2 Future Work

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 RMPIM system would appear to be one continuous aluminum "shell" surface (Figure 4.1).

Within the tooling, one could bury all exit and entry holes from welding, the interlaminate 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.
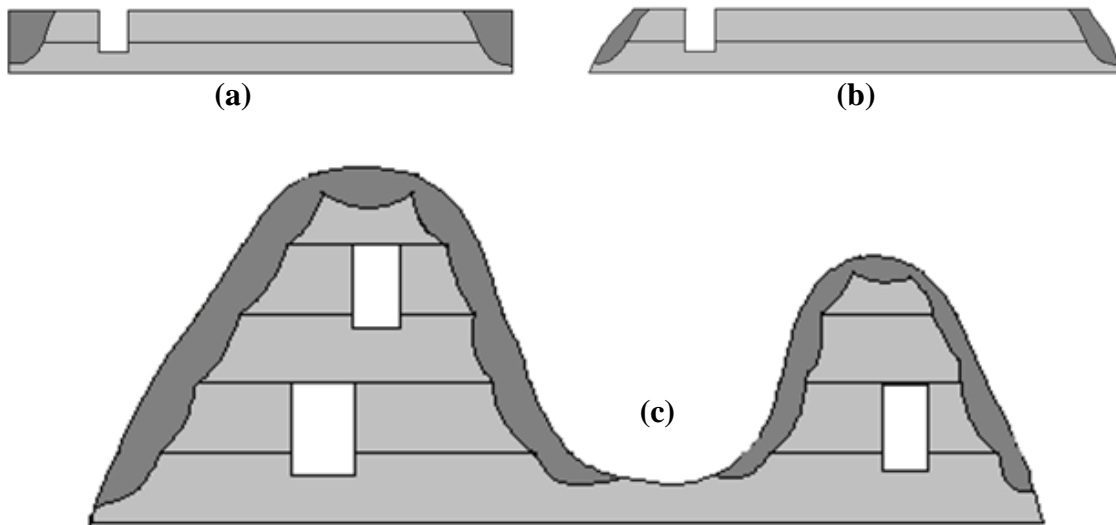
Figure 4.1 - Seam free laminated tooling (a) Two layers friction stir welded, (b) Two layers after machining through profile welds, and (c) Illustration of a seam-free tooling stack up, with laminations, exit holes, etc contained within the tool surface

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