Experimental Studies on Assessment and Reduction of Surface Waviness for Weld Deposition based Additive Manufacturing

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Approval Sheet

This thesis entitled "**Experimental Studies on Assessment and Reduction of Surface Waviness for Weld Deposition based Additive Manufacturing**" by Kumthekar Nitin Balu is approved for the degree of Master of Technology from IIT Hyderabad.

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Dedicated to

To my parents and beloved one

Abstract

Weld deposition based Additive Manufacturing (AM) is one of the economical and efficient ways for fabricating mesoscale metallic objects. This study focuses on the use of Gas Metal Arc Welding (GMAW) based weld-deposition for obtaining the near-net shape of the object, subsequently to be finish machined to the final dimensions. The near-net shape in most of the techniques is obtained through a series of weld-deposition and face milling for each layer. The interlayer face milling is needed because of the uneven surface produced during weld-deposition. However, this operation increases the total time of the process and also reduces the material utilization. Hence, this study focuses on reducing the surface waviness of a given layer eliminating/minimizing the need for interlayer face milling.

The surface waviness is caused mainly due to improper process parameters and repetitions/gaps arising in area-filling paths. While there is sizable literature on suitable process parameters, the effect of the area-filling path on the surface waviness is not fully analysed. The current work presents different experimental studies carried out for studying the effect of different area-filling features on the surface waviness.

Accordingly, three area filling patterns namely spiral-in, spiral-out, and rectilinear with different surface waviness have been described. The material utilisation is measured using a 3D scanner and face milling. Both approaches gave similar results signifying the suitability of 3D scanner approach. Subsequently, the multi-layer experiments are also carried out for different area filling patterns and surface waviness is measured for 5-layer. Rectilinear is found to be the best. In the rectilinear pattern, different overlapping methods namely offset overlap, and criss-cross overlap is also explored. Among these methods, criss-cross shows the best R_t value.

Abbreviation

AM	-	Additive manufacturing
GMAW	-	Gas metal arc welding
3D	-	3 Dimensional
RP	-	Rapid prototyping
RT	-	Rapid tooling
RM	-	Rapid manufacturing
FDM	-	Fused deposition modelling
CNC	-	Computer numerical control
LOM	-	Laminated object manufacturing
SLS	-	Selective laser sintering
EBM	-	Electron beam melting
3DP	-	3 Dimensional printing
SLM	-	Selective laser melting
MIG	-	Metal inert gas
TIG	-	Tungsten inert gas
PAW	-	Plasma arc welding
PDM	-	Plasma deposition manufacturing
GTAW	-	Gas tungsten arc welding
HLM	-	Hybrid layer manufacturing
EMW	-	Electromagnetic wave
LENS	-	Laser engineering net shaping
DMD	-	Direct metal deposition
TOM	-	Tangent overlapping model
NTSD	-	Nozzle to the top surface distance

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Chapter 1

Introduction

Additive manufacturing (rapid manufacturing) is an automatic process in which manufacturing of objects directly from their CAD models without using any advanced tooling geometry. Additive manufacturing, also mentioned as layered manufacturing, rapid manufacturing or 3D printing has drawn significant focus on decreasing product development time and increasing the complexity of the geometries. RP uses a divide and conquers approach in which the complex geometrical 3D part divide into respective 2D slices that are very easy to manufacture by additive manufacturing. Furthermore, physical part builds from bottom to up direction, which avoids the chances of collision. Here, rapid prototyping and rapid tooling (RT) is an effective tool in layered manufacturing development where time to market matters. RP cuts down the product development time, and RT cuts down production time. However, RP&T tool is still limited to the production of the only prototype, mostly included non-metallic materials. The dream of manufacturing is to extend the total automation in the production of real life components. But, the following are some of the bottlenecks for these evolutions.

- Poor quality
- short life
- Long cycle time
- Cost

The above problems become an essential factor while making metallic components in rapid manufacturing. To overcome these problems, different approaches for metallic manufacturing are developed.

1.1 Approaches to Metallic Manufacturing

The following are some of the approaches for rapid manufacturing of metallic objects.

1.1.1 CNC Machining

Computer Numerical Control (CNC) is the automation machine which is operated by precisely programmed commands. Machine tool function on the numerical control is programmed with CNC machining language (G-Code). CNC machining is a subtractive approach for metallic manufacturing. It has best features like good surface finishing, better accuracy, good quality and handling many materials. But it requires human intervention to do path planning and finally, it becomes time-consuming. In this process material wastage is more. Hence it is costly. The CNC milling operation as shown in figure 1.1.

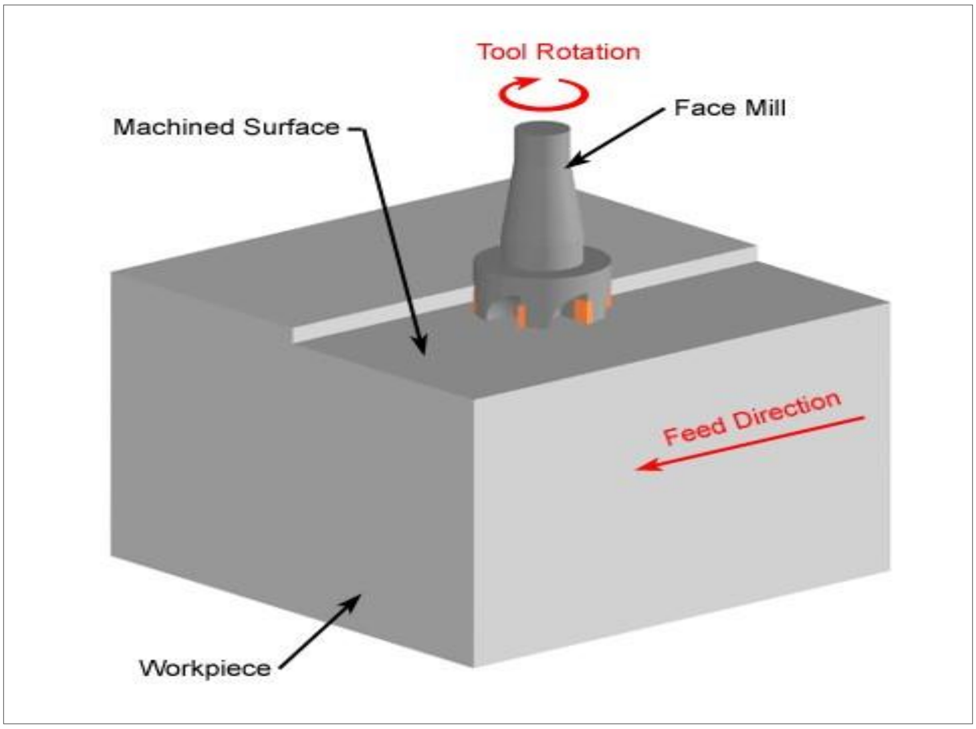


Figure 1.1. CNC Milling operation [17]

1.1.2 Laminated Manufacturing

Laminated Object Manufacturing (LOM) is an additive based manufacturing in which sheets of material are bonded to form an object. It has the main feature that different material can be added. It requires more energy to cut sheet layer by layer.

The process is performed as follows steps:

- The sheet is adhering to a substrate with a heated roller.
- The desired shape of the part is traced by Laser.
- Laser cut the non-part area.
- The platform of completed layer moves down.
- New material is feed with rollers for next layer.
- The process is repeated.

The schematic representation of laminated object manufacturing is shown in figure 1.2.

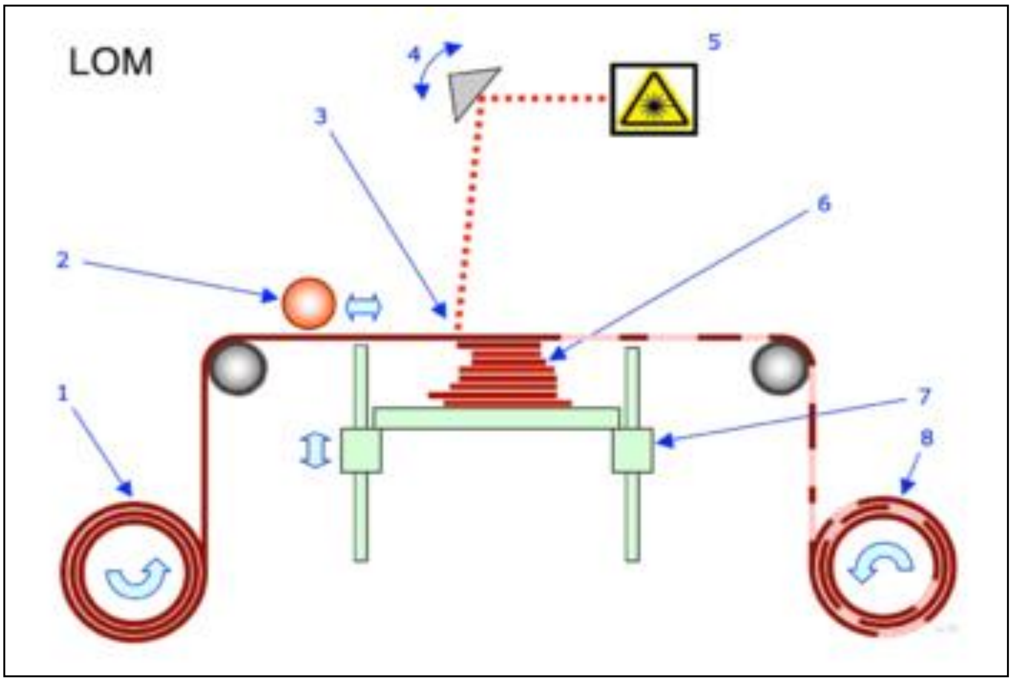


Figure 1.2. Schematic Diagram of Laminated object manufacturing:
1.Foil supply, 2. Heated roller, 3. Laser beam, 4. Scanning prism,
5. Laser unit, 6. layers, 7. Moving platform, 8. Waste foil [18]

1.1.3 Powder Bed Technologies

A powder bed technology is an additive manufacturing process in which layer is realised by first spreading the powder and then it is melted by focussed energy source that may be a laser, electron beam (EB), Arc or a simply jet of liquid binder. Further, it can be classified into different types based on their energy sources. Selective laser sintering (SLS), Electron beam melting (EBM), 3D printing (3DP), Selective laser melting (SLM) these are some processes of powder bed metallic manufacturing. This process can make the porous part, and it is fast. But it has a low surface finish. The schematic representation of powder bed technology is shown in figure 1.3.

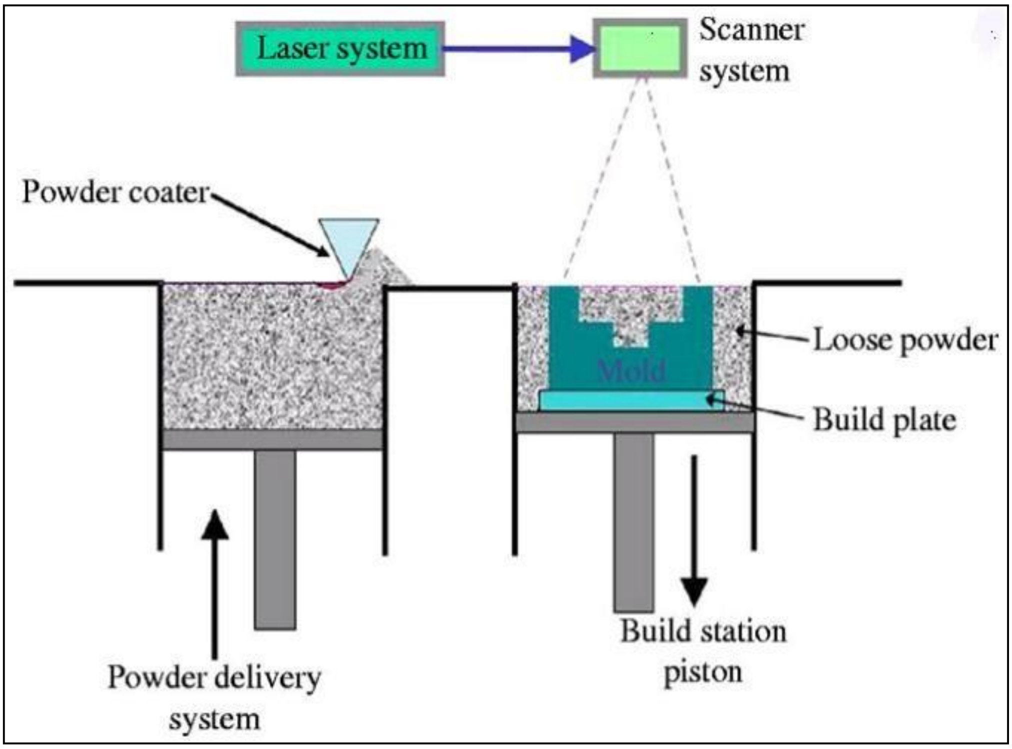


Figure 1.3. Schematic illustration of additive manufacturing powder bed system [19]

1.1.4 Deposition technologies

Deposition is a process in which layer is realised by melted material come out through the nozzle. Fused deposition modelling is commonly used for modelling and prototyping of plastic material. Further, this process is extended for metallic material through welding deposition processes. Welding deposition can be done by using three energy sources i.e. Laser based deposition, EB based deposition and Arc based deposition. The schematic of laser based deposition is shown in figure 1.4. Among all these processes Laser and EB based gives more accuracy and quality. But, these energy sources find less deposition rate, less efficiency, and high energy requirement. On the contrary Arc based gives high deposition rate and efficiency. Arc based deposition uses many arc welding processes such as Metal inert gas (MIG), Tungsten inert gas (TIG), Plasma arc welding (PAW) and recently developed plasma arc with powder feed i.e. Plasma deposition manufacturing (PDM). The schematic of MIG, TIG and PAW based deposition is shown in figure 1.5.

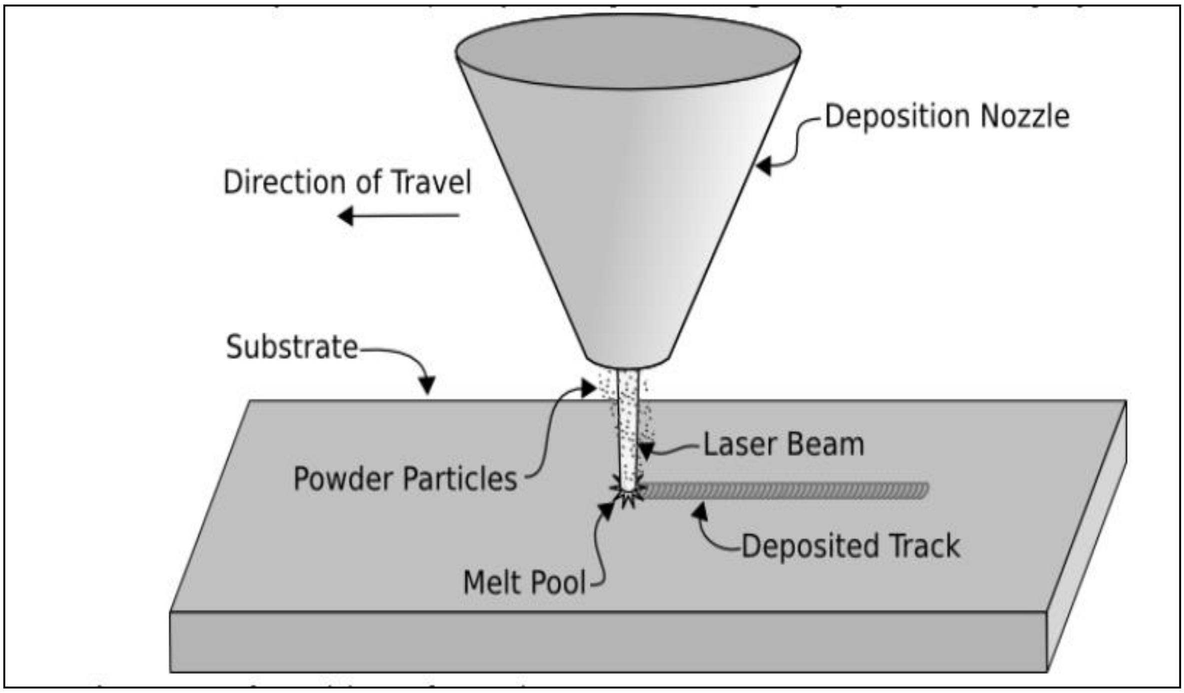


Figure 1.4. Schematic of a coaxial laser metal deposition system with powder injection [20]

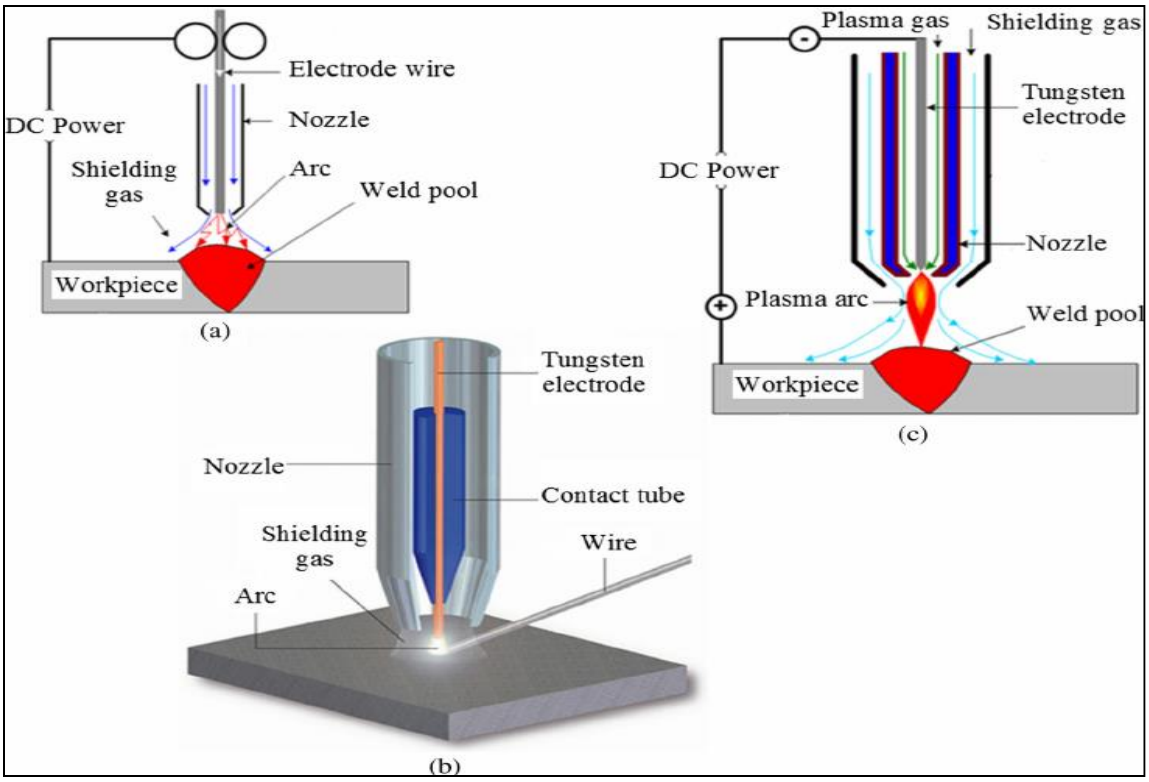


Figure 1.5. Arc welding based deposition. (a). GMAW based deposition. (b) GTAW based deposition. (c) PAW based deposition

1.1.5 Hybrid Technologies

It is the combination of additive process and subtractive process in which first make the near net shape of the object through layer by layer from laminated manufacturing, powder bed manufacturing or deposition technology. Then final dimensions of near net shape object are done by CNC machining. This is two stepped process which combines benefits of the both additive and subtractive process. Additive approach gets near net shape in less time, and the subtractive process can finish the final accurate dimension with high quality. The following figure 1.6 shows advantages and disadvantages of these technologies. Hybrid layered manufacturing added the advantages of both additive manufacturing and CNC manufacturing. ArcHLM machine is developed at IIT Bombay. It uses an advanced welding process which is called as pulsed synergic gas metal arc welding (GMAW). The main advantage of this setup is its capability of retro fitment to any existing CNC machine. Figure 1.7 shows a 3-axis ArcHLM machine by integrating Argo 1050P 3-axis CNC machine and a Fronius TPS 4000 welding unit.

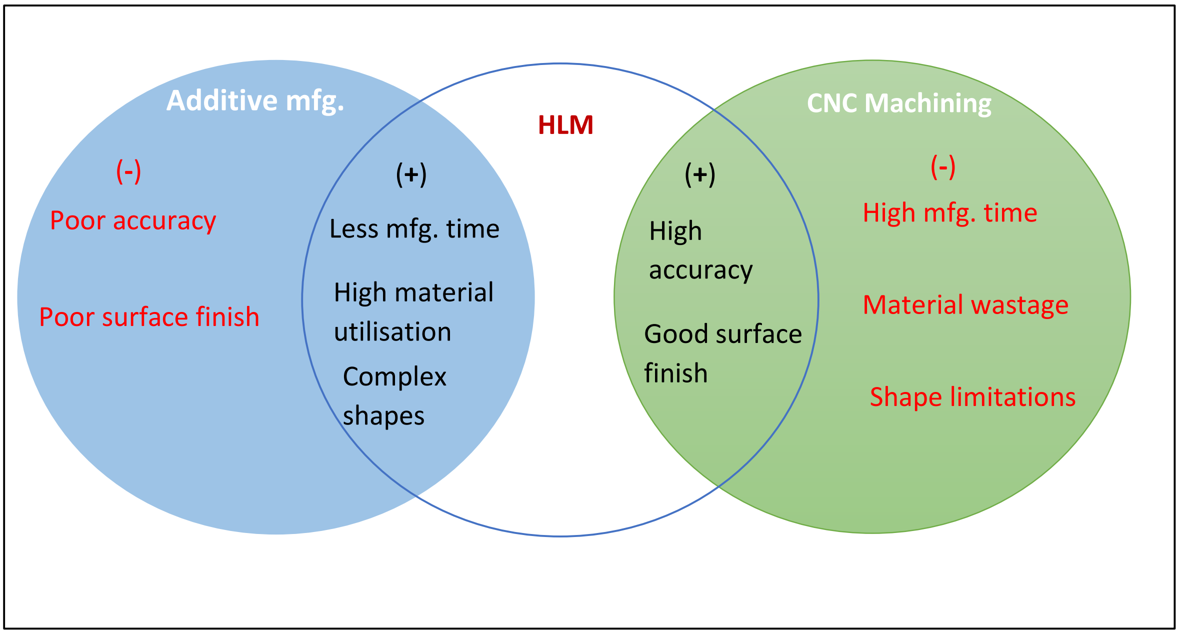


Figure 1.6. Combination of benefits of the additive manufacturing and CNC machining

Figure 1.7. A 3-axis ArcHLM machine (integration of Argo 1050P 3- axis CNC machine and Fronius TPS 4000 welding unit) [10]

1.2 Problem Definition

The main objective of this study is to reduce surface waviness of deposition using different path patterns and different process parameters. While manufacturing of different geometries, the deposition of the layer will not give completely flat area filling that must be required for next layer of deposition. Deposition finds some defects like uneven surface, porosity, etc. at the middle portion and edge of geometry. To avoid this problem, many researchers use a hybrid approach in which Gas metal arc welding is using for deposition of metal materials, and CNC milling is using a subtractive process for the surface finish to make flat surface of deposition. But this hybrid approach is expensive due to material wastage and time-consuming process. Thus this study tries to eliminate/minimise the interlayer face milling. This can be done with reducing defects like porosity, waviness by optimising path planning. The whole studies are based on to find out the best possible area filling pattern and step-over values for the single and multi-layer deposition.

1.3 Summary

Various approaches to metallic manufacturing are discussed in this chapter. Among these approaches, hybrid technology gives better economical outcomes. In this approach, the additive process is used to make the near net shape of the object from laminated manufacturing, powder bed manufacturing or deposition technology. Among all these additive processes, deposition process has more benefits. There are many deposition processes available which classified by their energy sources such as a laser, electron beam, and arc. An arc-based energy source gives more weld deposition rate. Thus integration of GMAW based welding unit with CNC milling machine is used for the present study.

Chapter 2

Literature Review: Improving the Geometrical Accuracy of weld deposition components

Additive manufacturing is developed for design and fabrication of CAD model. The earlier studies focus on AM which is concentrated on the manufacturing of non-metals objects. The today's market demanded metallic components with minimum manufacturing and product development time. Nowadays, much research is going on to the production of metallic objects by using additive manufacturing. But, while manufacturing metallic components by additive manufacturing, there are many limitations such as poor surface finishing and accuracy. The recently many literature add the benefits of different additive manufacturing and CNC manufacturing so that the process will get customized components with minimum manufacturing and product development time. Further, some studies counter that the CNC machining is material wasting and time-consuming process that becomes an uneconomical process. Thus it is very essential to minimise or eliminate the CNC surface finishing during the multi-layer depositions. And depositions also have some defects such as uneven surface and porosity. To reduce the effect of these uneconomical and imperfect processes and to control the geometry, different approaches and techniques are used.

The extensive literature survey is divided into following four sections as per their studies.

- Control of deposition parameters
- Selection suitable area filling paths
- Bead modelling for accurate prediction
- Online monitoring for corrective compensation

2.1 Control of deposition parameters

Vishal Pushpa et al. [1] presented experimentation on layer thickness and yield of deposition by changing step-over and current parameter. Welding is a process with several interacting parameters. Hence, it requires more than one parameter to control for any change in the desired output. This difficulty is overcome by the synergic control which can adjust the any desired welding parameter and it regulates the related parameters to provide the desired outcome. The experiment is done by changing step-over value with respect to changing the current.

It is found that the layer thickness steadily increases with current. As the step-over value increases, the layer thickness decreases non-linearly. The yield rapidly increases with increasing mean current. As the step increases, the yield increases in the starting and then decreases. From above observation, one can easily find out the optimum value of step-over value for a given current.

The concept of uniform and adaptive slicing is studied Panchagnula J.S. and S. Surya [2]. This paper presented inclined slicing methodology for a metallic object with overhangs by using higher order kinematics of machine. In weld deposition of inclined layer different ways of process parameter is used. It concludes that varying torch speed is more effective than varying the wire feed parameter.

A methodology for understanding the relationships between process parameters and the bead area geometry is presented by D. Ramos et al.[3]. The effect of the process parameter for GMAW in the prediction of bead geometry has been reported. Experimental results have found that the process parameters such as the welding speed, wire feed and welding voltage influence the weld bead area in the process.

Shekhar Srivastava and R.K. Garg [4] presented the effect of the various process parameters on welding of IS:2062 using GMAW process with copper coated mild steel filler wire. Bead geometry variables, heat affected zone, bead width, bead height and area of penetration are greatly influenced by welding process parameter i.e. welding speed, welding current, shielding gas flow rate, arc travel speed and contact tip-work distance, etc. The mathematical model has been developed from response surface technology. As ANOVA predicts the significance of process parameters, wire feed rate followed by welding current and travel speed has been found as the sequence of effective parameter among all other used parameters. And gas flow rate is the least effective parameter.

2.2 Selection suitable area filling paths

Donghong Ding et al.[5], The study focuses on a developing fully automated system using robotic gas metal arc welding to additively manufactured the metal component. The process of fabrication of thin walled structure by MAT based path is shown in figure 2.1. In this, a thin walled aluminium structure has been fabricated automatically using only a CAD model as informational input. They introduced a new technology named as Medial Axis Transformation (MAT) is able to generate a set of closed loop paths which cover entirely the sliced layers of thin walled structures.

Gap free paths can be achieved the algorithm through offsetting the medial axis of the given geometry towards its boundary. This novel methodology of path planning for the additive manufacturing process is developed in D. Ding et al. [6]. This gap free path improves the quality of the fabricated components. As compared to traditional path pattern, proposed MAT-based path pattern is particularly beneficial for additive manufacturing of thin walled structures. Furthermore, the adaptive MAT path for void free deposition can be implemented by using the single bead ANN model and multi bead overlapping model in Zenxi Pan et al. [7]. The established strategy is tested through experimental depositions. The results show that the developed MAT strategy is capable of producing depositions with high quality and geometrical accuracy through an automated selection of process parameters for the wire and arc additive manufacturing.

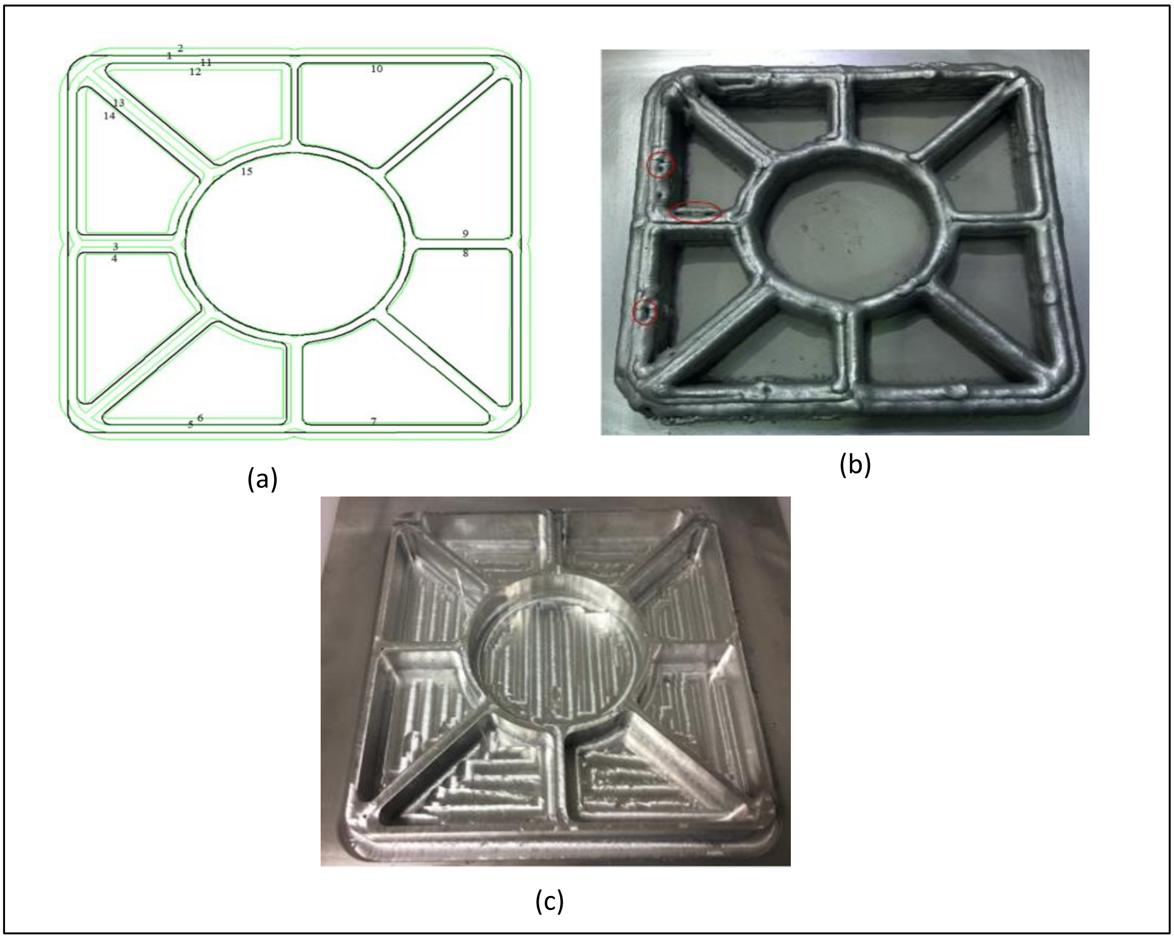


Figure 2.1. Experiment of thin walled structure: (a) MAT-based paths for thin walled structure (b) Near-net shape of the deposited aluminium structure (c) Final finished thin walled part [5]

Kao. J et al. [8] presented the optimisation of the deposition path for the complex geometries which having sharp corner features. This paper developed optimised deposition paths which are based on optimised cross-sectional geometry and adaptive-offset technique. The medial axis transformation (MAT) approach is also introduced to optimise the cross-sectional geometry so that smooth deposition could be produced for the least amount of excess deposition.

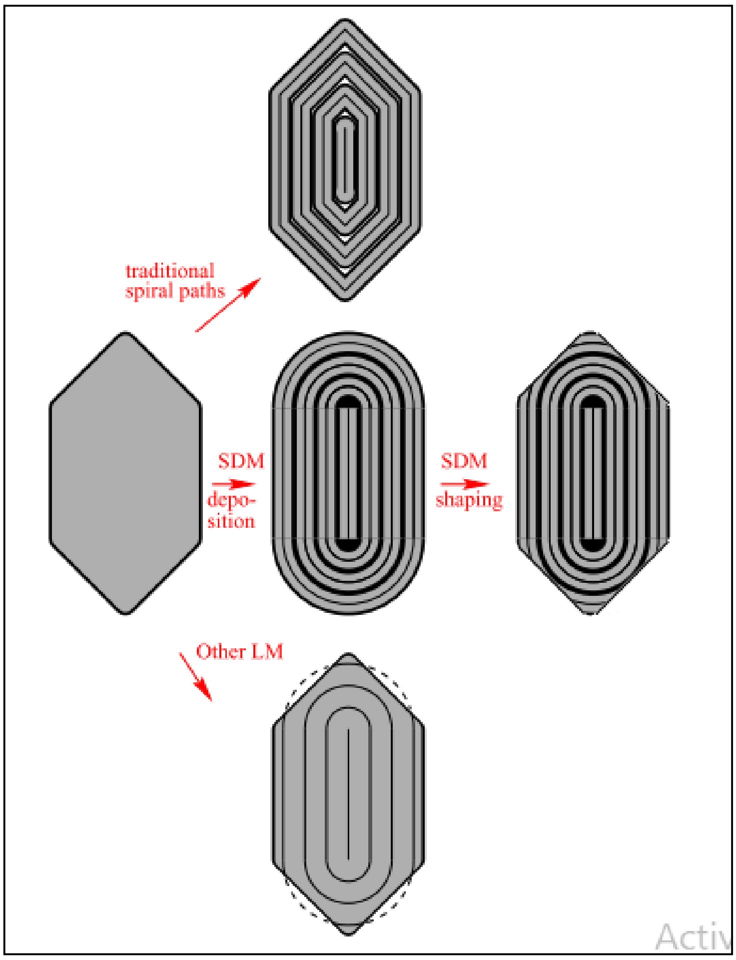


Figure 2.2. The possible solutions to the offset problems [8]

G.Q. Jin et al. [9] presented an adaptive approach to improve the process planning of rapid manufacturing for the complex components such as biomedical models. A mixed tool path generation algorithm is developed to generate contour tool paths along the boundary and offset curves of each sliced layer. Non-Uniform Rational B-Spline (NURBS) curves are introduced to represent the boundary contours of the sliced layer. This algorithm helps to preserve geometrical accuracy, and zigzag tool-paths to fill the internal area of the sliced layer which simplifies the deposition process and speeds up fabrication.

2.3 Bead modelling for accurate prediction

S. Suryakumar et al. [10] presented the model formations of single bead and overlapping multiple beads build through HLM process. The authors have developed a multi-bead overlapping model that assumes a symmetric parabolic cross-sectional of the bead.

It concludes that Bead geometry is affected by the size of filler material, wire feed, torch speed and step-over value. From the bead experiment, it is calculated that the optimal step-over value can be equal to two-third of the width.

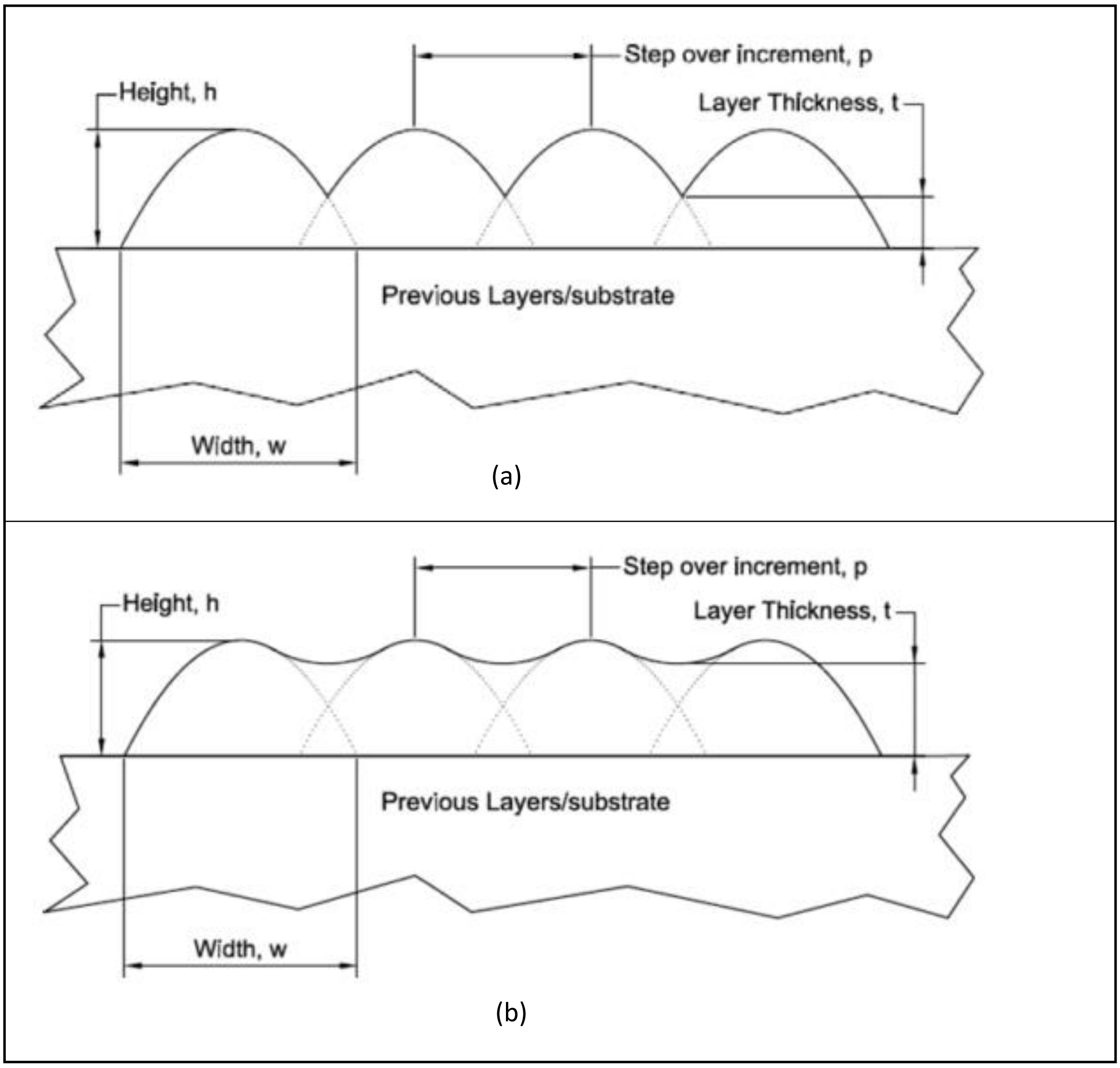


Figure 2.3. Models for multi weld bead: (a) The profile predicted by the initial model. (b) The profile with the profile predicted by improved model [10]

Jun Xiong et al. [11] is presented an experimental study for determining the optimal model of the bead cross-section profile fitted with a circular arc, parabola, and cosine function. A necessary condition for the overlapping model of multi-bead is proposed, by comparing the actual area of the bead with the predicted area of the three models. The results show that different models have different center distance and surface quantities of adjacent beads. From the experimental results shows that the ratio of wire feed rate to the welding speed considerably influences the shape of the welding bead. It is found that as the ratio of the wire feed rate to the welding speed is more than 12.5, the arc model for the single bead section profile has higher accuracy than the other two functions. When it is less than 12.5, the parabola model is more reasonable.

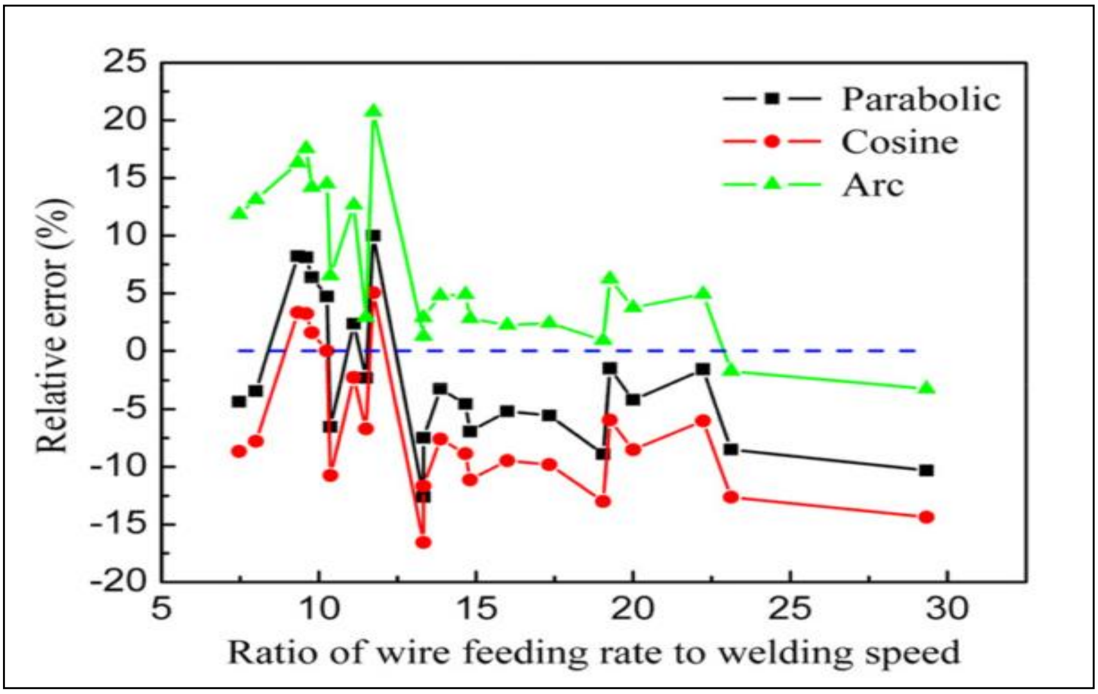


Figure 2.4. Comparison of relative error for actual and predicted area of weld bead cross-section [11]

In additive manufacturing, it is very important to model the geometry of single weld bead and multi overlapping weld bead to achieve high surface quality and dimensional accuracy of the fabricated objects. Zenxi Pan et al. [12] developed the single bead and overlapping bead model for robotic wire and arc additive manufacturing. The tangent overlapping model (TOM) is established, and the concept of critical center distance for stable multi bead overlapping process is developed.

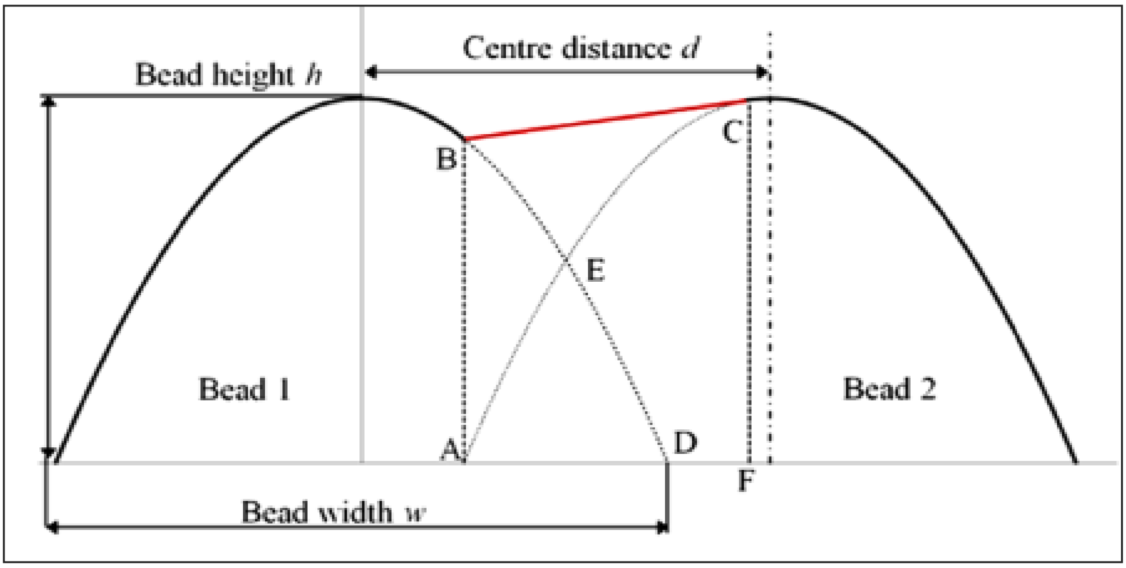


Figure 2.5. Schematic diagram of tangent overlapping model (TOM) [12]

2.4 Online monitoring for corrective compensation

Mazumder et al. [13] developed closed loop direct metal deposition (DMD) for fabrication of macro- and microstructures. This paper studied the effect of the laser processing parameter and multiple height control sensors on the characteristics of the fabricated parts.

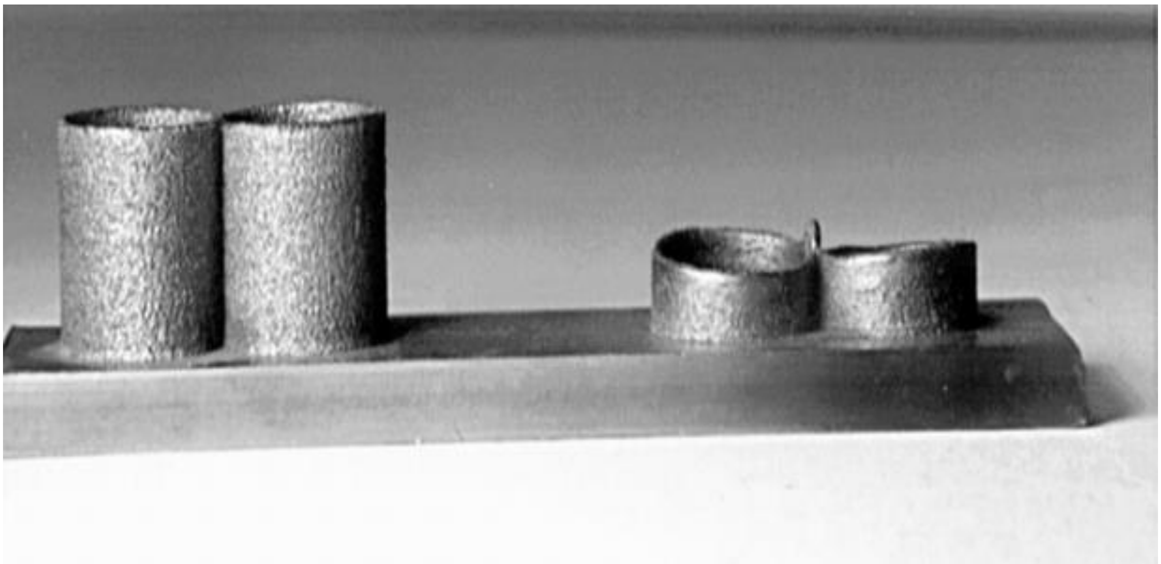


Figure 2.6. Fabrication of 8 number structure with height controller: (left) with height controller, (right) no height controller [13].

A computer vision sensing system is designed to monitor and control the geometries of the deposited weld beads using a composite filtering technique [14]. In that, a corresponding image processing technology is used to extract parameters of the deposited weld beads, and an on-line of the beads is realised based on a segmented neuron self-learning controller. It found that GMAW-based layer deposition process, combining the intelligent detection and control system, is capable of saving materials and energies more than 10% compared with the open-loop system. The deviation in the nozzle to the top surface distance (NSTD) will cause the instability of the process. J. Xiong et al. developed a passive vision system is to monitor the NSTD in layer additive manufacturing [15]. An adaptive control system is designed to keep the NSTD constant. The effectiveness is evaluated through deposition of single bead multi-layer walls, and results confirm that the process stability can be improved by the developed controller.

A. Herlic et al. [16] presented the height control strategy for laser wire deposition. In this research, a 3D scanning system is developed and integrated with robot control system for automatic in-process control of the deposition. The goal of this technique is to maintain the stable deposition means deposition of the flat surface after each deposited layer and the deviation in the layer height are compensated by controlling the wire feed rate on next deposition layer, based on the 3D scanned data, using iterative learning control.

Many kinds of literature suggest that dimensional accuracy and quality of geometry can be achieved through different processes and its process parameters, bead models, feedback technique and path planning. In that many processes uses a CNC machine to the surface finishing of the weld deposition for the geometrical accuracy. But, CNC machining is used to get a better accuracy of fabrication at the expense of material wastage and time. This approach will increase the accuracy of fabricating parts but decreases the material utilisation. Hence, this study focuses on reducing the surface waviness of a GMAW deposition layer and helps to eliminate/minimise the need of interlayer face milling.

2.5 Summary

This chapter presented the several literature surveys on different techniques and approaches to control of geometry. The different techniques for control of the deposition parameter, selection of suitable area filling paths, bead modelling for accurate prediction and online feedback system for corrective compensation of deposition are discussed.

Chapter 3

Experimental Set Up

This chapter is divided into four sections that are weld deposition setup, position, integration of welding unit with a milling machine, slicing & path planning tools for weld deposition and 3D scanner & Reverse Engineering.

3.1 Weld deposition setup

The hybrid approach uses the combination of additive and subtractive manufacturing. In this setup, GMAW unit and CNC milling machine are used to achieve the benefits of the hybrid approach. The following sections explain about the welding unit and CNC machining unit along with their integration.

3.1.1 Weld deposition unit

In this study, GMA based weld deposition unit is used to deposit the wire material to make components. This machine with TransPuls Synergic 3200 model is fully digitised and microprocessor-controlled metal inert gas (MIG) power source with maximum output 320 A. It gives good weld properties and efficiency (91%). The VR 4000 wire feeder with 4-roller driver is used to feed the filler wire through weld torch. In this study wire diameter of 0.8 mm is used and the same diameter of liner guides the wire from wire feeder to welding torch. Shielding gas with a mixture of Argon and CO_2 (i.e. 82% Argon and 18% CO_2) is used.
The power source and wire feeder for welding are shown in figure 3.1.

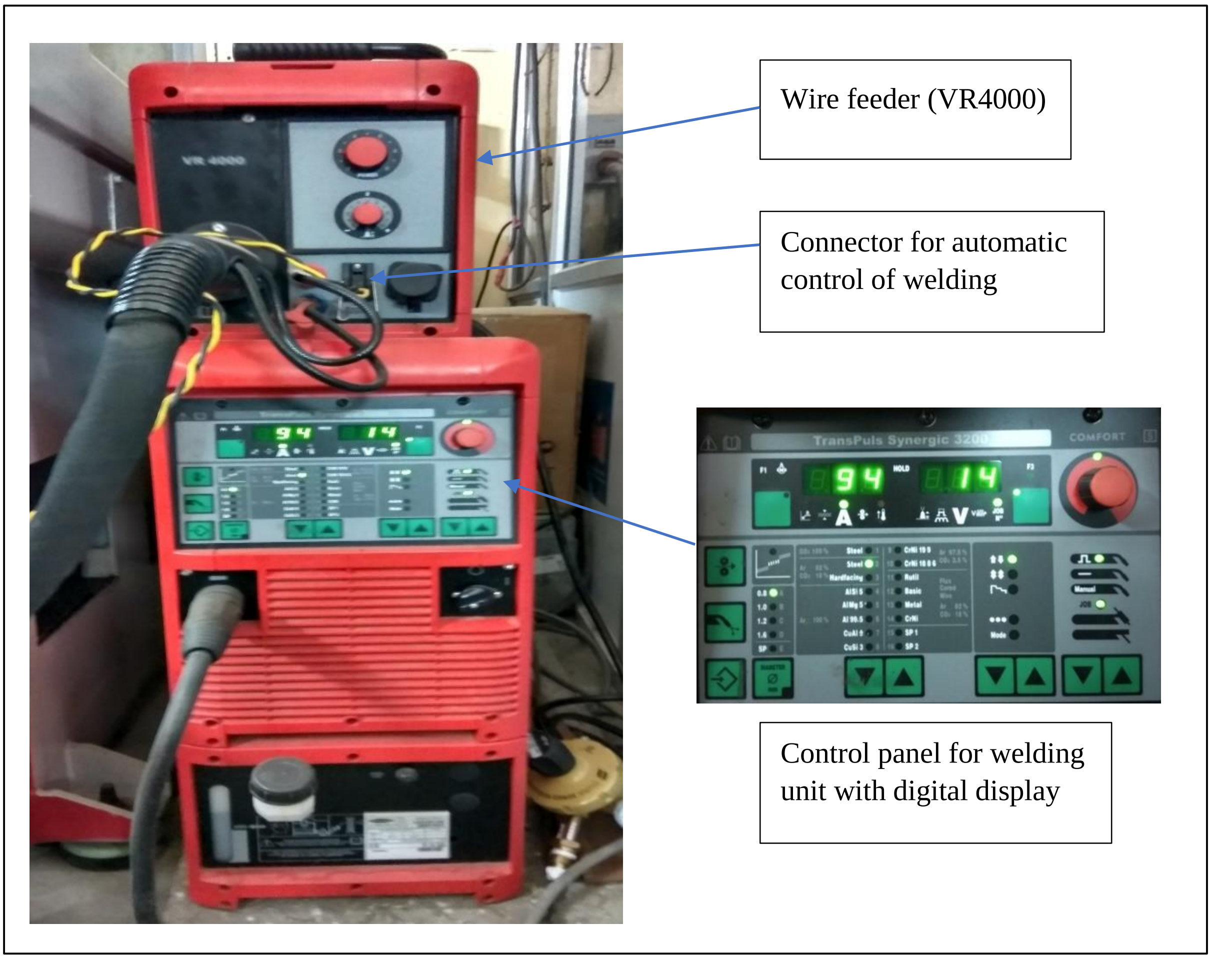


Figure 3.1. Welding power source and wire feeder

3.1.2 Motion control unit

Compact MTAB CNC milling machine is used to control the torch movement which is mounted on the spindle head of the machine. It has a three axis capability used to do machining of the deposited weld and give the torch movement along these axes. The MTAB CNC milling is shown in figure 3.2. The specification of the machine is given in table 1.

Figure 3.2. Compact MTAB 3 axis CNC milling machine

Table 1. Specification of the MTAB compact milling machine

Parameter	Value
L ×W × H (mm)	2200 × 1570 × 1250 (Approx.)
X Axis travel (mm)	250
Y Axis travel (mm)	150
Z Axis travel (mm)	250
Repeatability (mm)	± 0.005
Positional accuracy (mm)	0.010
Max. Speed of axis drive (rpm)	6000
Spindle motor speed (rpm)	4000

3.1.3 Integration of welding unit with milling machine

In the setup, GMA based welding deposition unit is integrated with the CNC milling machine. In this hybrid approach of manufacturing, GMA based welding is used as an additive manufacturing, and CNC milling machine is used as a subtractive manufacturing.
The following are some significant advantages of this combination of CNC milling and welding unit:

- Total automation of near net deposition and its surface finishing is possible.
- Integration does not require any proper design specification; thus it can easily combine with any CNC milling machine.
- Arc weld deposition is economical, faster, simple and safer than laser and EB based deposition.
- The weld deposition unit is mounted the on same spindle head, so no additional control is required for axes movement.
- It is easy to switch between weld deposition mode and CNC regular mode.

Figure 3.3 shows the integration of weld deposition unit to the CNC milling machine head.

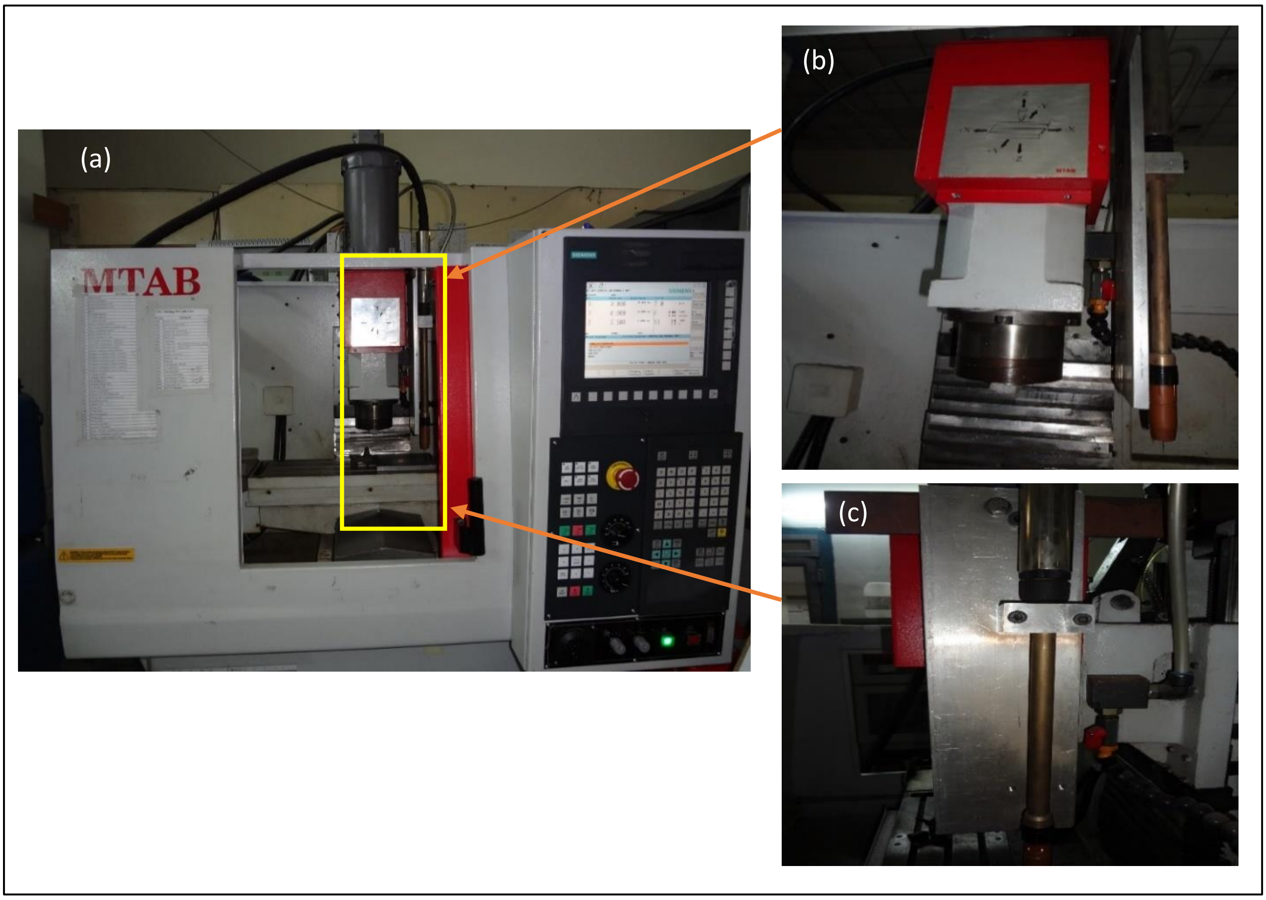


Figure 3.3. Construction of welding torch with the CNC milling spindle head: (a) MTAB milling machine with attached welding torch. (b) Front view. (c) Side view

3.2 Slicing & path planning tools for weld deposition

In this study, the welding torch path is to be generated to make the metallic components. There different type of softwares are available to generate a path for a welding torch. The CNC machine needs a G-codes that can be produced from different slicing software. There are many open source softwares such as Slic3r, Kisslicer and Cura can be used to generate G-codes for the process. It is made for polymer deposition. But, these softwares can be used for code generation of weld deposition path. Among these open sources, slic3r has a capability to generate code for weld deposition path. Hence, this study uses a Slic3r package in which input file must be in STL format. There are many softwares available like Pro-E, Catia, SolidWorks, Solid Edge ST8, etc. which can produce STL file of any component. Here, it uses the solid edge to produce input model for Slic3r. The difference between some of the parameters of fused deposition modelling and welding deposition with slicing softwares is shown in table 2.

Table 2. Difference between parameters of FDM and welding deposition in slicing software

Parameter	FDM	Weld-deposition
Layer thickness	0.1 - 0.3	1 – 3
Outer loops	Yes	No
Density	Vary	100 %
Print speed	Low	High
Temperature	Required	No
Support material	Applicable	Not applicable
Colour	Applicable	Not applicable
Multiple extruder	Can use	Cannot use
Surface finishing	Less	More

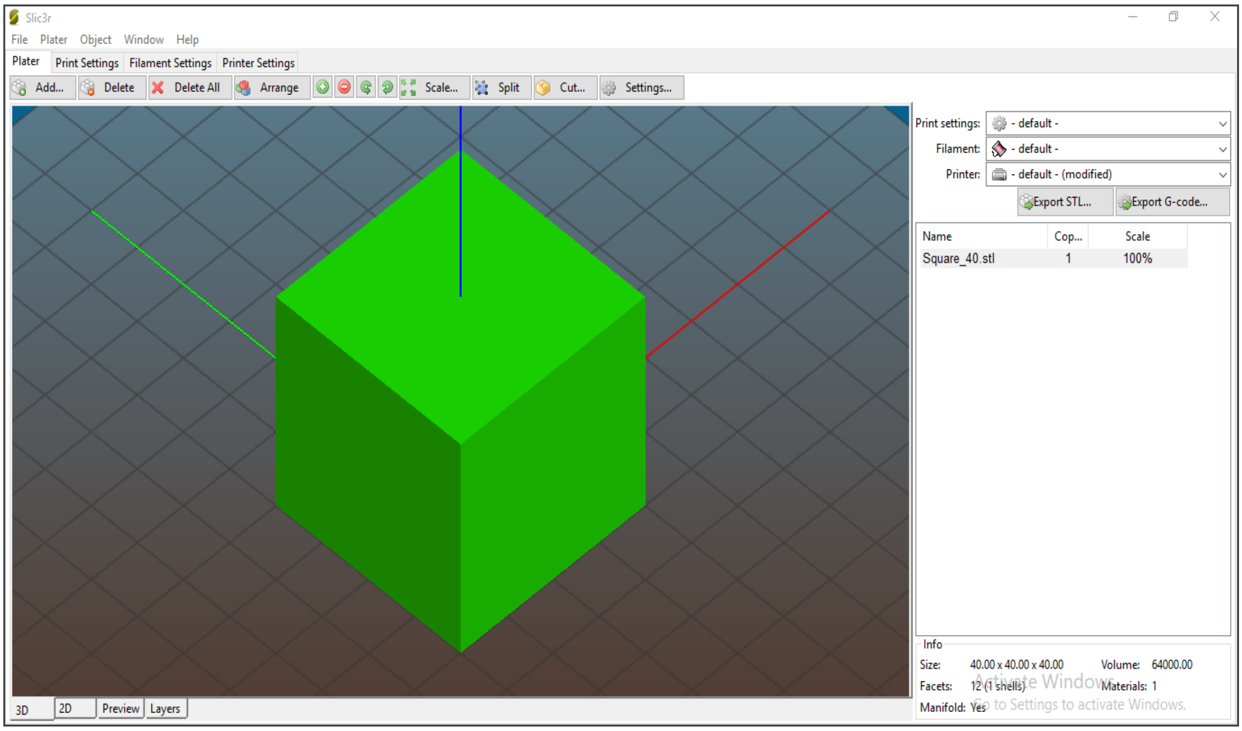


Figure 3.4. Silc3r plater window with input of square geometry

The loaded geometry of square cube (40 mm side) in Slic3r software is shown in figure 3.4. The range configuration settings for Slic3r is given in table 4. that can be modified for different geometries and area filling paths with a different step-over values. Further, visualisation and editing of the generated path can be done in CIMCO Edit V5 software.

3.3 A 3D scanner & Reverse Engineering

The data cloud is needed to the evolution of waviness of deposited weld surface. A 3D scanner is used to get that data cloud with laser scanning. Then that scanned data points are used to get the waviness value which is then used to find an appropriate area filling paths for weld deposition.

A 3D scanner is a device that analyses a real-world object to collect data on its shape, and the collected data then can be used to construct digital three-dimensional models. The hand held FARO 3D scanner arm is shown in figure 3.5. It creates a 3D image through the triangulation mechanism. The principle of laser triangulation mechanism is shown in figure 3.6.

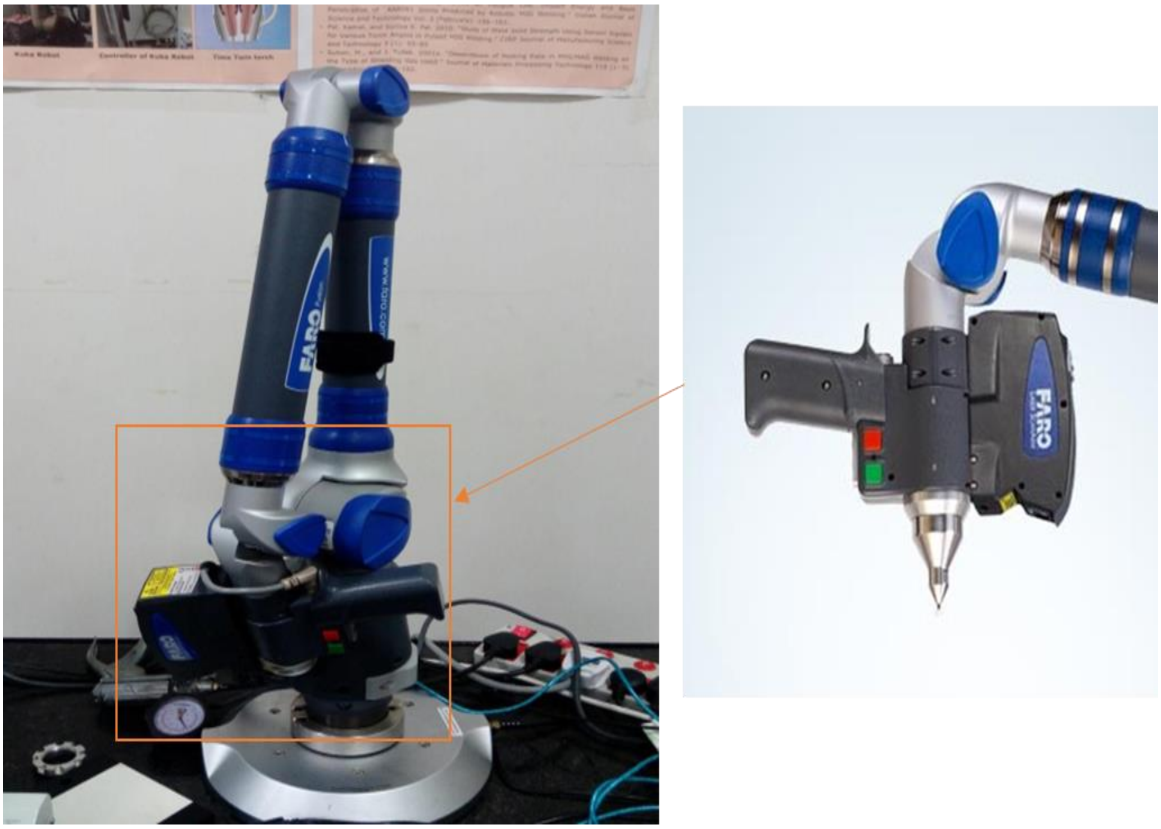


Figure 3.5. A 3D FARO scanner with an enlarge hand held arm

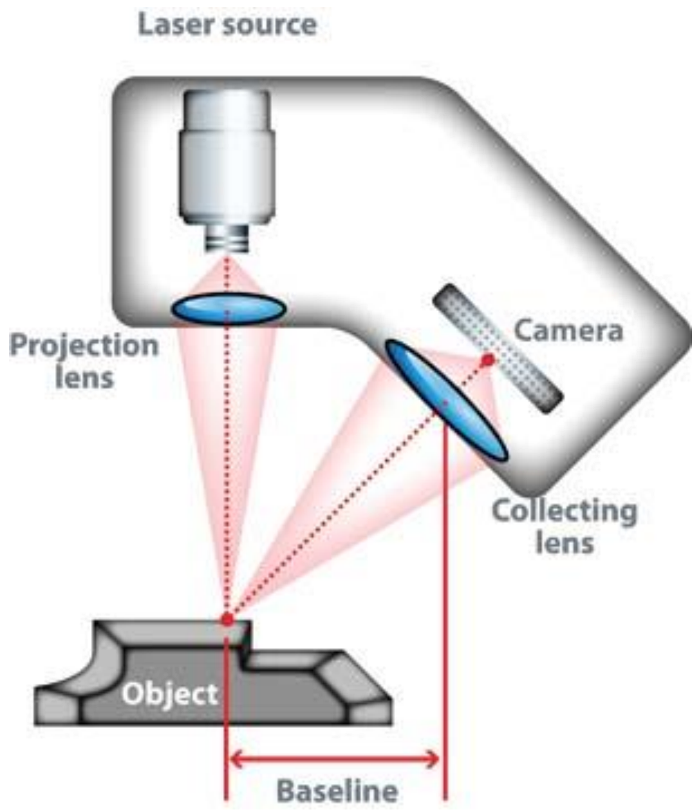


Figure 3.6. Principle of 3D laser scanning

Laser triangulation is accomplished by projecting a laser line or point on to object and then capturing its reflection with a sensor located at a known distance from the laser's source. A 3D object or surface is captured in the form data cloud. That data cloud further processed in Geomagic software that is connected to FARO arm to collect the scanning data. When the raw data cloud is captured through scanning arm, it will be having holes, spikes and some redundant data that has to remove for better processing of data cloud.

3.4 Summary

This chapter described an information of weld deposition unit, CNC milling machine, slicing & path planning tools and 3D scanner. The construction of weld deposition unit with CNC milling machine is discussed. A 3D scanner which is used to get a data cloud of the weld surface and its principle is discussed.

Chapter 4

Single-layer deposition experiments

4.1 Experimental methodology

This chapter describes the experimental technique and approach for the investigation of path planning for single-layer weld deposition. Firstly, the geometry to be deposited, welding material and process parameters are selected. Copper coated low carbon steel (ER70S-6) is used as a filler material for the weld deposition. It is used wire material with the diameter of 0.8 mm. The properties of filler wire material are listed in Table 3. These experiments are carried out to find the surface waviness value and material utilisation efficiency of single-layer deposition, so that efficient area filling path for deposition can be observed. Those are done with different area filling patterns at different step-over values. The configuration process parameters for Slic3r and CNC machine to both single-layer and multi-layer experiment are listed in Table 4.

Table 3. Weld material properties

Description	
AISI specifications	ER70S-6
Type	Low carbon steel
Commercial name	MW-1 from ESAB
Wire diameter (mm)	0.8
Type of structure	Solid
Shielding gas	82% Ar +18% CO_2
Yield tensile strength (MPa)	430
Ultimate tensile strength (MPa)	595
Density (kg/m^3)	7833.413

Table 4. Configuration process parameter of Slic3r and machine

Configuration setting	Parameters	Values
Weld-deposition Setting	Layer Height (mm)	1.5 – 2
	Perimeter	0
	Step-over value (mm)	1, 1.25, 1.5, 1.75 & 2
	Solid top layer	0
	Solid bottom layer	0
	Fill density	100%
	Fill pattern	Rectilinear
	Skirt	0
	Solid infill speed (mm/s)	6 – 25
	First layer speed (mm/s)	6 – 25
	Extruder	1
	Extrusion width (mm)	1.822 – 4.423
	Infill overlap	0
Filament setting	Diameter (mm)	0.8 & 1.2
	Extrusion multiplier	1
	Nozzle diameter (mm)	1.7352 – 4.2123
	Wire material	ER-70S-6 (copper coated)
	Current (amp)	95 – 165
	Wire feed (mm/s)	4.7 – 10
	Diameter of milling cutter (mm)	25
	Spindle speed (rpm)	2000 – 3000
	Nozzle gap (mm)	8 – 12
	Shielding gas	82%Argon+18%CO_2
	Gas flow rate (L/min)	8 – 12

The main objective of this experimentation is to calculate the waviness value and material utilisation efficiency for different area filling paths with different step-over values at constant process parameters.

Figure 4.1 shows the flowchart of the single-layer deposition experimentation. The automation of process is achieved through MTAB milling machine. Process planning is attained from slicing software (Slic3r & CIMCO Edit V5). Here, GMA based weld deposition uses a synergic mode integration of welding. First CAD model (square cube with 40 mm side) in STL format is made by using modelling softwares like Pro-E, Solid Edge ST8, etc. This file is used as an input in Slic3r to generate G-codes for torch movement path. Different parameters such as step-over, wire diameter, layer thickness, nozzle diameter and torch speed can be given in to Slic3r while slicing the geometry. This generated path can be visualised and edited in CIMCO software.

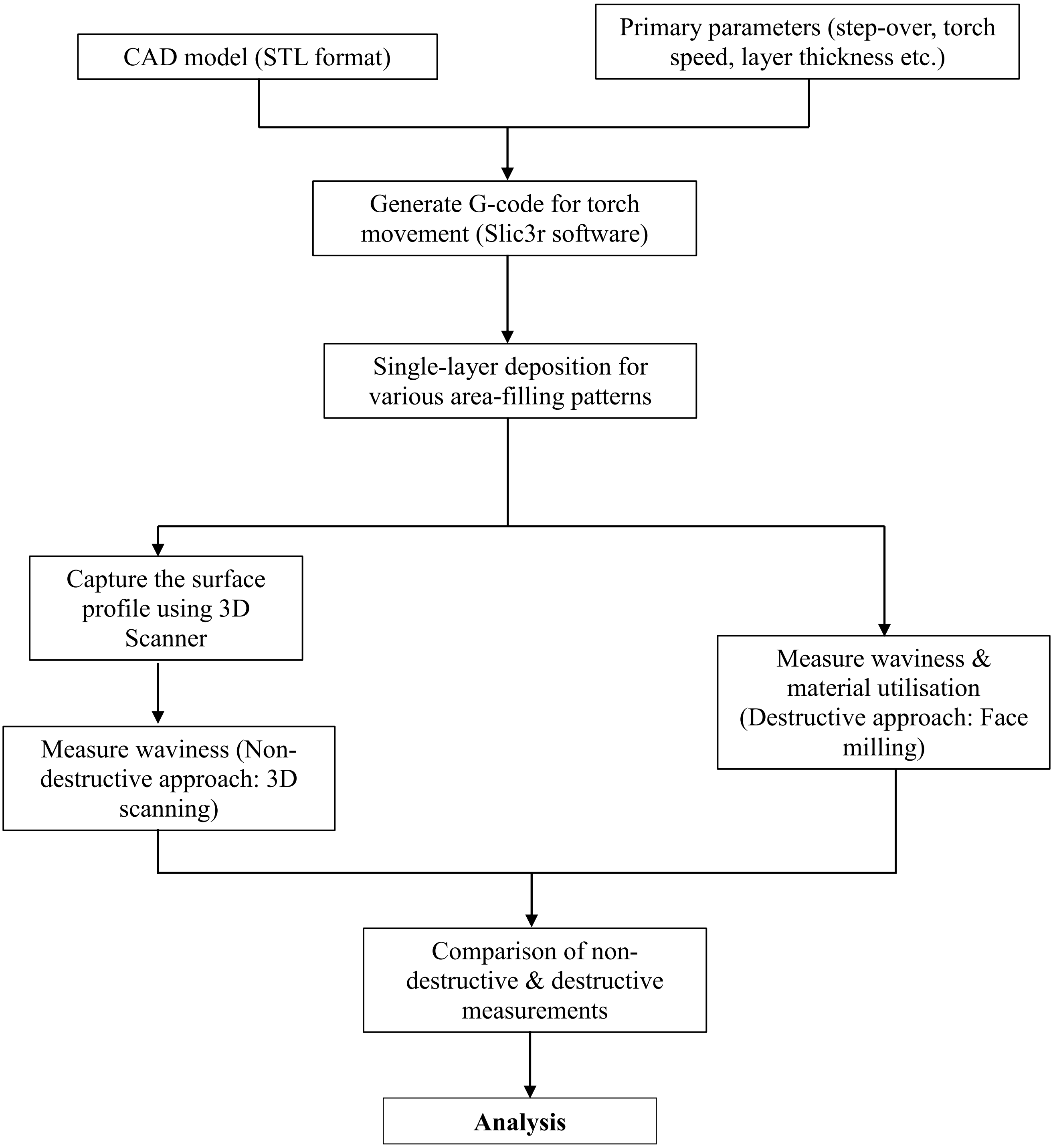


Figure 4.1. Flowchart of process of single-layer experiments

Figure 4.2 shows the command windows of Slic3r software for slicing of the cube (40 mm sides) with a step-over value of 2 mm. After setting all this process parameter in Slic3r, it slices CAD model into equal layer thickness up to their total height (40 mm). Then it generates G-codes for every layer according to area filling pattern, step-over value, extrusion width, and nozzle diameter which are set in the process configuration setting.

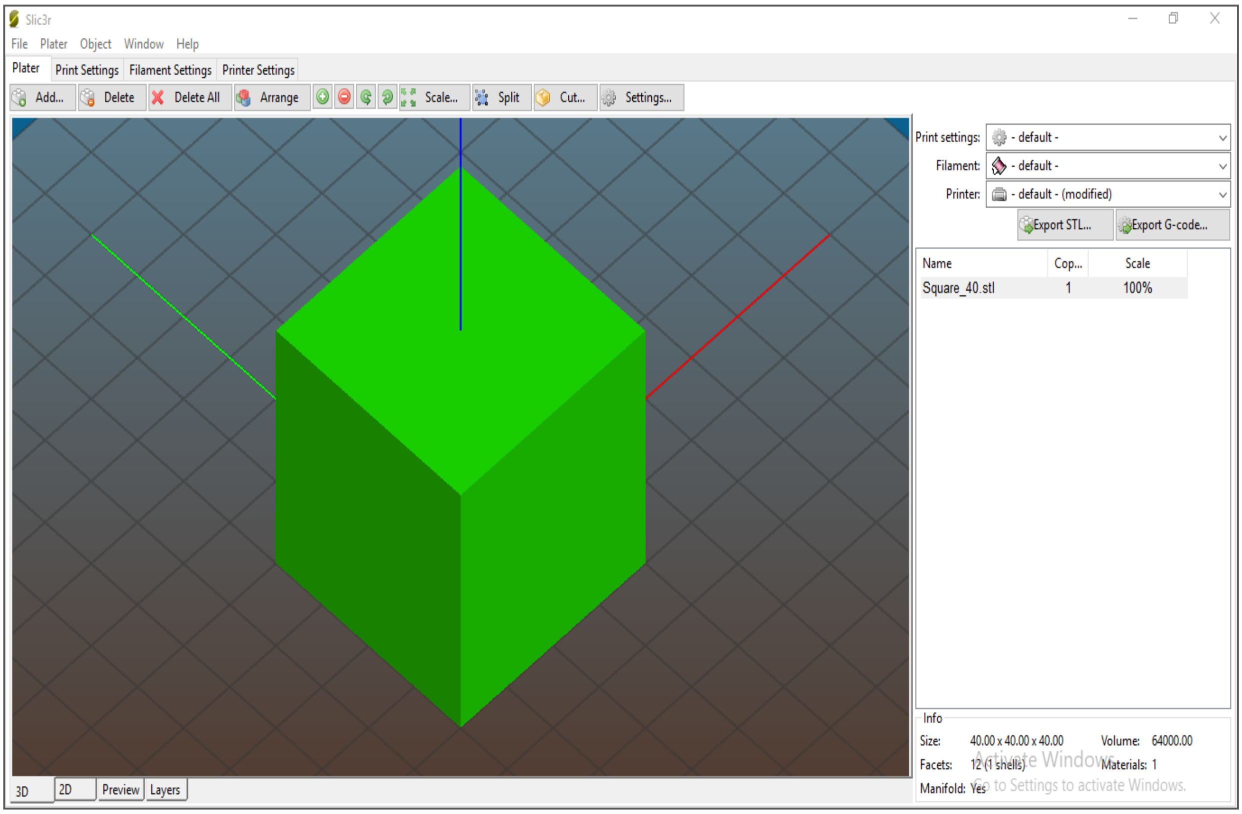


Figure 4.2. Plater window in Slic3r software with input of square geometry

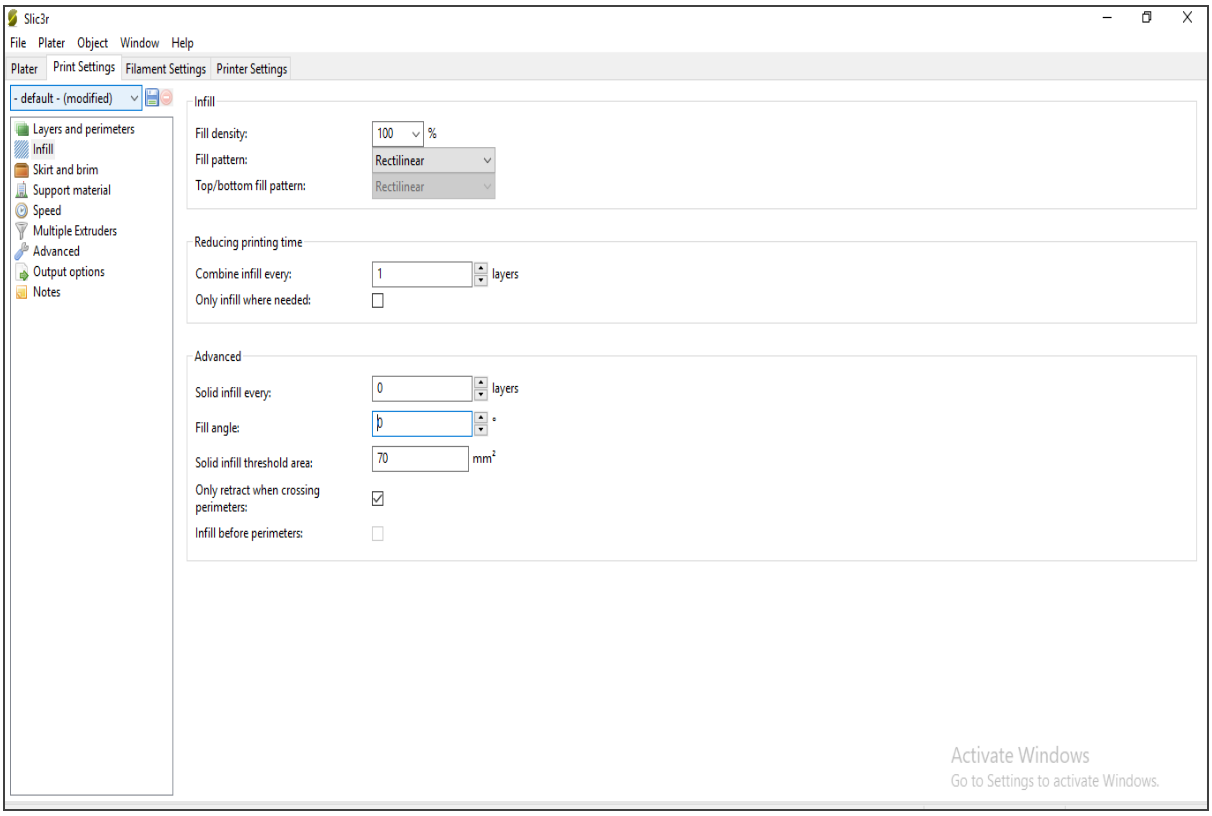


Figure 4.3. Infill command window in print settings

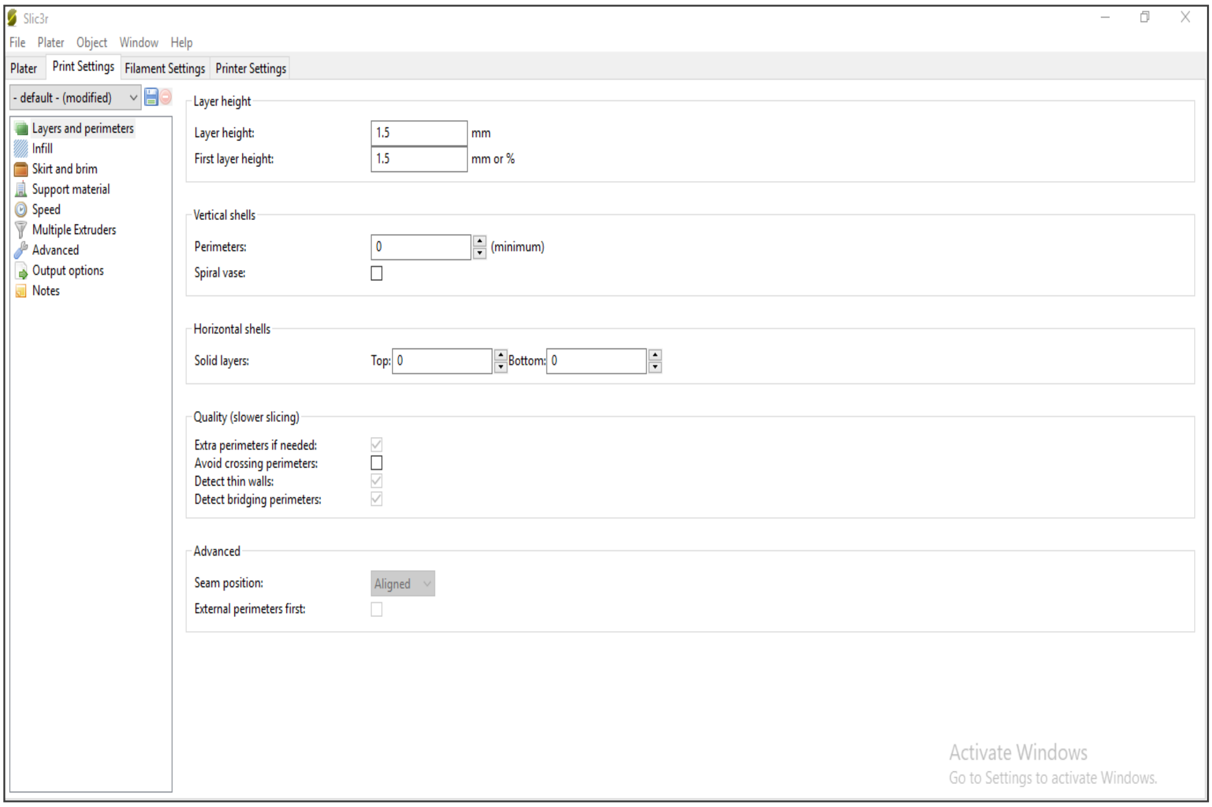


Figure 4.4. Layers and perimeters command window in print settings

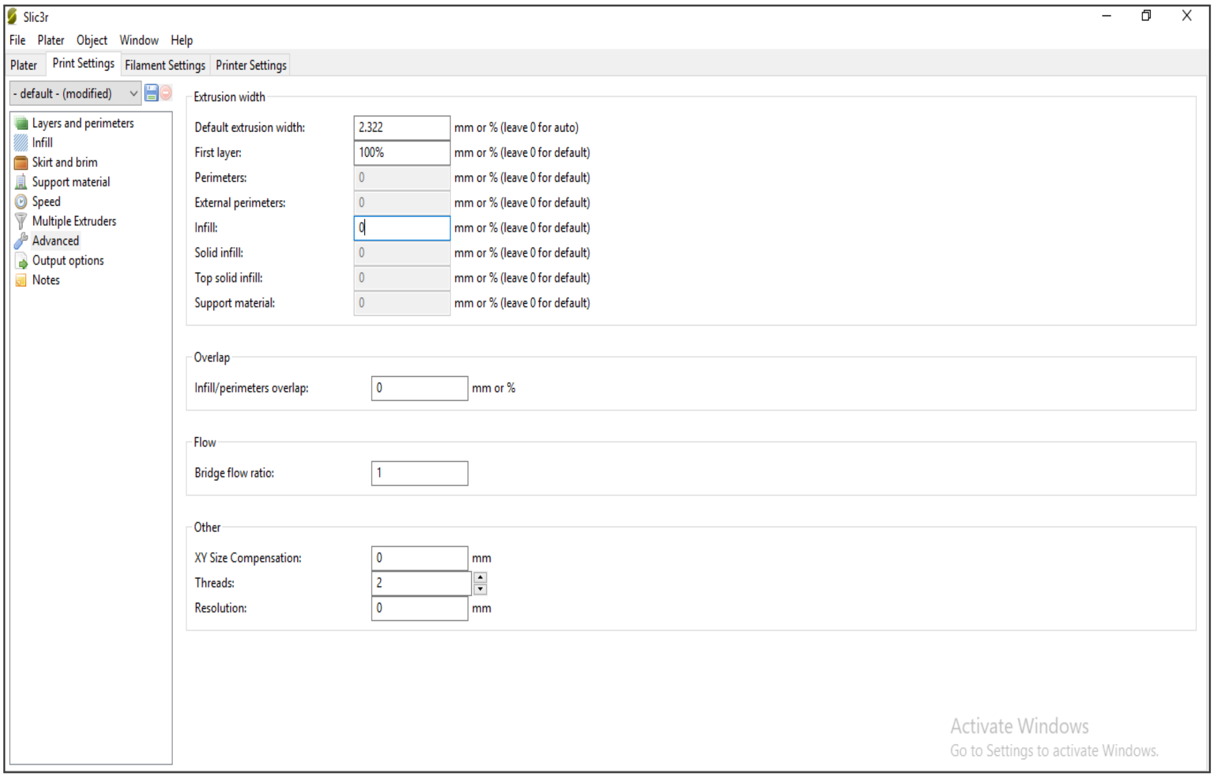


Figure 4.5. Figure. Advance command window in print settings

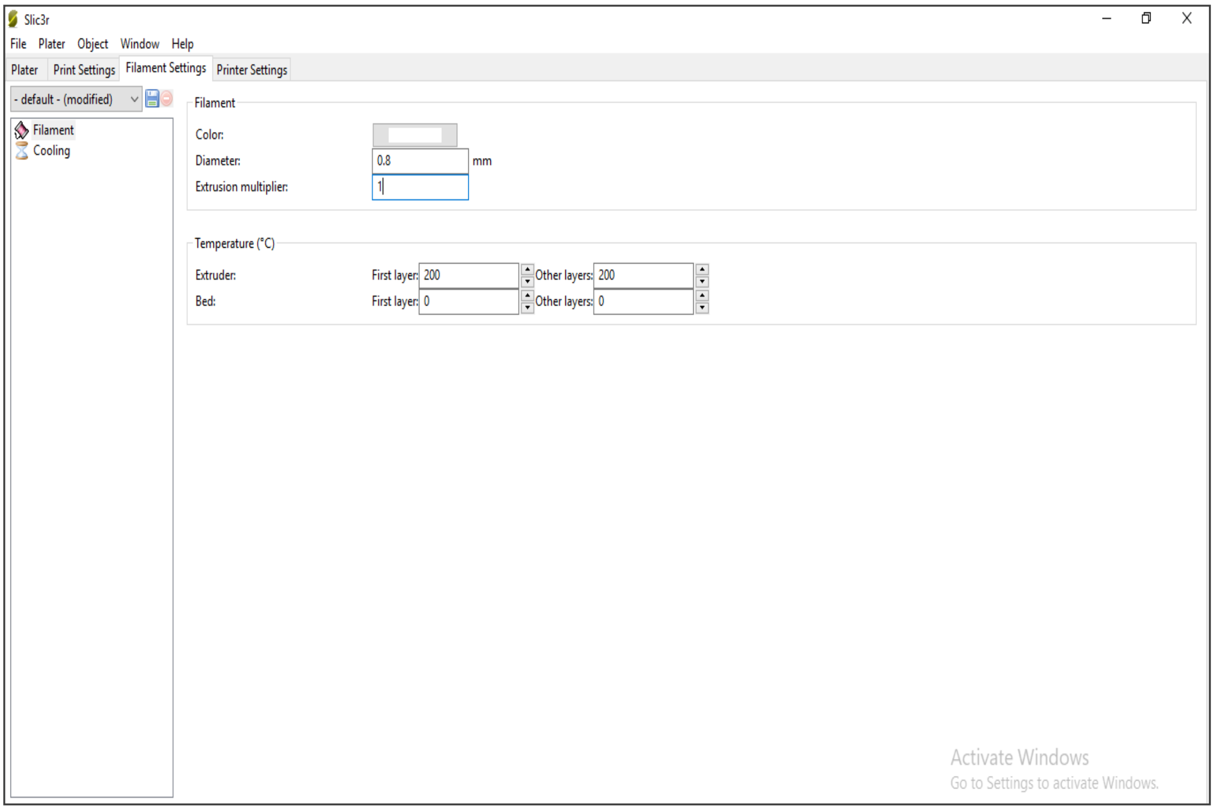


Figure 4.6. Filament settings window

The movement of the welding torch is equivalent to movement of CNC spindle head. Thus it will be accurate with same CNC program code which is generated by Slic3r. The generated code can be visualised in CIMCO software; there it can be clear that how G-code will generate the path for a welding torch. This software can generate new G-code for weld deposition path by writing. Figure 4.7 shows the single-layer welding path along with G-codes for step-over of 2 mm that generated by Slic3r. The different welding deposition patterns with a step-over of 2 mm are shown in figure 4.8.

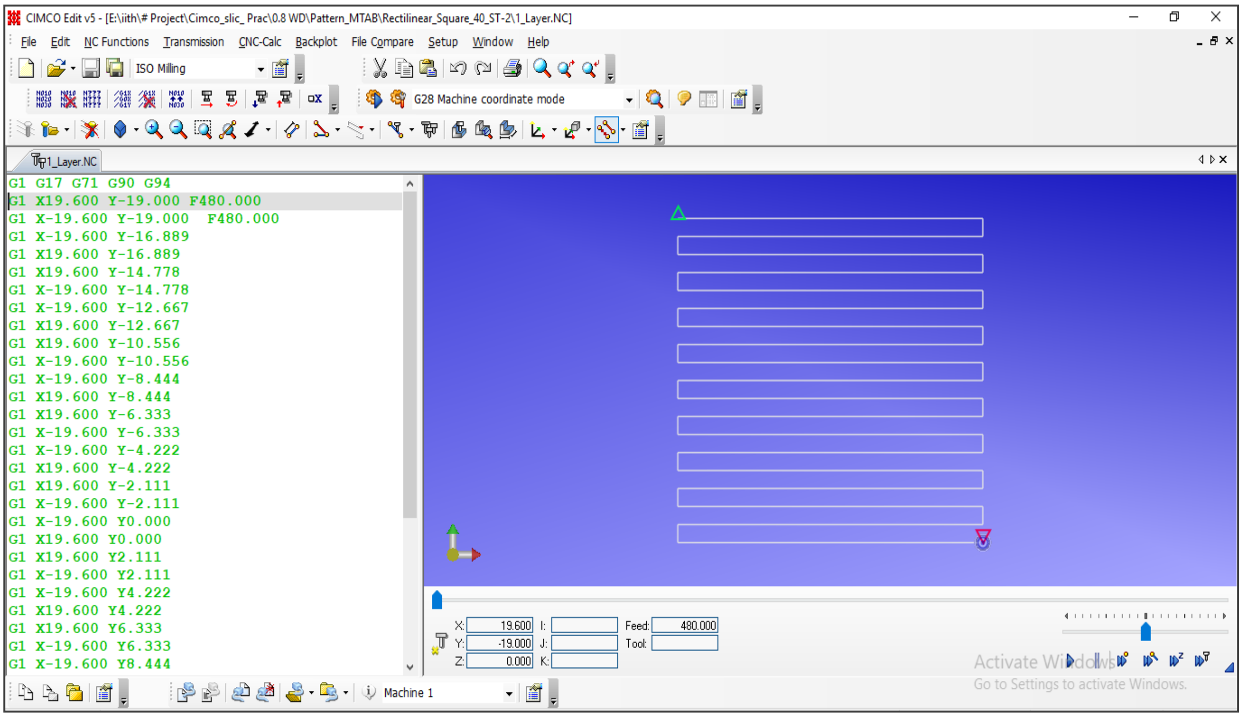


Figure 4.7. Path visualisation of generated code for step-over of 2 mm in CIMCO software

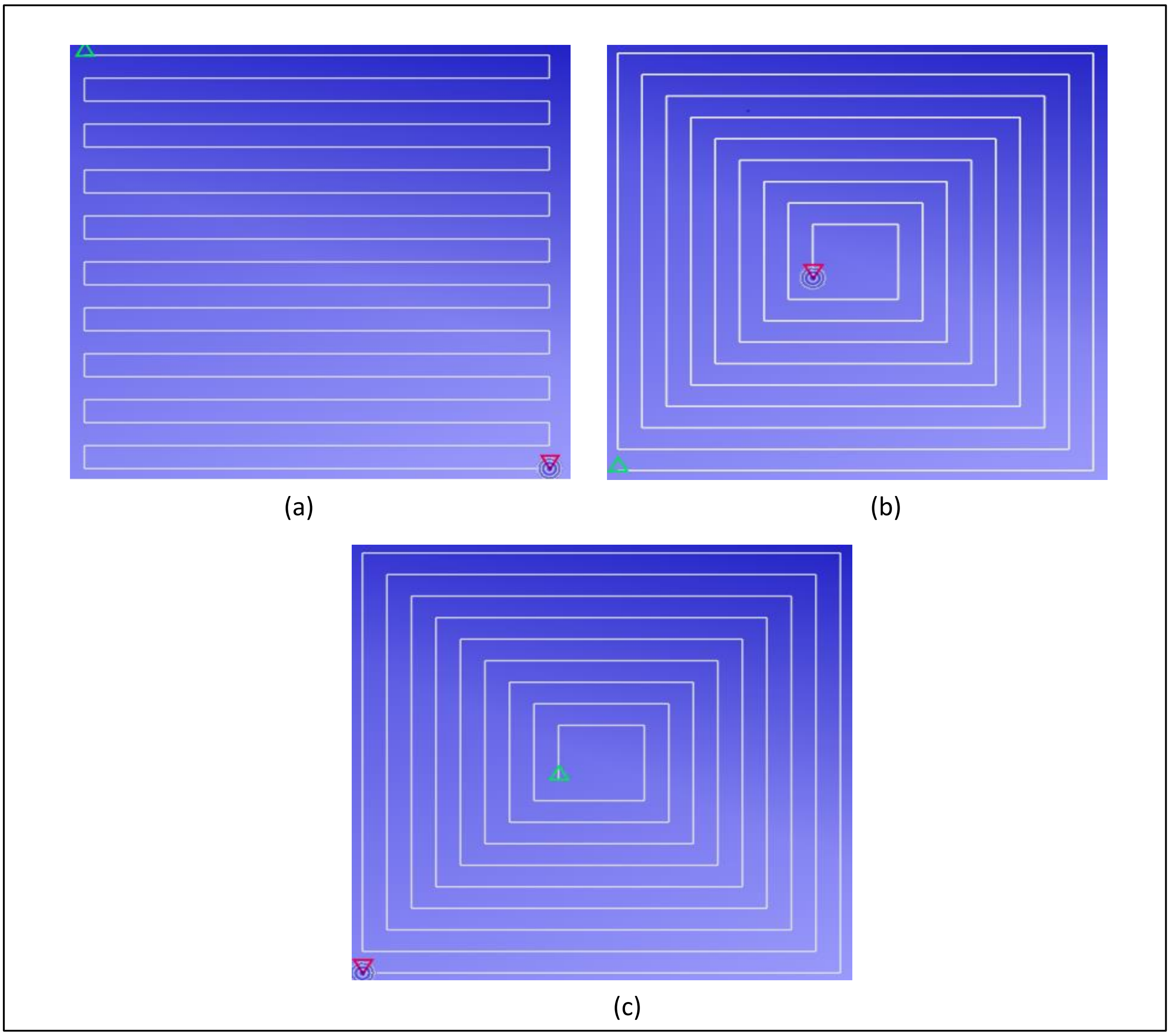


Figure 4.8. Welding deposition patterns: (a) Rectilinear path (b) Spiral-out (c) Spiral-in

Firstly, the GMAW based welding deposited the single-layer by keeping constant CTWD (Contact Tip Work Distance) i.e. 9-10 mm. And welding efficiency can be calculated to know how the GMAW process efficiency resulted for different path patterns. It can be calculated by their theoretical and experimental weight of depositions. It is the ratio of experimental weight to theoretical.

- Experimental weld deposition = A-B

Where, A= Weight of plate after deposition
B= Weight of base plate before deposition

- Theoretical weld deposition = $\rho \times \pi (r)^2 l$

Where, ρ= Density of ER70S-6 filler wire material
r= Radius of the filler wire
the length of wire deposited (l)= wire feed rate × welding time

To calculate waviness value, a 3D scanner is used. That collects the data cloud of weld surface and then processed in MATLAB code to find R_t value (i.e. maximum distance from the highest point to lowest point of the data cloud). It can be called as non-destructive approach. Laser scanning captures the data cloud of weld surface and stored in Geomagic software in the form of STL file. It has left holes and spikes after scanning the weld surface, and that improper scanned surface is relieved by post-processing in the software. The only 30 mm square portion is taken from the centre of deposited layer for waviness findings. The extra part of scanning will be removed because it has discontinuous and unstable deposition at the edges. The code is written in MATLAB to read the STL file of refined data cloud and to find R_t value. The Same procedure will be followed to get waviness value of weld deposition for different area filling patterns and step-over values.

Figure 4.9 & Figure 4.10 shows the single deposited layer of rectilinear path & further processing of data cloud of that weld surface in the Geomagic software.

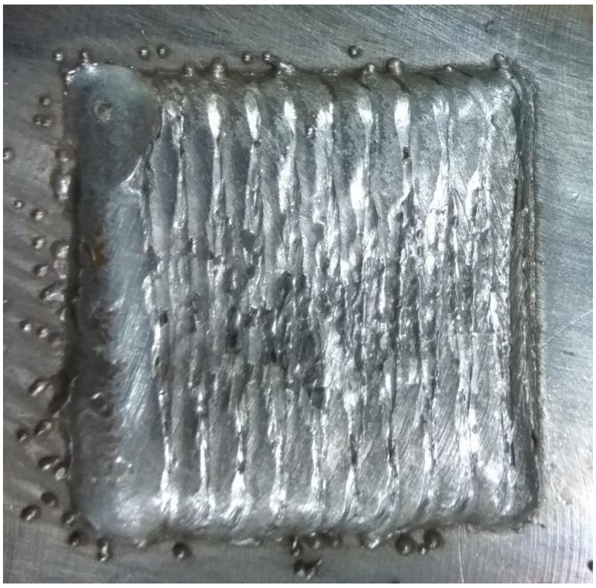


Figure 4.9. Single-layer deposition for rectilinear path

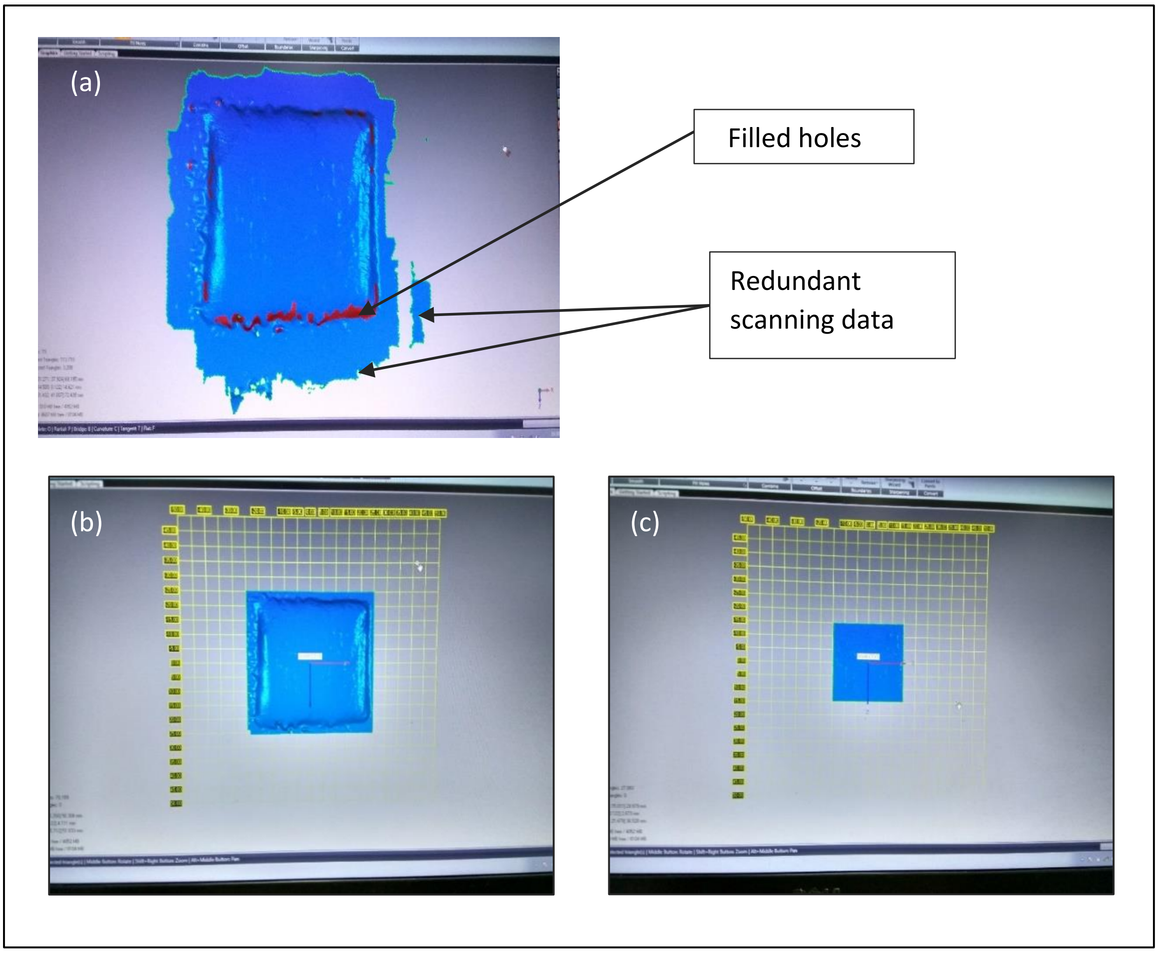


Figure 4.10. Data cloud processing in Geomagic software: (a) Raw data cloud scanned by FARO laser arm and filled hole (b) Removed redundant scanning data (c) Selected data of 30×30 mm from the centre

Now, waviness value can be calculated by face milling of weld surface to compare material utilisation efficiency and with the non-destructive approach. It is the destructive approach in which face milling cutter is used to clean an uneven surface up to no-void criteria of deposited weld surface. The waviness value (R_t) is measured from highest point on the surface to the lowest point of the surface i.e. no-void surface. The material utilisation efficiency is calculated to find efficient area filling path.

It can be calculated as,

$$\text{Material utilisation efficiency} = \frac{\text{Weight of deposition after face milling}}{\text{Weight of deposition}}$$

4.2 Results & Discussion

Some preliminary experiments are carried out to find the suitable process parameters for single-layer and multi-layer deposition experiments. It is observed with changing current for different welding speed. The surface of deposition should be prepared (face milled) before starting the experiment to get good deposition. Figure 4.11 shows the deposition of the single bead with different torch speed and welding current.

Figure 4.11. Deposited Single bead for torch speed of 400 & 600 mm/min with different current (95-185)

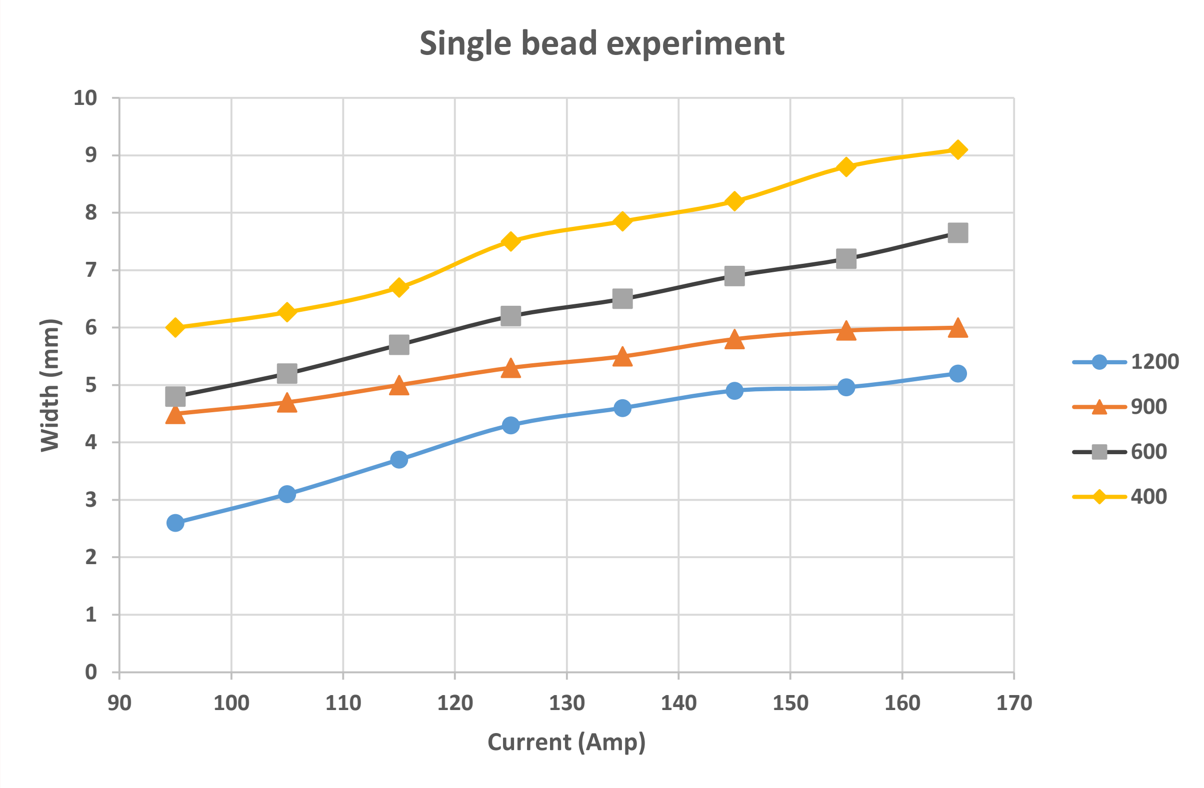
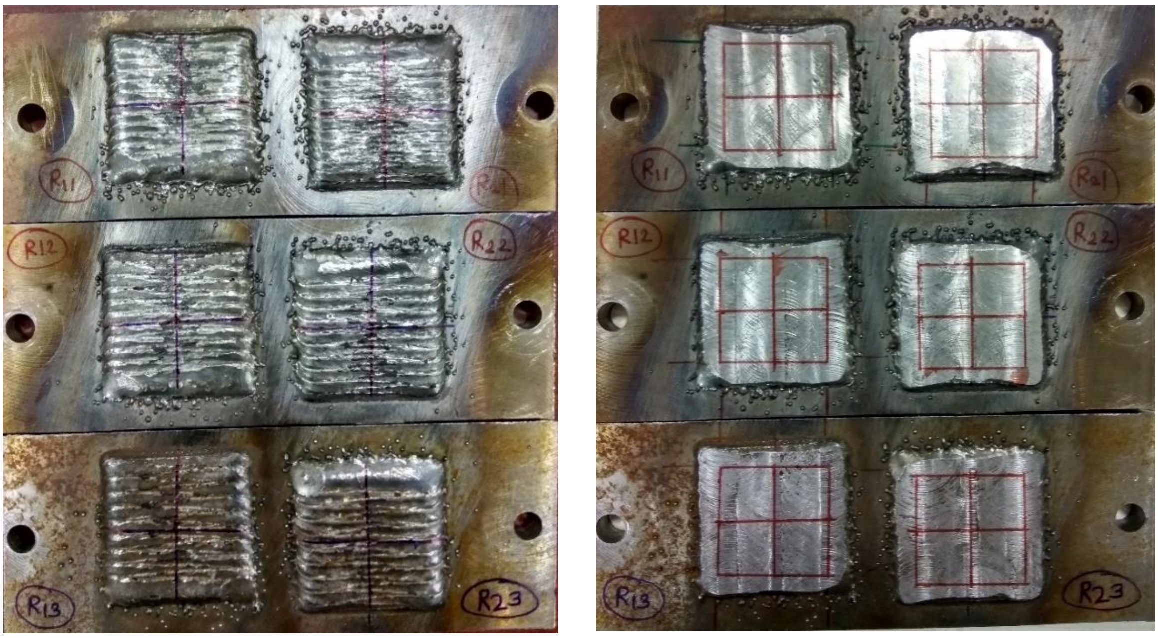


Figure 4.12. Experimental finding of the width with different current for different torch speed

The figure 4.12 summarises the experimental findings of the same. The width is calculated for different torch speed with the corresponding current. These experiments are carried out with four torch speed values (400, 600, 900 & 1200) along with a range of current (95 Amp to 165 Amp).

The average width of deposited beads is measured using digital Vernier caliper along with their length. The main intent of this experiments is to find the efficient torch speed with less current. From observations of the graph (Figure 4.12), torch speed of 480 mm/min and current of 95 Amp are selected for further experiments.

A single-layer of square (side of 40 mm) geometry is deposited for different area filling paths with constant current and torch speed. The process parameters for single-layer deposition are given in table 5. The surface waviness of deposited surface is caaalculated by a laser scanning. After getting the waviness value from the non-destructive approach, the deposited surface is further milled by CNC milling machine to calculate the R_t values and material utilisation efficiency. The edges of deposited layer are not considered while measuring the waviness value. That value is measured only in the square of 30 mm from the centre of deposited geometry. The deposited single-layer for the rectilinear path with a different step-over and after surface milling for the same is shown in figure 4.13.



(a) (b)

Figure 4.13. Single-layer deposition of rectilinear path: (a) Before surface milling (b) After face milling

Table 5. Process parameter for single-layer experiments

Parameter	Value
Layer thickness (mm)	1.5
Step-over value (mm)	1, 1.25, 1.5, 1.75 & 2
Current (amp)	95
Voltage (volt)	21.7
Wire feed rate (mm/s)	90
Gas flow rate (L/min)	10
Torch speed (mm/min)	480
Milling cutter speed (rpm)	2500

The experiments of a single-layer for different area filling paths are carried out to observed the welding efficiency, the material utilisation efficiency and relative R_t values of destructive & non-destructive approach. Welding efficiency of this GMAW process is found around 95 %. The material utilisation efficiency for different area fillings paths with a different step-over value is shown figure 4.14. From this graph, one can have observed the efficient area filling path for single-layer deposition. The rectilinear and spiral-out paths have more efficiency than spiral-in the path. The rectilinear and spiral-out has nearly same efficiencies for higher step-overs (i.e. 1.5-2 mm). When the step-over is decreased less than 1.5, then material utilisation efficiency started increasing for the rectilinear path and decreasing for spiral-out and spiral-in path. Hence rectilinear path can be used for less value of step-over for deposition and spiral-out a path for the higher value of step-over. As material utilisation efficiency is quantitatively nearly same for rectilinear and spiral-out filling paths, this study is more focused on these paths for further multi-layer experiments.

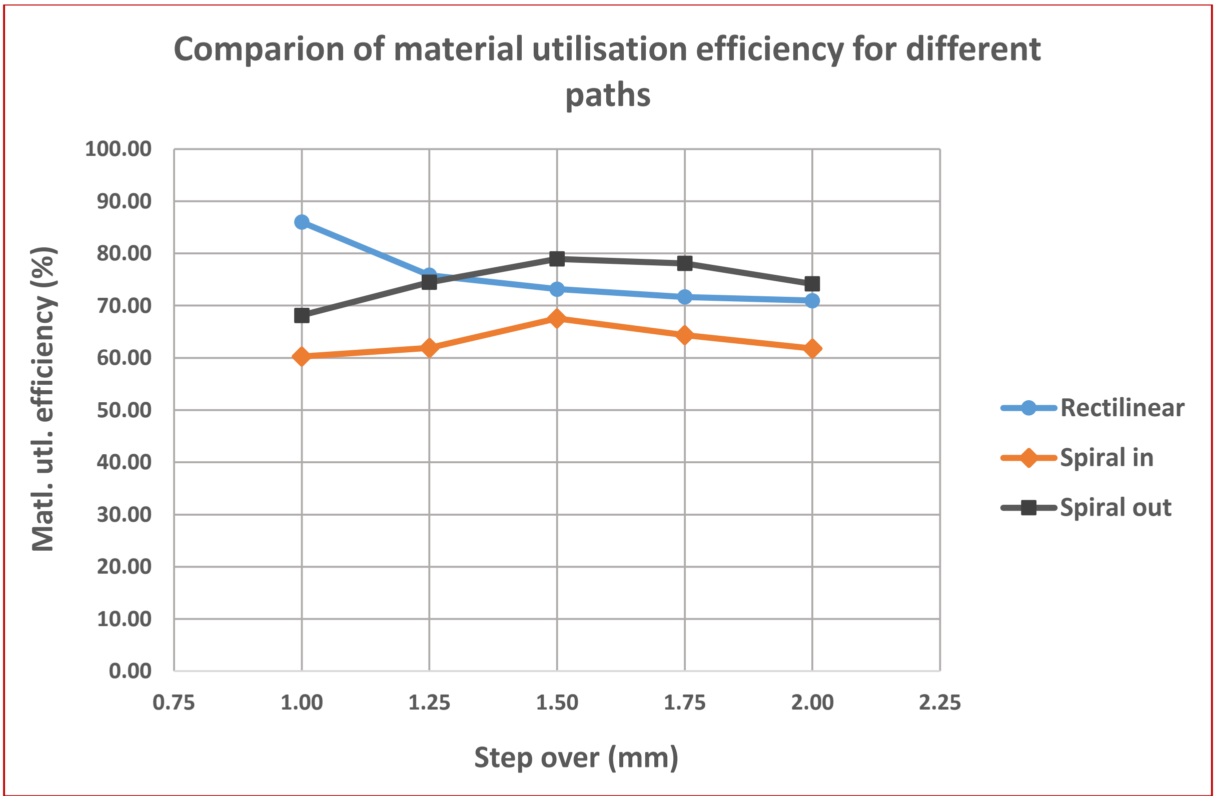


Figure 4.14. A graph of single-layer experiments of material utilisation efficiency for different area filling paths at different step-overs

To calculate R_t value from the destructive approach, weld deposited surface is chopped up to the no-void surface by a milling machine. This approach is an uneconomical due to material wastage and time-consuming. To avoid this expensive approach, the non-destructive approach is used to calculate waviness value without any material wastage. The waviness values from both approaches are compared to check the relative difference between them. The relative comparison of waviness values from destructive and non-destructive approach is shown in figure 4.15. The quantitative difference between these two approaches is not sizable. The Relative percentage difference between these two approaches is around 7.5. Thus, to calculate waviness values of multi-layer experiments non-destructive approach can be used.

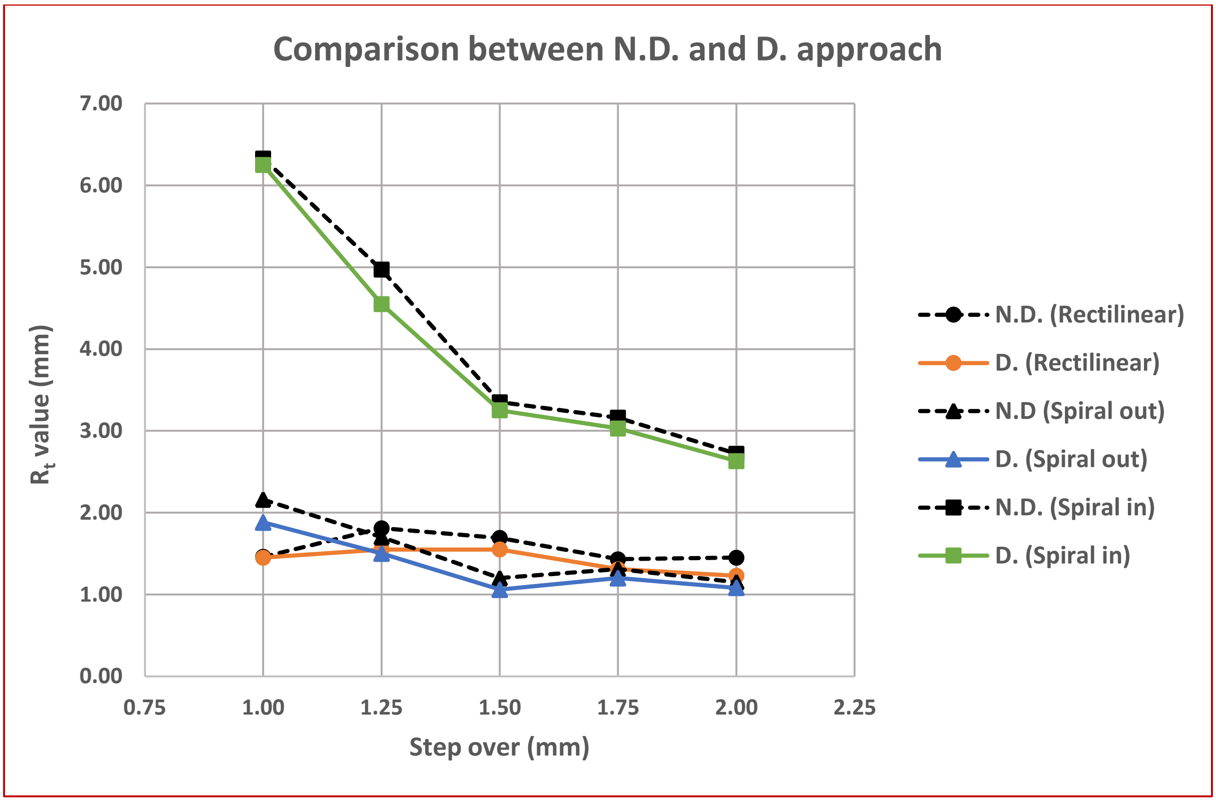


Figure 4.15. Comparison of waviness value between non-destructive and destructive approach

4.3 Summary

Preliminary single bead experiments are carried out with different torch speed and different current to get suitable process parameters (i.e. torch speed and welding current). These parameters is used for both single-layer and multi-layer experiments. Then, single-layer experiments are conducted to get an efficient area filling pattern at different step-over values. In this experiments, surface waviness which is calculated by destructive and non-destructive approach is compared. And material utilisation efficiency is calculated to find an efficient area filling pattern for a given square geometry.

Chapter 5

Multi-layer deposition experiment

5.1 Experimental methodology

Single-layer experiments are performed for investigate the comparison between the destructive and non-destructive approach to calculate surface waviness value. The non-destructive approach is used a 3D scanner to measure surface waviness, and the destructive approach used face milling to measure surface waviness by chopping material. This experiment is focuses to find surface waviness and maximum possible height for different patterns.

Figure 5.1 shows the flowchart of multi-layer deposition experiments path. Process planning for this experiment is same as of single-layer experiment. First CAD model (square cube with 40 mm side) in STL format is made through modeling software like Pro-E, Solid Edge ST8, etc. This file is used as an input in Slic3r to generate G-codes for welding torch path. From generated multi-layer path of G-codes of the cube, select the only single-layer path code and insert that code into CNC machine to deposits the geometry up to the fifth layer.

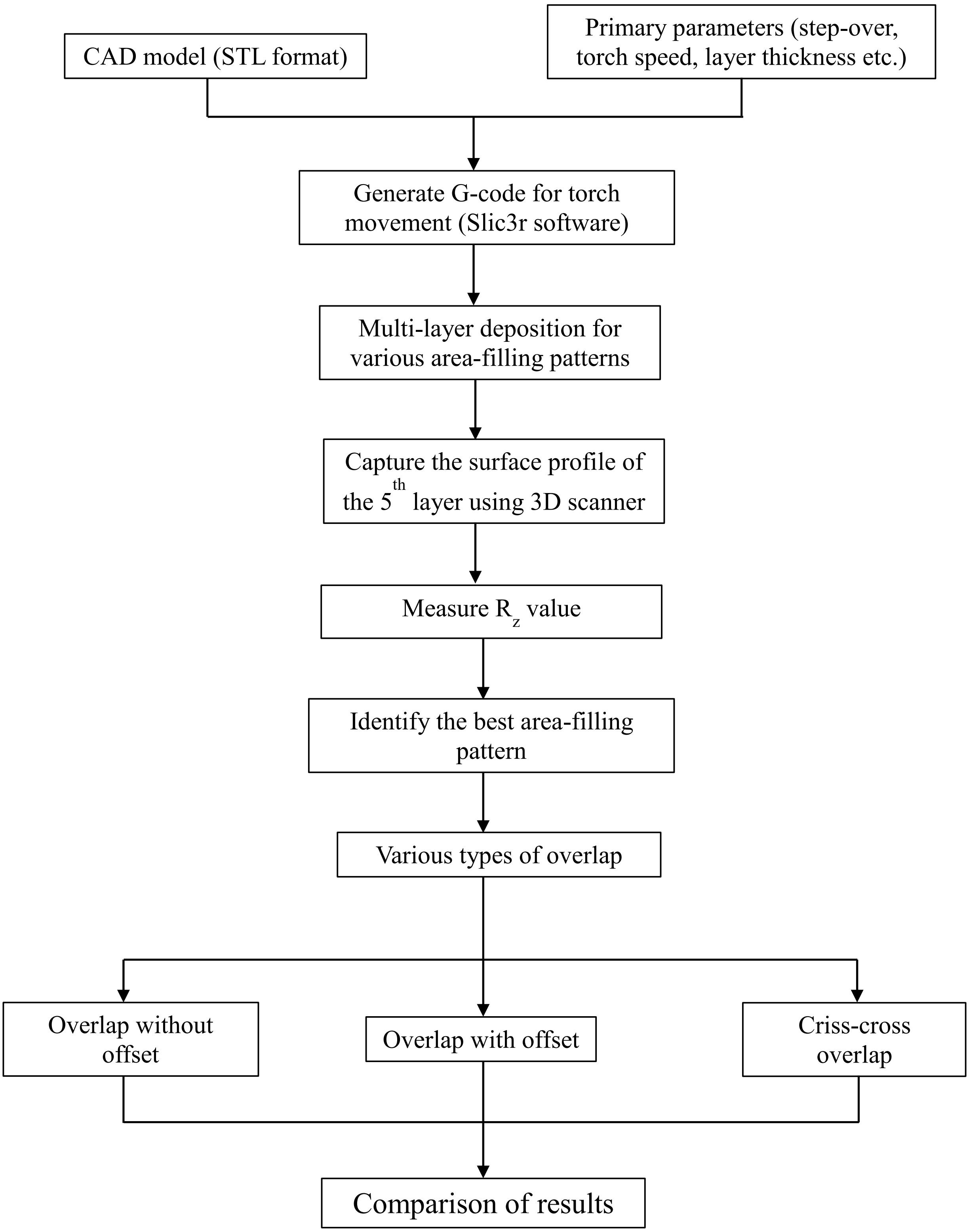


Figure 5.1. Flowchart of process of multi-layer experiments

After deposition of all three patterns with a different step-over values, the spiral-in the filling pattern has found more inefficient due to its high waviness value. Hence, spiral-out and rectilinear paths are more effective for multi-layer deposition. Further, in a rectilinear path, waviness value can be reduced and get the more effective path. For this purpose, two new adoptions in the overlaps of the rectilinear path are developed. It is done with the different starting point of deposition for each layer of five-layer deposition. The one is with offsetting the path of next layer with respect to the previous layer in the transverse direction by half of the step-over value. And the second is criss-cross type pattern one over another layer which is like next layer is shifted by 90 degrees with respect to the previous layer.

Figure 5.2 shows the illustration of the multi-layer experiment. It is shown that the five-layers are deposited on the base plate of mild steel. It should be clean and smooth surface before starting the deposition. Weld material deposited up to five-layer with different area filling paths at different step-over values. A laser scanning is used to calculate R_t value (i.e. waviness) of the 5th layer deposited surface. Total height is measured with a digital Vernier caliper. And maximum possible height is calculated by following formula,

- Max. Possible height = Total height –R_t value

  Where, R_t= Distance from highest point to lowest point of the data cloud

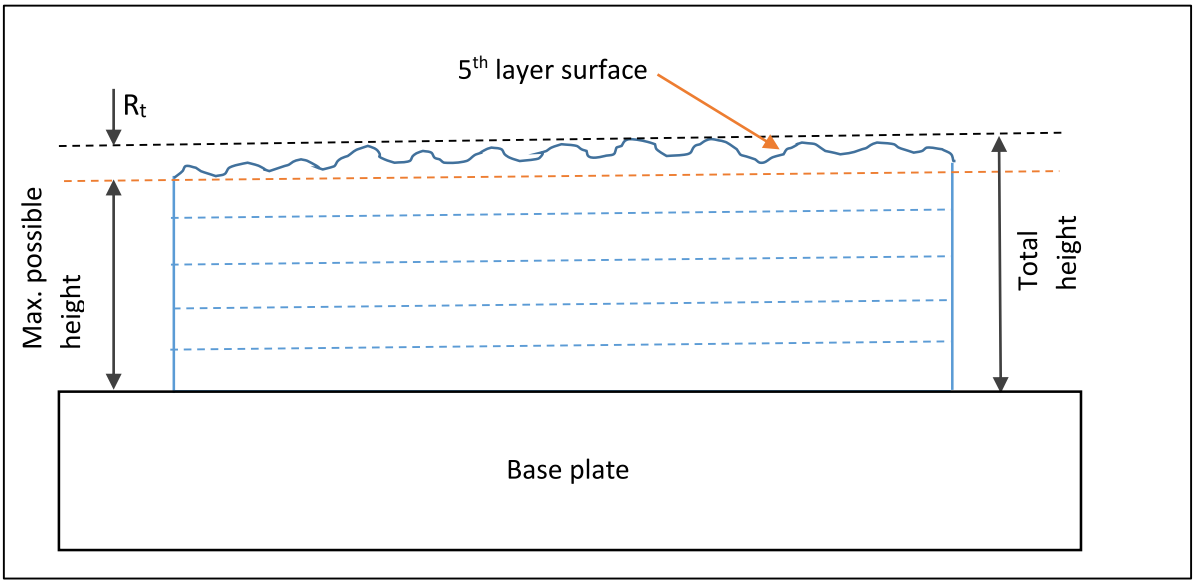


Figure 5.2. Illustration of multi-layer experiment

5.2 Results & Discussion

Layered manufacturing uses the layer-by-layer technique to fabricate the real object from their CAD model. In this process, waviness value of the deposited layer surface plays the key role to achieve the maximum possible height (i.e. usable height) from the base plate. Here, in this study, the multi-layer experiments are carried out to find the best area filling path. The best area filling path is decided on the basis of surface waviness. So, R_t values of all the surfaces deposited with above mentioned area filling patterns are measured. First, the square geometry of side 40 mm is deposited up to 5 layers for different area filling paths with a different step-over values. The process parameters for multi-layer deposition are given in table 6. After deposition of each layer required sufficient time for cooling to get deposited material solidify which means next layer should not flow down over the previous layer. The waviness value of 5th layer surface is measured by a 3D scanner. The comparison of R_t values for different area filling paths with a different step-over values is shown in figure 5.3.

Table 6. Process parameters for multi-layer experiments

Parameter	Value
Layer thickness (mm)	1.5
Step-over value (mm)	1, 1.25, 1.5, 1.75 & 2
Current (amp)	95
Voltage (volt)	21.7
Wire feed rate (mm/s)	90
Gas flow rate (L/min)	10
Torch speed (mm/min)	480

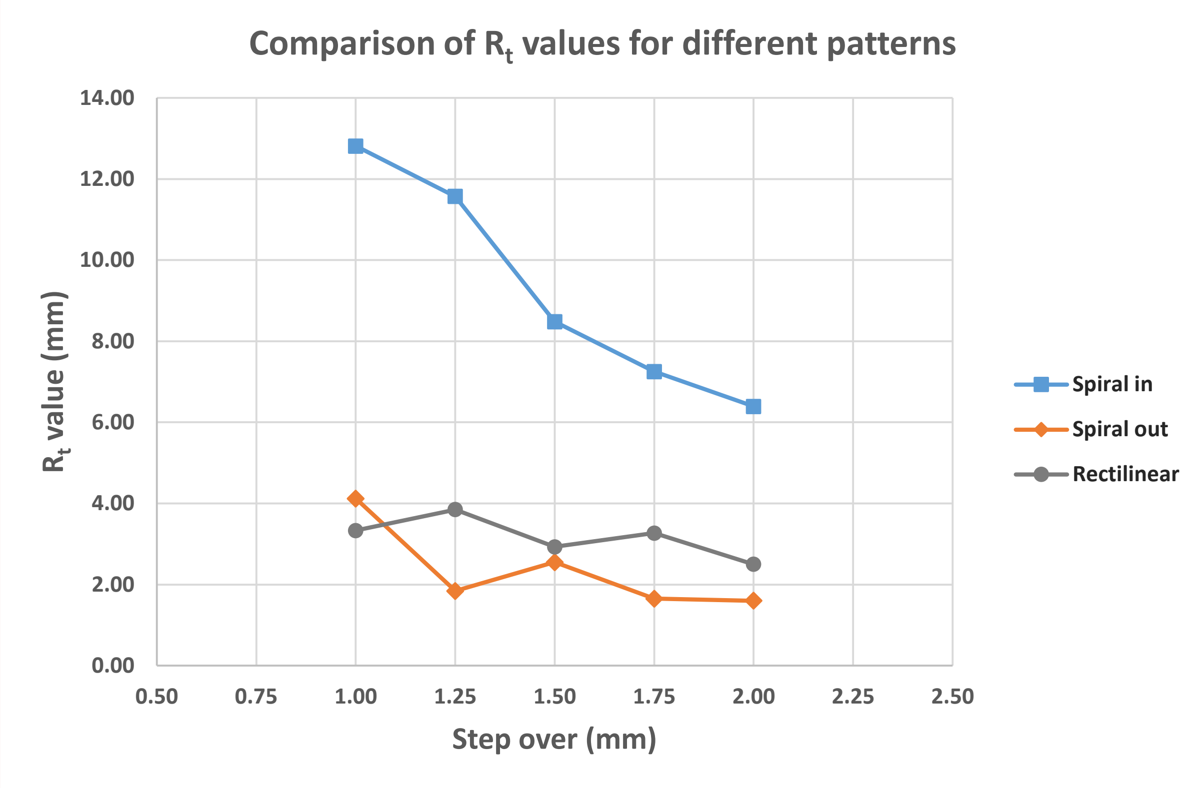


Figure 5.3. Comparison of waviness value for different patterns in multi-layer experiments

From figure 5.3, It can be shown that the waviness value (R_t) of the spiral-in the path is substantially more than other two path patterns. Hence, spiral-out and rectilinear path can be used for more good results.

Figures 5.4 shows the experimental results of maximum possible height for rectilinear, spiral-out and spiral-in path patterns which is calculated through subtraction of waviness value from a total measured height of five-layer deposition. The spiral-in path is not suitable for multi-layer deposition due to its high surface waviness. Other two paths are much efficient to multi-layer deposition. It can be shown that there is a close difference between the values of maximum possible height for the rectilinear and spiral-out path.

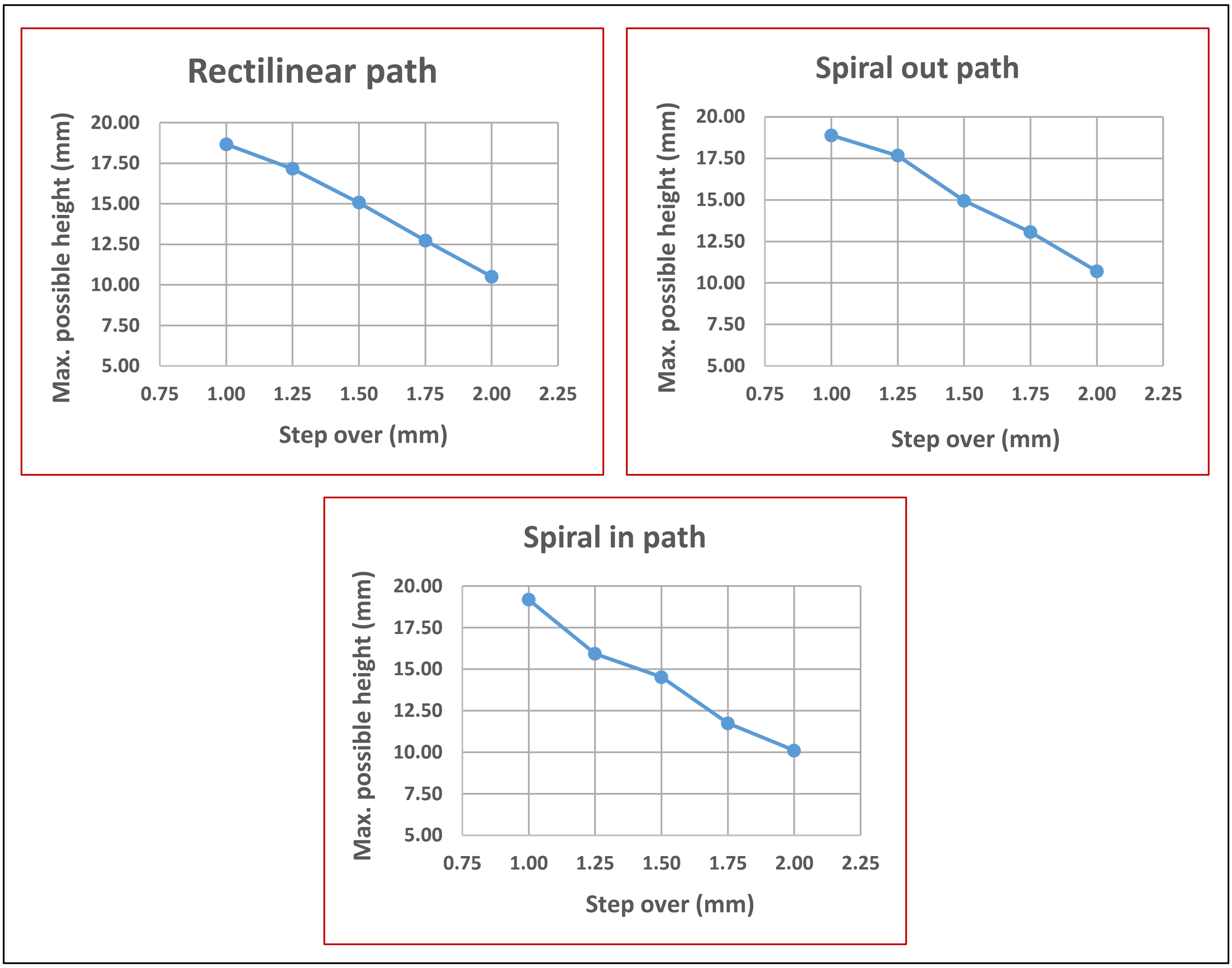


Figure 5.4. Maximum possible height of multi-layer experiments for different area filling pattern

From figure 5.4, It can be shown that the step-over value decreases, the maximum possible height increases, and vice versa. And spiral-in the path is an uneconomical for multi-layer deposition due to the higher value of waviness than other two paths.

Further, in a rectilinear path, some adoption in the overlaps methods are developed along with a layer of deposition. The rectilinear path introduced two more methods of overlapping to get better maximum possible height.

Figure 5.5 shows the waviness value for different types of rectilinear path patterns with different step-over values. It can be shown that the criss-cross type pattern has less waviness value than other two pattern system. In other patterns, overlap with offset pattern has less waviness value than the same overlap (without offset) pattern.

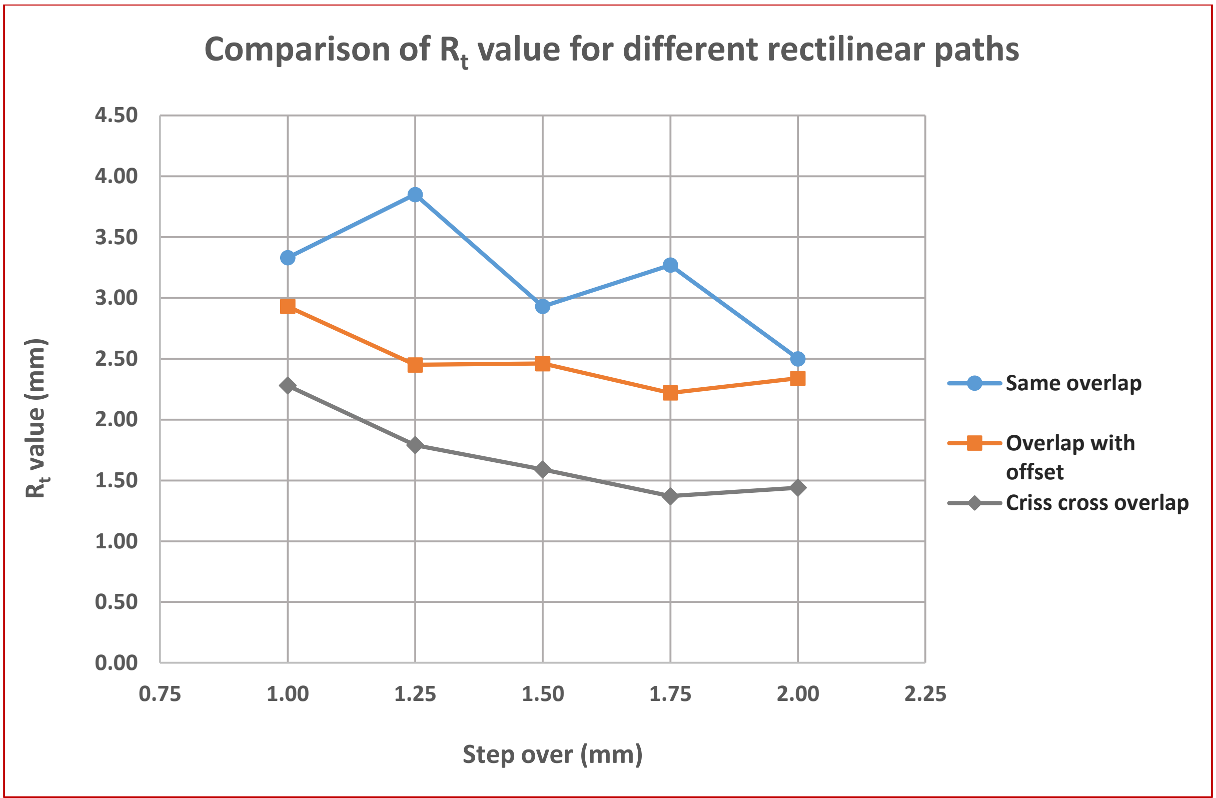


Figure 5.5. Comparison of waviness value of different rectilinear patterns in multi-layer experiments

Further, Maximum possible height is measured by subtraction of waviness value from the total height of five-layer deposition. Figure 5.6 shows the maximum possible height for different rectilinear filling patterns with different step-over values. It can be shown that rectilinear path with criss-cross overlap has a more maximum possible height as compared to other two overlaps. In these two patterns, a rectilinear path with offset overlap has more usable height as compared to the rectilinear path with the same overlap.

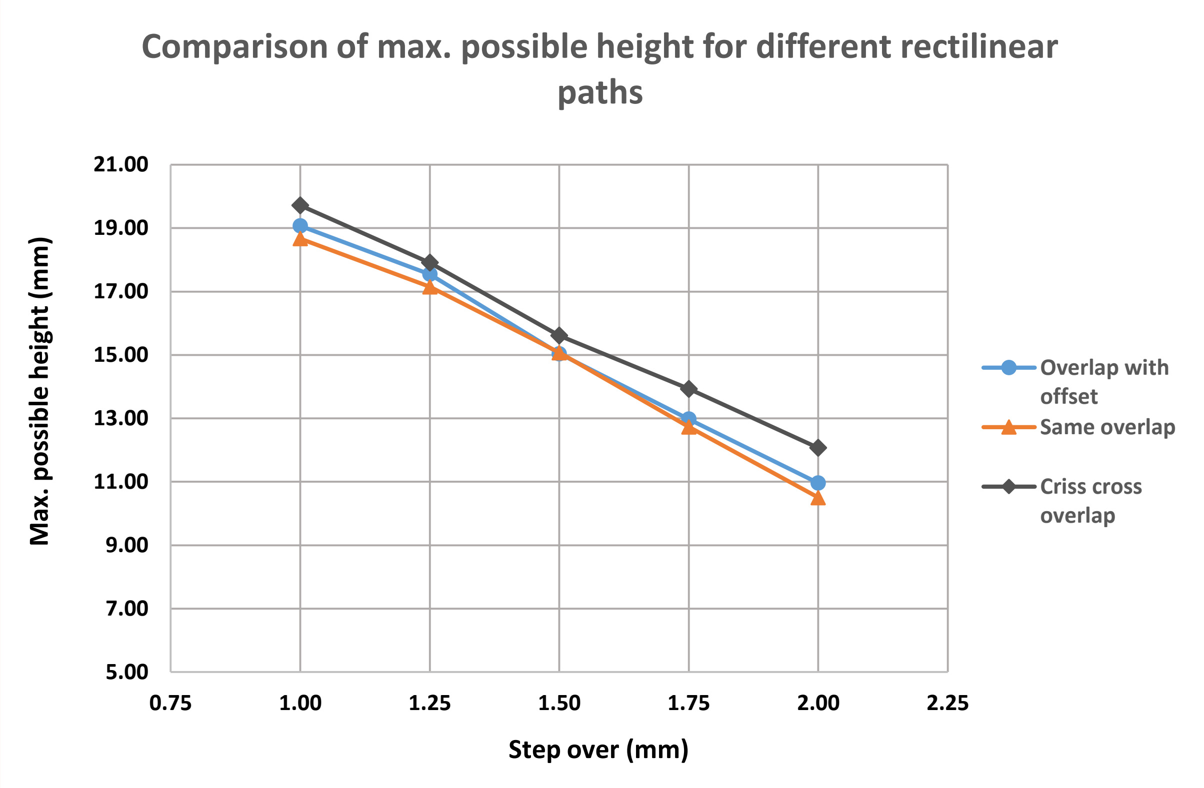


Figure 5.6. Comparison of maximum possible height for different rectilinear patterns in multi-layer experiments

In all rectilinear patterns, the maximum possible height is increases as step-over value decreases and vice versa. Hence the more suitable and efficient combination of pattern and step-over is the rectilinear path with criss-cross overlap at the step-over value of 1 mm.

5.3 Summary

Multi-layer experiments are conducted up to five-layer deposition to calculate the maximum possible height for different filling pattern deposition with a different step-over values. In the rectilinear filling pattern, some adoption in overlap method is developed to get good results. The criss-cross pattern found more efficient among the all three patterns of the rectilinear path. Likewise, more efficient path pattern is found with a minimum waviness value.

Chapter 6

Conclusion & Future Scope

The metallic objects manufacturing through arc welding based additive manufacturing and CNC machining will give more economic impact. In the current study, GMA based welding deposition unit is integrated with compact M-TAB milling CNC machine. A GMA is used as an additive process which has more deposition rate than other any processes. The CNC milling machine is used as a subtractive process in which is used to face milling of weld deposition. This combination of both processes can manufacture parts economically, accurately and quickly.

The following are some of the significant advantages of this combination of CNC milling machine and GMA welding unit:

- Total automation of near net deposition and its surface finishing is possible.
- Integration does not require any proper design specification; thus it can easily combine with any CNC milling machine.
- Arc weld deposition is economical, faster, simple and safer than laser and EB based deposition.
- The weld deposition unit is mounted the on same spindle head, so no additional control is required for axes movement.
- It is easy to switch between weld deposition mode and CNC regular mode.

Weld deposition finds surface waviness while manufacturing the components. CNC milling machine is used to remove that waviness by chopping. This approach becomes an uneconomical due to material wastage and time-consuming. It can be minimised/eliminated through proper path planning of weld deposition.

Single-layer experiments are carried out to find the waviness value and material utilisation efficiency for different area filling patterns. It is found that the comparison of waviness value calculated from both approaches i.e. destructive and non-destructive shows the close difference. So, waviness of weld surface is measured by a non-destructive approach. Material utilisation efficiency is calculated for three different patterns namely rectilinear, spiral-out, and spiral-in and it is found that rectilinear and spiral-out shows the more and close results. Spiral-out found to be less value of efficiency. Hence, both paths are efficient which can be used for weld deposition.

Multi-layer experiments are carried out to find the maximum possible height for different area filling patterns. Surface waviness influences calculation of maximum possible height. From the experimentation, It is found the more waviness value in spiral-in pattern as compared to other two patterns. The waviness value is calculated with the help of nondestructive approach. The rectilinear and spiral-out patterns have maximum possible height with minimum surface waviness, and it is nearly same. The rectilinear pattern has good deposition which is having less spatters. In the rectilinear pattern, two overlapping methods namely offset overlap, and criss-cross overlap is developed to get the better reduction in waviness. It is found that the criss-cross overlap has more maximum possible height with less waviness value as compared to other overlap methods. Hence, the criss-cross pattern is more efficient and suitable for multi-layer weld deposition.

Surface waviness value of multi-layer deposition can be predicted by R_t value of single-layer deposition. The prediction can be accurate when the effect of material flow is accounted throughout the multi-layer deposition. The smoothening function can be used to account the material flow effect. While manufacturing the complex shape of geometries, the area will not fill completely at the corners. Path patterns can be modified to overcome the gaps at the corners of geometries while manufacturing.

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