B.TECH. PROJECT REPORT

On

Design and Development of Wire Arc Additive Manufacturing Setup for Fabrication of Complex Parts

By

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DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Design and Development of Wire Arc Additive Manufacturing Setup for Fabrication of Complex Parts

A PROJECT REPORT

Submitted in partial fulfilment of the
Requirements for the award of the degrees

Of
BACHELOR OF TECHNOLOGY
in
MECHANICAL ENGINEERING

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INDIAN INSTITUTE OF TECHNOLOGY INDORE
NOVEMBER 2019

CANDIDATES' DECLARATION

We hereby declare that the project entitled **"Design and Development of Wire Arc Additive Manufacturing Setup for Fabrication of Complex Parts"** submitted in partial fulfilment for the award of the degree of Bachelor of Technology in 'MECHANICAL ENGINEERING' completed under the supervision of **Dr. Yuvraj K Madhukar (Assistant Professor),** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

AMOD PATIL

UMESH KUMAR LODHI

CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Dr. Yuvraj K Madhukar
Assistant Professor
Discipline of Mechanical Engineering
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Preface

This report on “Development and Control of Wire Arc Additive Manufacturing of Complex Parts" is prepared under the guidance of Dr. Yuvraj Kumar Madhukar.

Through this report we have tried to give detailed information on control and optimization of wire arc additive manufacturing as well as development of rotational axis for CNC machines . The report contains illustrated pictures of manufactured setup and various 3D objects manufactured with the help of the WAAM setup.

We have tried to the best of our abilities and knowledge to explain the content in a lucid manner.

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B.Tech. IV Year

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Acknowledgement

We would like to thank **Dr. Yuvraj Kumar Madhukar** for giving us the opportunity to work on this project. We are grateful for his guidance and cooperation throughout the project. We are indebted to him for sharing his valuable knowledge and expertise in the field of Additive Manufacturing.

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Abstract

Wire arc additive manufacturing has been used to manufacture complex metal parts which were difficult to manufacture with conventional methods. The other possible application of the process could also be seen as in repairing of expensive worn out parts of machine or machine components. The aim of phase-1 of this project is to manufacture geometrical features like overhang and inclination using 3 axis gantry CNC with MIG welding power source as deposition tool. Definition of overhangs for inclined parts was presented. Effect of offset distance, wire feed rate, travel speed was discussed. Importance of cooling rates and intercooling in between layers is also demonstrated. Basic propeller and impeller blade shape was deposited using 3 axes Wire Arc Additive Manufacturing (WAAM) setup. Propeller blades were manufactured in a layer by layer structure as a single part. Under the normal cooling circumstances for MIG welding, overhangs needed for propeller blades were also deposited successfully.

Phase-2 of this project was based on design and manufacturing of 4th axis and its use in depositing the parts which were impossible using 3 axis CNC. Developed 4th axis could be used as A-axis in both additive and subtractive manufacturing machines. Added advantages due to rotational axis were observed compared to developed part on 3 axis machine. Spiral and basic fan blade shape were deposited on cylindrical workpiece using 4 axis WAAM setup.

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1. INTRODUCTION

Wire arc additive manufacturing (WAAM) process has gained significant popularity now-a-days in academic research as well as in industry. The major advantage of this process could be seen in terms of its higher deposition rate and cost effectiveness compared to other metal based additive manufacturing techniques i.e. selective laser melting (SLM), laser engineered net shaping (LENS), 3d printing etc. [1]. WAAM has been used to fabricate metal parts with different geometrical features. It could also be used to repair previously manufactured parts by machining the broken part and reprinting on it. The process holds great potential to become a very helpful tool in industry where parts used generally tend to get worn out overtime. Among other Additive Manufacturing processes, WAAM is capable of manufacturing intermediate to large size components because of higher deposition rates, potentially unlimited deposition size depending on setup constraints and low capital and feedstock costs [2].

In the presented experimental study, the WAAM process has been extensively studied for the manufacturing of inclined, overhangs and enclosed structures. With WAAM, enclosed shapes as well as weight reducing hollow structures like honeycomb structures can also be manufactured [3]. Previously an attempt has been made to fabricate these structures using 5 axis CNC setup which helps in keeping the base layer in every deposition straight below next deposition preventing any overhang possible [4]. The present study demonstrates the overhang deposition could also be made without the need of more axes as same as fused deposition modeling (FDM) of polymer. Thus, in this article, the focus was on making inclined and overhanging structures using 3-axis setup. The 3-axis gantry system was designed and developed in house for the purpose. A successful attempt has been made to automate the process using computer numerical control (CNC). Further, trajectory planning has been developed with respect to part geometry to be manufactured. The deposition parameters i.e. voltage, wire feed rate; scan speed was optimized to ensure the proper deposition.

2. MOTIVATION

- Additive Manufacturing is becoming increasingly popular as more advancements in research are being done in this field.
- Additive Manufacturing of metals would facilitate manufacturing complex geometric shapes with less material wastage compared to traditional machining processes.
- WAAM process uses approximately 95% of the raw material added which is significantly greater compared to SLM, SLS which use less than 60%.
- A prototype of the world's first class approved ship's propeller has been produced using Wire Arc Additive Manufacturing. The 1,350mm diameter propeller – named WAAMpeller.

Fig 2.1 *WAMPELLER*

3. PHASE I - Development of 3 axes Setup and Deposition

3.1 Development of Setup

WAAM setup used in the experiment consists of 3 axes CNC developed inhouse (Fig. 1). It was driven by hybrid servo motors (3-70 kg-cm torque) with RHINO motion controls drivers. The Mach3 control board and software package was used to provide programmable control with respect to CAD (computer aided design) geometry.

A MIG welding power source (model: KEMPPI FastMig Pulse 450) was utilised as deposition method with argon as a shielding gas. Base metal plate used for depositions was made of Mild Steel. E70s-6, 0.8 mm diameter, Cu- coated alloy steel wire was used for deposition.

A DC output MIMY SMPS of 48V, 5.2A with 3 divided outputs was used.

3.2 Automation of the Process

For automation of the process, two independent units need to be automated and should be in synchronization. First, 3 axes CNC and its control depending on path of deposition. The programming of the CNC was done in standard ‘G and M’ coding. Second, the MIG torch activation where it is necessary and be shut down while relocating it. Also, dwells between layers should also be included in the automation process. Relay circuit was used for the torch switching (ON or OFF). The entire system was controlled from mach3 circuit board.

(a)  (b) (c)

Fig 3.1 . : (a), (b) are images of mach3 software, (c) is an image of Mach3 board.

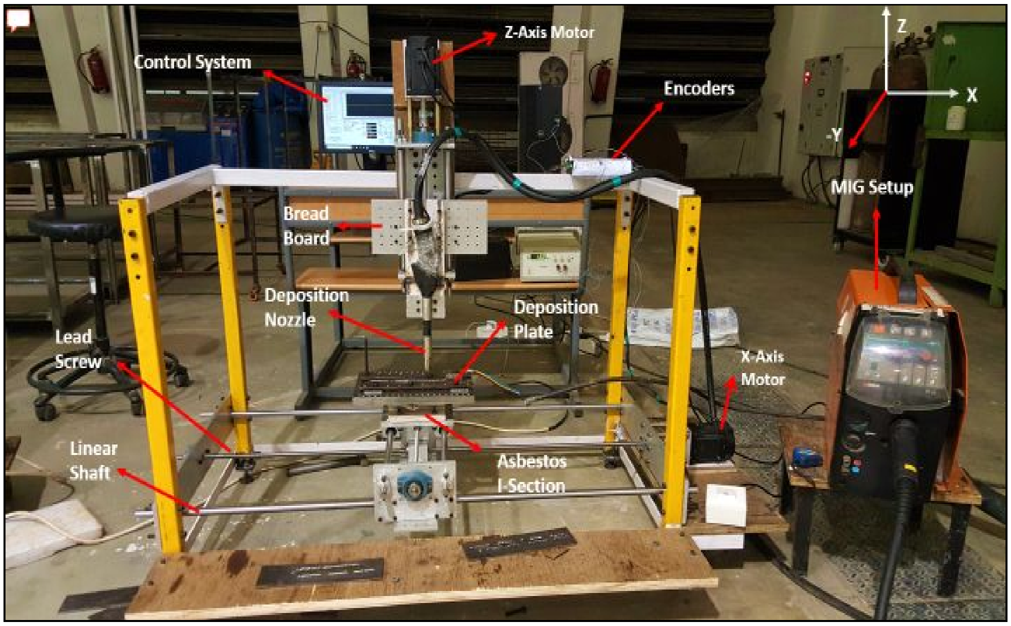


Fig 3.2 Setup image

3.3 Dimension Controlling Parameters

While using MIG as deposition tool, the arc is generated between base metal plate and feed wire which melts and deposits on plate. Therefore, the shape of the bead/ structure being deposited strongly depends on wire feed speed, input voltage and travel speed of deposition tool. These parameters were varied during the experiment to obtain the desired layer dimensions. The other parameters such as gas flow rate and stand-off-distance were kept constant as 10 l/min and 3.5 mm respectively.

Effects of individual parameters:

1. Input voltage

The input voltage was varied between 10V to 25V. In this range, lower voltage (~10V) results in less bead width, spatter and height compared to higher ones. However, the arc was not stable enough to melt the wire uniformly; hence it leads to non-uniform bead deposition. Higher voltage (~25V) results in uniform deposition and acceptable bead width and height but results in slight spatter around the deposition. It was observed that the voltage range between 14V to 21V was optimum for uniform deposition.

Due to delay in initiation of arc at the start of deposition, height of layer deposited was comparatively lower than the average height. While depositing multiple layers, this error adds up and can be clearly seen if the initial point is kept same for deposition of each layer. To compensate for this error, G-codes need to be optimized such that initial point of deposition change periodically for each subsequent layer.

2. Wire Feed speed

The wire feed speed was varied from 2.5m/min to 3.5m/min. It was observed that the higher feed speed results in thicker bead width. By speeding up wire feed, the arc length become shortened, which leads to drawing of much higher current, this higher current then consumes more wire, maintaining consistent higher wire feed deposition, thus it is self- regulating process.

3. *Tool travel speed*

While maintaining above two parameters constant, the travel speed of tool can also be varied. The higher feed velocities (greater than 500mm/min) require sudden acceleration and deceleration while starting and stopping of motor respectively. Often it causes sudden jerk in the motion, hence non-uniform deposition and high chance of motor/shaft damage. Though this parameter may help in deciding layer dimensions, it is recommended to maintain this velocity within safe limits. Of course, the lower travel speed increases the deposition time. It was observed that the travel speed ranging between 100m/min to 500m/min produced desired deposition.

3.4 Result and discussions

3.4.1 Deposition of Single Bead thin Wall

In general, a thick flat plate is often used as a base for the purpose of WAAM based deposition process. The flat surface of this plate is convenient for the first base layer to get deposited. To build the three-dimensional structure, the next layer must be deposited on the first layer which is not completely flat. Hence, the increment in height would be different for subsequent layers. Therefore, for specific parameters, increment in height per layer was decided based on the second layer. Relatively thicker bead was made for the first layer as to provide strong support to further layers. The base layer shown in figure below was deposited at 21V, 3.5m/min wire feed and

300 mm/min tool feed, while subsequent layers were deposited at 15V, 3m/min wire feed and 500mm/min tool feed. Fig. 1a and ‘b’ shows the pictorial view of deposited thin wall. With this setup the thin wall of 2.78 mm thickness (and 15.5 mm height, not limited to) was achieved successfully.

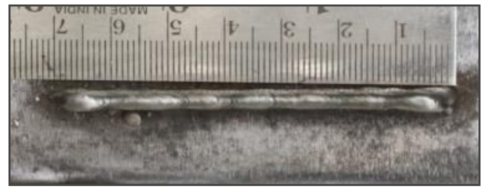
(a)  (b) 

Fig 3.3**.:** 25-layer thin wall and its top view

3.4.2 Deposition of Cylindrical Part

Cylindrical part deposition was similar to single bead wall. The only difference is, initial point and final point of deposition must be same due to closed spine. The G-code was updated accordingly. In case of cylindrical part deposition, the arc delay and under-deposition was compensated by choosing different starting point of start for each layer. It was observed that keeping the start point 90^0 apart for each layer results better in terms of uniformity in deposition. Fig. 2 ‘a’ and ‘b’ shows the pictorial view (top and front respectively) of deposited thin wall cylinder. The effective wall thickness was 3.08 mm and height was 28 mm.

Here the deposition parameter for base layer was 21V, 3.5m/min wire feed and 300 mm/min tool feed. While subsequent layers were deposited at 15V, 3 m/min wire feed and 500 mm/min travel speed.

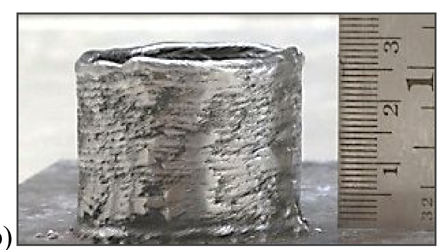
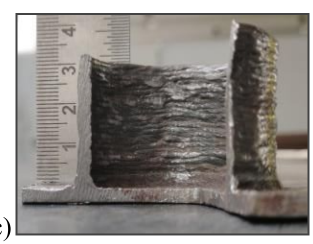
(a)  (b)  (c) 

Fig.3.4 (a) Top, (b) front and (c) sectional view of deposited hollow cylinder

3.4.3 Deposition of Square Part

This is also another example of simple deposition with starting point kept at different corners for each subsequent layer. Fig. 3a and ‘b’ shows the pictorial view of 4.40 mm thick square part. The deposition parameters were 21V, 3.5m/min wire feed speed and 300 mm/min tool travel speed.

Fig.3.5**.** (a) Top view of deposited hollow square.

3.4.4 Aim of Overhang parts

The overhangs are necessary for making many featured parts. It could be realized in terms of offset in deposition in successive layers. The amount of overhang required depends on the part geometry and hence inclination angle of the individual wall. The extent of overhang could be decided by changing the percentage overlap between two layers i.e. a percentage overlap of 90% implements 10% width of that layer hanging away. There are chances that molten material would flow down instead of forming overhang if it is not cooled down instantly. So cooling rate is crucial in choice of overlap percentage and making of overhang features. Lower overlap leads to large molten pool offset from the centre of deposition layer. Overlap percentage between subsequent layers during deposition results in an unsolidified material which is easy to flow down to previously solidified layers [5].

Fig 3.6**.** An overhang

3.4.4.1 Deposition of Inverted Hollow Frustum

Frustum is a good example of an overhang part. Fig. 4a and 'b' shows the pictorial view (top and front respectively) of deposited hollow cone. Base circle diameter chosen was 40 mm and base layer bead width was of 4.5mm. The deposition specifications were 21V deposition voltage; 3.5m/min wire feed rate and 300 mm/min tool travel speed. Each successive layer was shifted to 0.5 mm radially outwards in order to ensure 90% overlap. It was continued till last 30th layer. The topmost layer deposited has a diameter of 69 mm. Height of end product was 32 mm.

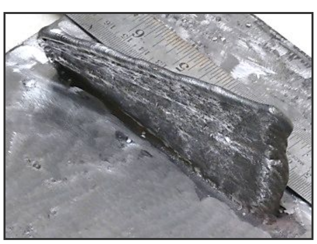
(a) 

(b) 

Fig. 3.7. (a) Top and (b) front view of deposited hollow cone.

3.4.4.2 Deposition of Impeller Blade

This is the example of overhang part where the shifting in layer deposition varies through the length and going to have the maximum shift at the ends. Each layer length was kept constant at 120mm. Overlap percentage was varied from 100% at the centre to 82% at the ends. Horizontal shift between ends of subsequent layers for 82% overlap was 0.8mm. Width of each layer was kept constant at 4.5mm. Deposition parameters were 21V, 3.5m/min wire feed rate and 300 mm/min tool travel speed. Fig. 5 shows deposition of an impeller blade of 34 layers.

(a) 

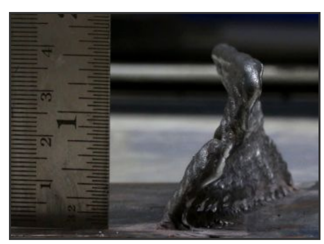
(b) 

Fig 3.8: Deposited impeller blade of 34 layers and its front view.

3.4.4.3 Deposition of Propeller

Propeller is a great example to demonstrate application of overhangs in developing complex parts. Fig. 6 shows the pictorial view of deposited propeller of 25 layers. Here each layer consists of 3 blades of length 40mm connected to the hub of radius 20mm. Each subsequent layer was offset by an angle of 0.6 degrees clockwise. Width of each layer was kept constant at 4.5 mm. The deposition parameters were 21V, 3.5m/min wire feed rate and 300 mm/min tool travel speed. Height of end product was 31 mm.

(a) (b) (c)

Fig. 3.9**.** Deposition of a propeller

3.5 Effect of cooling in WAAM

In WAAM, the rate of cooling is a very important factor as it affects final quality of product considerably. It’s because the process involves the metal wire melting and layer by layer deposition. Therefore, it is very important to cool the previous layer so that it won’t melt again while depositing the upper layer. While deposition of overhangs, the portion of layer which hangs needs to cool down immediately so that it can hold its position. In WAAM few more challenges appear as the conventional ways of cooling cannot be used i.e. adding force convection may encourage many reactions or change in metallurgical or mechanical properties. The only cooling source during GMAW welding is through the inert gas (argon) flow and the conductive heat transfer. This limits the quality of finish achieved for large overhangs. The calibration was attempted to ensure the achievable maximum overlapping with good quality finish. Around 80% overlap under given cooling circumstances was found to give good quality overhang. In order to solve layer-wise cooling; it is a good idea to allow each layer to cool down to certain temperature before the next layer deposition. Inter-pass cooling between layers increases the chances of heat to flow through beads and allows more stability in it. So, cooling is very crucial parameter in metal additive manufacturing process and proper ways to tackle it should be provided to negate any failure (as shown in Fig. 6).

Fig. 3.10 Deposition with no cooling time given between subsequent layers.

<u>Phase II</u>- Development of 4^{th} axis and deposition

4.1 Development of Rotational axis

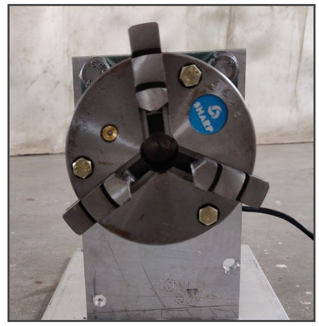
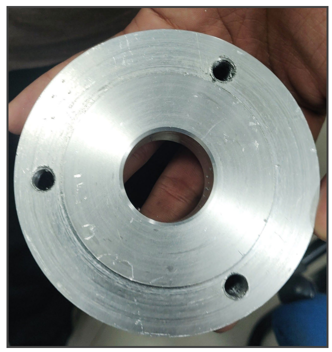
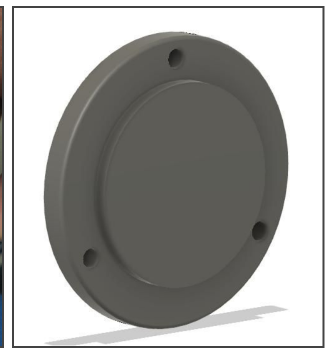
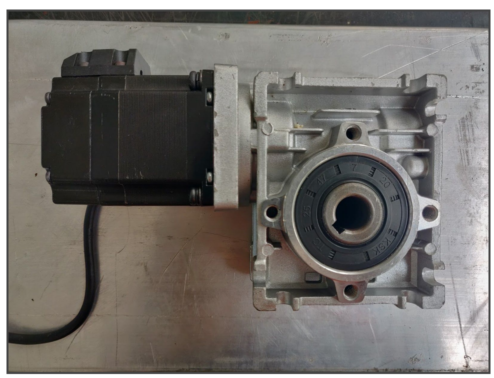
In phase-1 , overhangs were deposited using 3 axis setup but steeper slopes were impossible because there were limitations on what overlap percentage we can achieve over 3 axis setup. Therefore fourth axis was introduced in setup. To avoid flowing of molten metal , we can angle the workpiece using rotary axis to avoid steep slopes for flow. It also expands the types of workpieces we can use of WAAM . Printing over cylindrical , spherical surfaces can be achieved using fourth axis which is also denoted as A-axis .

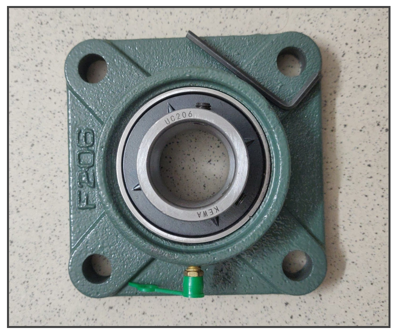
4.2 Design of A-axis

Following design constraints were takes into consideration while designing A-axis :

- Existing 3 axis setup had insulating material I section as a base for fourth axis which reduced overall strength
- So load placed on machine will result in vibrations. Considering this , we tried to reduce weight as much as we could.
- All supporting plates were made of aluminium to minimize weight.
- Only one bearing was used for limited loads but while designing , additional bearing and supporting plate can be added if required for depositing
- Considerable space is given to add tail-stock if required
- Additional holes were made to accomodate auxiliary grounding.
- Additional space is given for second Motor support plate if necessary in further operations.
- Motor shaft was made in 3 parts in which insulation was added to avoid any current pass straight through motor shaft.
- Additional measures stated ahead were taken to avoid any current leak to motor circuits.
- Supported bearings were used to minimize errors like eccentricity.

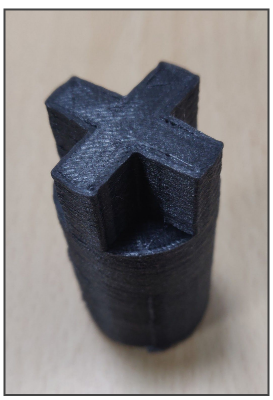
4.3 PARTS INVOLVED IN FABRICATION OF 'A' AXIS

PART NAME	IMAGE OF PART
3 Jaw Self- centering chuck	
Backplate for chuck	 
Hybrid motor of torque 10kgcm with 10:1 gear ratio	

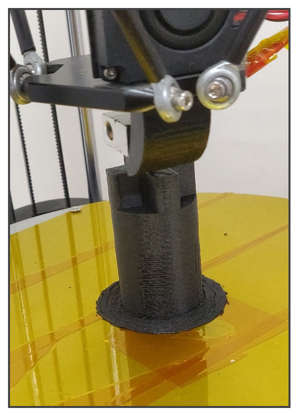
Supporting plate for motor- 2	
Bearing of diameter 30mm	

4.4 Fabrication of insulating coupler

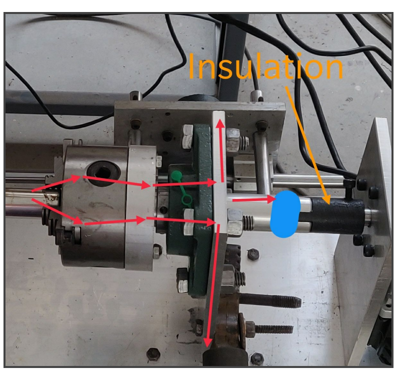
WAAM generates lots of heat while operating which needs to be taken care of . Also high current flow is generated through metal parts to complete circuit . Due to the fact that motor is connected directly to chuck and workpiece by means of a single conducting shaft , there is chance of current leak through motor in case the provided grounding material is rusted overtime . To protect the motor shaft needs to be insulated. It can be achieved by insulating workpiece and chuck at their contact and adding ground to workpiece by means of conducting wire brush. This way, whole setup will be insulated but heat would have no place to spread. So we used insulating coupler to separate shaft. By doing this bulky chuck, bearing and support plate can be used as a heat sink. And motor will be protected both thermally and electrically. One drawback in that there is still chance of current leaking through base plate to motor. To avoid that motor contacts were insulated.



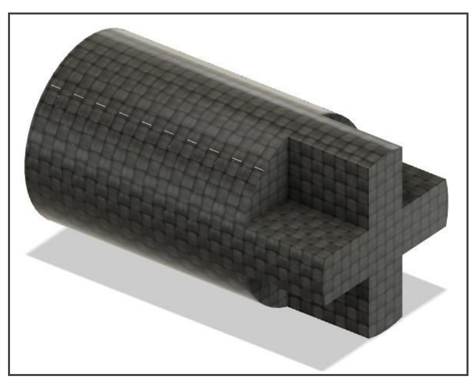
(a) Finished part



(b) Printing in process



(c) Direction of heat flow



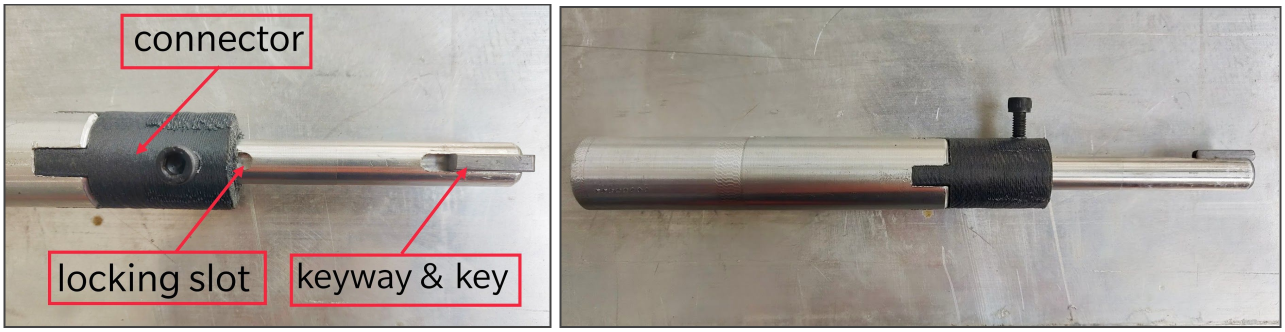
(d) CAD design of insulating part

Fig 4.1 Insulating coupler

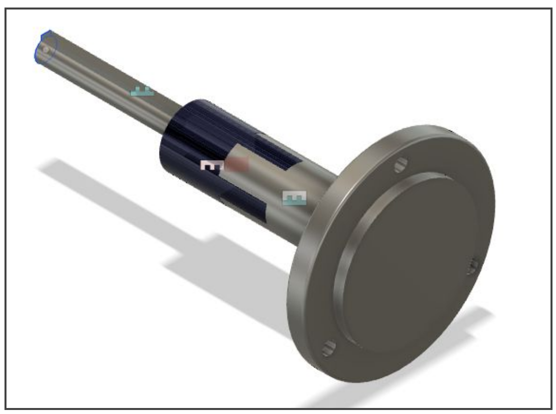
4.5 Assembly of Shaft

Motor shaft was locked by using a threaded bolt through insulator resting in locking slot.

Simple ‘+’ shaped locking slot was made in 30mm diameter shaft to connect the other end of the insulator.



(a) Image of shaft



(b) CAD image of shaft attached to backplate

Fig 4.2 Shaft Assembly

4.6 Grounding for safe welding

In 4 axis CNC , workpiece will be rotating. So we can not ground rotating base easily. Even with the brush , there is a chance of sparking. To have a safe welding, whole rotational axis in mounted over an insulating material I section which prevents current leaking to CNC machine’s metal body. Insulating coupler is added to shaft to protect motor from direct shaft currents. Extra insulation is provided at the contact points as well as bolt contacts to protect any current leaks to motor. Additional holes were provided on baseplate to add an auxiliary earthing.

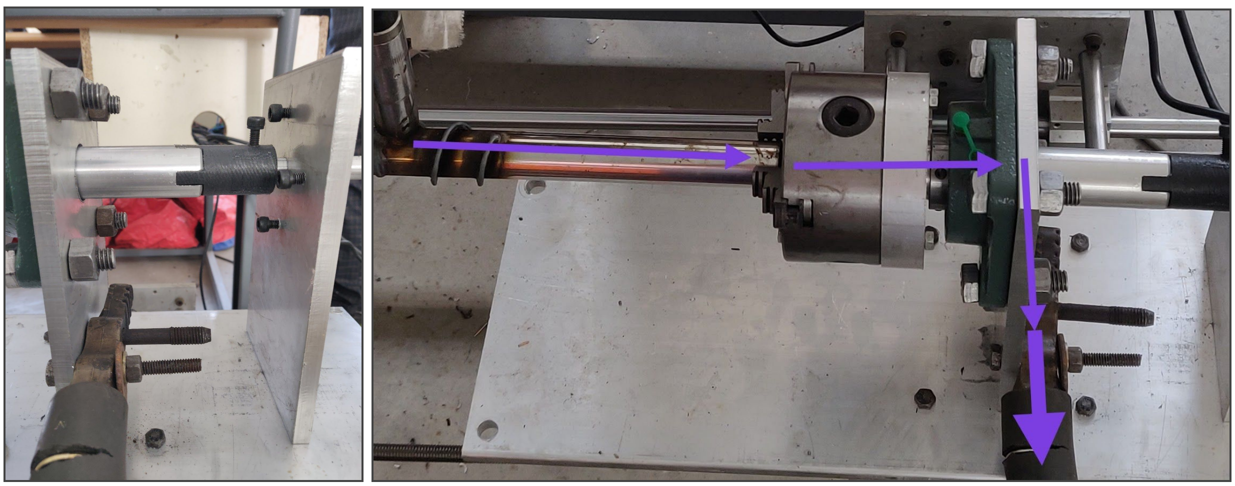
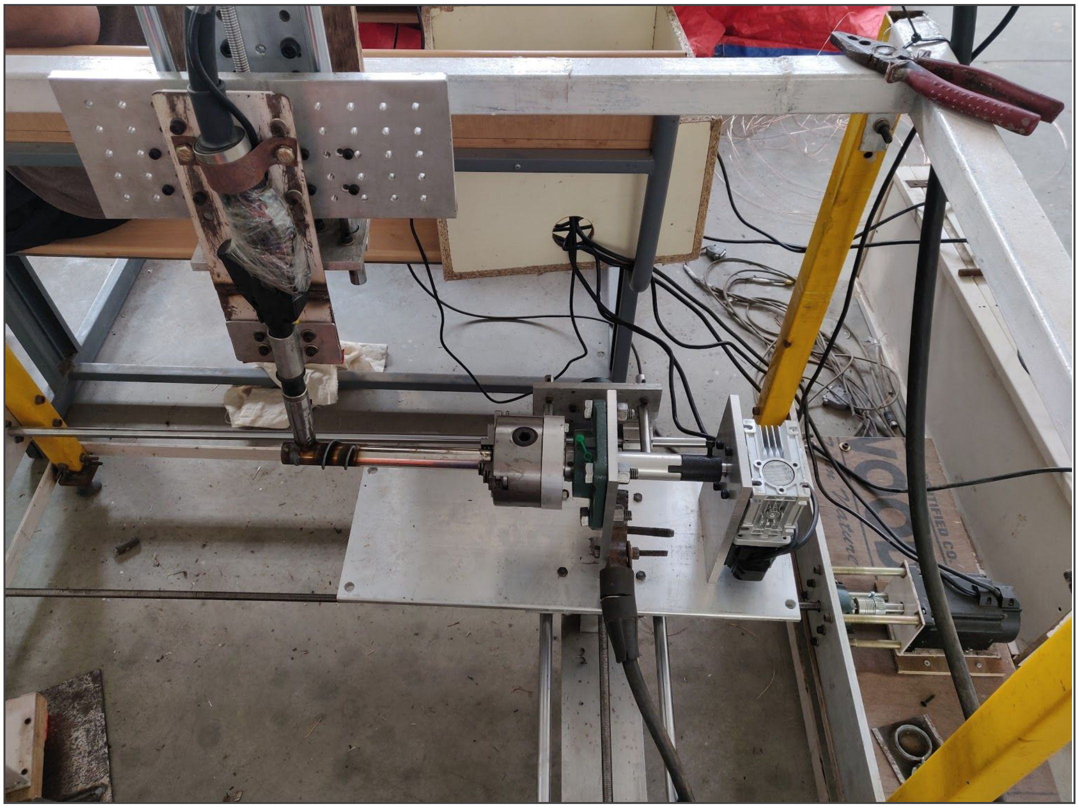


Fig 4.3 earthing provided at one of the supporting plate.

4.7 Images after assembly of all individual parts



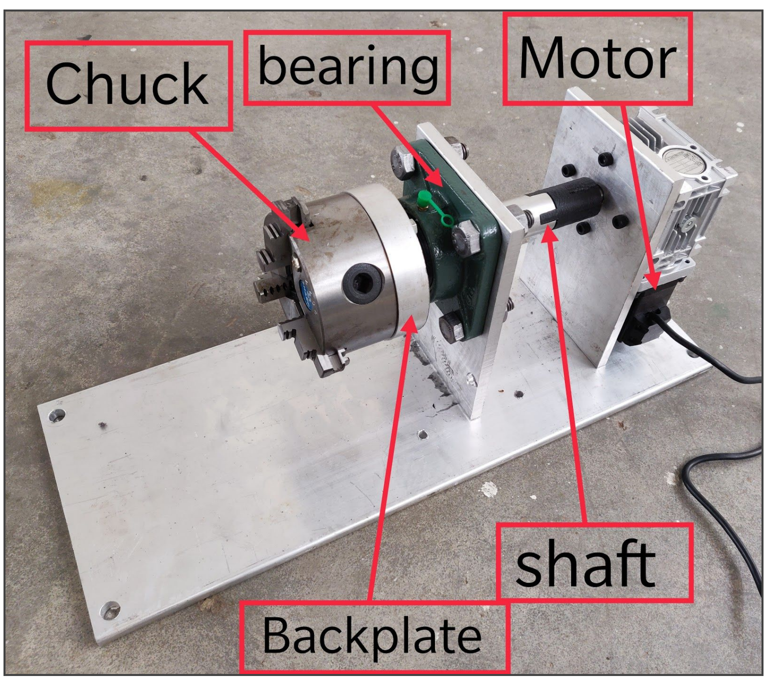


Fig 4.4 Whole mounted assembly ready for use to deposit desired parts.

4.8 Result and discussions

4.8.1 Deposition of helical geometry utilizing 4th axis

X,Y,Z motors have lead screws attached to them so rotational velocity of A-axis doesn't necessarily match with others. To have uniform deposition , rotational velocity was first calibrated as required. As base settings , velocity was 300mm/min , acceleration was 250mm/secsq and steps per sec were 100.

Using the above settings, workpiece of 29mm diameter was connected as a base for printing. Welding voltage was 16V , wire feed speed was 2.75m/min. Pitch for helix was adjusted by optimising X axis and 'A' axis velocity and distance travelled.

Fig 4.5 Deposited helical geometry

4.8.1 Deposition of simple impeller utilizing 4th axis

Base cylinder diameter was 29mm. 3 blade impeller was printed with 16 layers. Welding voltage was 16 V. Wire feed rate was 2.75m/min. Each round in printing deposited 2 layers in each blade. After that 5min cooling time was given between each round.

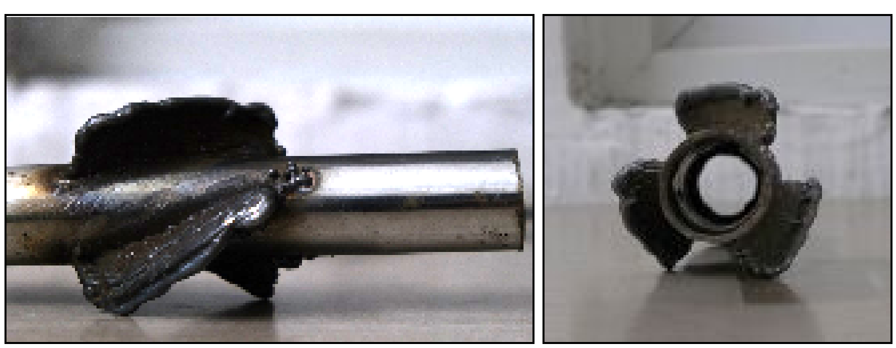


Fig 4.6 Images of deposited impeller

5. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

This thesis aims at fabricating thin walled, overhanging depositions using 3 axes WAAM setup,design and development of fourth axis as well as printing utilizing rotational axis. Conclusions drawn are as follows:

- Impact of input voltage, wire feed speed and tool travel speed on deposition quality was analyzed.
- Effects of overlap percentage on overhang inclination were illustrated through deposition of inverted frustum cone, impeller blade and propeller.
- Overhangs were manufactured using simple G codes with 3 axes setup.
- Cooling at regular intervals is necessary to prevent the molten pool from overflowing and keeping the wire from sticking to the torch.
- Propeller blades were manufactured in a layer by layer structure as a single part successfully optimizing all the parameters.
- Rotational axis also known as ‘A’ axis was designed and manufactured with minimal eccentricity and dimensional errors.
- Proper grounding and insulation was provided to protect important parts both thermally and electrically.
- Helical geometry and simple 3 bladed impeller was deposited successfully using final setup

5.2 Future scope

- Some further modifications can be done in setup such as welding followed with rolling for each layer to make suitable base for the next layer.
- Due to time constraint the mechanical properties of the fabricated parts have not been studied which can be considered for future scope.
- The studied analysis suggests the monitoring and control of deposition temperature could add great advantage to the process.
- TIG welding can be used instead of MIG to minimise spatter.

6. REFERENCES

[1] Johnnieew Zhong Li, Mohd Rizal Alkahari, Nor Ana Rosli, Rafidah Hasan, Mohd Nizam Sudin, FaizRedza Ramli, "Review of Wire Arc Additive Manufacturing for 3D Metal Printing*"*, May 2019. [Online].

Available:

https://www.researchgate.net/publication/332886203_Review_of_Wire_Arc_Additive_Manufacturing_for_3D_Metal_Printing

[2] S. W. Williams, F. Martina*, A.C. Addison, J. Ding, G. Pardal and P. Colegrove, *Material Science and Technology,* "Wire + Arc Additive Manufacturing", Vol.32, Iss. 7*,* page 641-647, April 2015.

[3] Panagiotis Kazanas, Preetam Deherkar, Pedro Almeida, Helen Lockett and Stewart Williams, *Journal of Engineering Manufacture 2012 226,* "Fabrication of geometrical features using wire and arc additive manufacture", February 2012.

Available: http://pib.sagepub.com/content/226/6/1042

[4] Jayaprakash Sharma Panchagnula, Suryakumar Simhambhatla, "Manufacture of complex thin-walled metallic objects using weld-deposition based additive manufacturing", *Robotics and Computer- Integrated Manufacturing,* Volume 49, Pages 194-203, Feb 2018. [Online]

Available: https://www.sciencedirect.com/science/article/pii/S0736584516301399?via%3Dihub

[5] Jun Xiong, Yangang Lei, Hui Chen, Guangjun Zhang, "Fabrication of inclined thin-walled parts in multi-layer single-pass GMAW-based additive manufacturing with flat position deposition", *Materials Processing Technology,* Pg 397-403, 2017

Journal homepage:

www.elsevier.com/locate/jmatprotec