The Role of Additive Manufacturing in the Era of Industry 5.0

Dr. Arun Kumar[1] and Dr.P. Rajeshwari[2]*

[1]Department of Mechanical Engineering, Bannari Amman Institute of Technology, Erode, India.*

[2]Department of Mechanical Engineering, Bannari Amman Institute of Technology, Erode, India.

Abstract--- The evolution of industry 5.0 enables the usage of smart machines and intelligent robots with the collaboration of human beings. Digital manufacturing without and with IoT technologies employs digital data for production as in Additive manufacturing (AM). The progressive growth of AM has transformed from prototyping to functional part development. Due to the advent of a less buy-to-fly (BTF) ratio, the manufacturing sector adopted AM technologies for large-scale production. Wire arc additive manufacturing (WAAM) is one such technology for fabricating unique functional parts both job-wise, as well as mass production. From the literature and as per the observations made by most of the researchers and industrial practitioners, features like end product surface finish and power consumption need to be studied for better sustainable WAAM products. WAAM is renowned for its potential progressive aspects in diverse fields. The deposition rate of WAAM is relatively high compared to the conventional manufacturing process. WAAM offers excellent dimensional accuracy, less buy to fly ratio, and design freedom over manufacturing. WAAM supports a rich set of materials library ranging from general purpose steels to industrial grade steels, alloys, and even functionally grade materials. It has applications ranging from aerospace, defense, medical applications, electronics, automotive industry, and even in fashion art, and jewelry. As the WAAM emerged into most revenue-generated sectors of the economy it has attained the attention of many researchers along with the manufacturing industry. In the current thesis, the evolution of the WAAM process from gas metal arc welding (GMAW) has been presented. The arc force involved in the WAAM process which affects the dimensional accuracy of the weld bead was studied. The prominent process parameters such as current, wire feed, weld speed, and torch angle significantly influence the build quality of the weld bead.

Keywords--- WAAM, Graph Theory, Utility Concept, Welding Robot, Surface Roughness, Power Consumption, Process Optimization

I. Introduction

Evolution of industry 4.0 coins the emerging technologies such as additive manufacturing (AM) and autonomous robots. Additive manufacturing, 3D printing, and rapid prototyping are often used interchangeably. Robot-assisted additive manufacturing has become popular and is found to be a potential segment in the manufacturing sector today. Though numerous fabrication methods are available, additive manufacturing is considered to be beneficial in terms of product variety, flexibility, and most importantly better buy to fly ratio (BTF). The adoption of AM technology increases product quality along with a notable rise in productivity (Ko et al. 2019). With the ease of AM technology, the role of AM has transformed from prototyping to functional part fabrication with relatively low cost and time as well. The produced functional part is more beneficial in terms of industry-standard product quality, complexity, flexibility, versatile material support, and increased BTF ratio (Dilberoglu et al., 2017). Similar to 3D printing and rapid prototyping, additive manufacturing uses the concept of layer-wise build and layup of flow layers. Although AM has a rich domain of materials library support for production, metal-based materials are famous for commercial and domestic applications. In the past couple of decades, metal additive manufacturing has emerged with its super-beneficial applications. The tremendous development in metal AM is due to its void-free structure development and enhanced product density. These advent features transform the AM to use metals like steel, Inconel, aluminum, chromium, copper, tin, zinc, titanium, and various alloys. WAAM (Wire Arc Additive Manufacturing) is inspired by Additive manufacturing, in which layers are deposited to build the desired model. With the strict compliance of the Rapid Prototyping (RP) process chain, AM is limited to only prototyping initially.
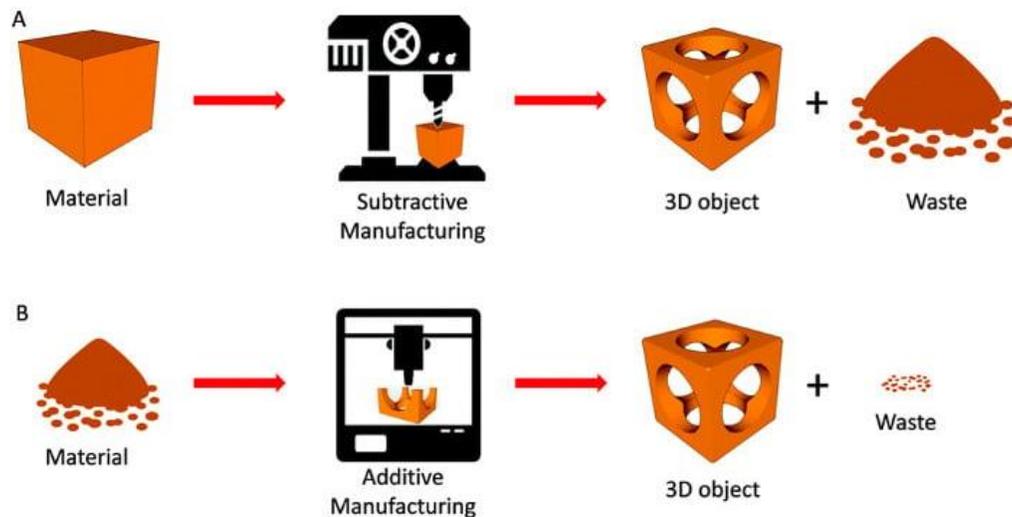
Figure 1: Additive Manufacturing

In recent times, this prototyping has been transformed into functional part manufacturing with the aid the new technologies such as wire arc additive manufacturing and the power-based fusion process of additive manufacturing, in contrast with both technologies, WAAM and PBF, WAAM is renowned for its excellent design customization, efficiency, and rich set of materials library and is prominent for its progressive potential applications in diverse fields. WAAM has emerged into various revenue-generated sectors of the economy not only in India but also across the world. This potential of WAAM has made the area to be fame and has become the research thrust of many research groups in world-class premier institutes (Kumar et al., 2022). As per the survey of compound analysis growth rate by Smart Tech Publishing shown in figure 1, the metal additive manufacturing or 3D printing market will generate $13billion in revenue in the next five years in various sectors such as Aerospace, defense, oil & gas, automotive, medical and even fashion art and jewelry. WAAM is inspired by the Gas Metal Arc Welding (GMAW) process. The process is controlled by a robotic arm and the process is called robot-assisted WAAM. In this process, the GMAW process is integrated with the robot's geometrical motion controller. The use of robots in the process enhances the quality of their outstanding precision in performing repetitive work and is programmed to perform the desired task.

II. Challenges of Additive Manufacturing

Mass production is still under the consideration of many researchers, as metal AM requires a large amount of inter-pass cooling to deposit the material properly with the required dimensions, which consumes more production time for the fabrication of the component. Smaller components are easily made compared to that large product. Further, the manufacturing sector is looking for alternatives to overcome this mitigating issue of temperature. This factor is responsible for the thermal history of the product (Liberini et al., 2017). The sequential parameter next to this issue is the formation of stresses and developing as residual stresses of the structure which need to be addressed carefully. The later challenging issue is the surface roughness of the component which leads to further post-processing operation. If the surface roughness is not addressed thoroughly, it leads to increased time for post-processing. Improper control of the surface roughness may also lead to the next layer deposition phenomenon which directly leads to the void formation in the structure that is to be built. Formation of voids results in the reduced structural quality of the product with less strength. Further, poor structural quality also leads to porosity in the microstructure. Heat input is another major concern to focus on, in which the thermal history of the previous weld bead leads to quality deposition of the later layer. Improper heat input may lead to improper solidification of the weld bead, which adversely impacts the build quality of the structure. Excessive heat input leads to weld bead sagging, which affects the improper weld bead quality. Economically emerging nations like China, India, Russia, Turkey, Japan, Brazil, and Mexico utilizes double power consumption in the manufacturing sector for production since 2017. As per the recommendation of the core imperative energy policies of the National Development and Reform Commission (NDRC), it has reduced the power consumption in the process and overall cost of production. Further, it also

recommended that the process reduced the toxic emissions of CO, NOx, HC, and PM which adversely affect human health. Apart from these emissions, the rise of CO2 makes the environment warmth which is a key factor for global warming. Hence it requires a feasible eco-friendly viable manufacturing system to safeguard the environment and natural resources. The later important issue to consider is the selection of suitable material, process parameters, and other auxiliary parameters such as shield gas supply, and the environment of weld bead deposition. For the specific application of AM appropriate material selection is crucial to have the desired feature and build quality with the required strength. Despite these challenges, metal AM methods exhibited their potential progressive applications in diverse fields. Due to the advantages of AM processes, large-scale industries across the globe are now developing manufacturing facilities using different AM technologies. Since AM processes use CAD technologies, the portability of the designs and communications is simple without boundaries which revolutionizes the manufacturing sector. AM enables the production of demanding products or custom-made specific products in time in figure 2 (Singh & Khanna, 2021).
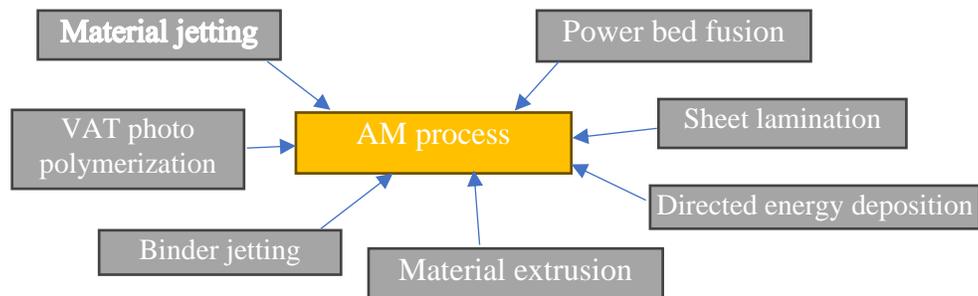

Figure 2: AM Process

III. The Use of Machine Learning in Additive Manufacturing

Machine learning-based feature modelling and the building is an evolving concept of industry 5.0. with the use of a smart machine in the field of manufacturing. The usage of smart machines and intelligent robots with the collaboration of human beings coins the concept of machine learning-based AM. Digital manufacturing without and with IoT technologies employs digital data for production as in Additive Manufacturing (AM). The progressive growth of AM has transformed from prototyping to functional part development. Due to the advent of a less Buy-To-Fly (BTF) ratio, the manufacturing sector has adopted AM technologies for large-scale production. Wire Arc and Additive Manufacturing (WAAM) is one such method for fabricating unique functional parts both job-wise, as well as mass production. Among the metal AM technologies, wire-based methods are more compliant with the standards of the manufacturing industry. The fusion of Artificial Intelligence (AI) and Machine Learning (ML) in AM technology needs to handle the data that is taken from the experimental runs. The use of AI and ML reduces the dependency on the optical and thermal monitoring of the process. The limitations of training the ML algorithms are the required reliable data and its availability (Ladani 2021a). The future generations manufacturing industry is escalated to lean manufacturing from industry 4.0, and the complexity of design, prefabrication, and inspection of quality burdens are addressed through AI integration in smart AM methods shows in figure 3 (Jin et al., 2020).

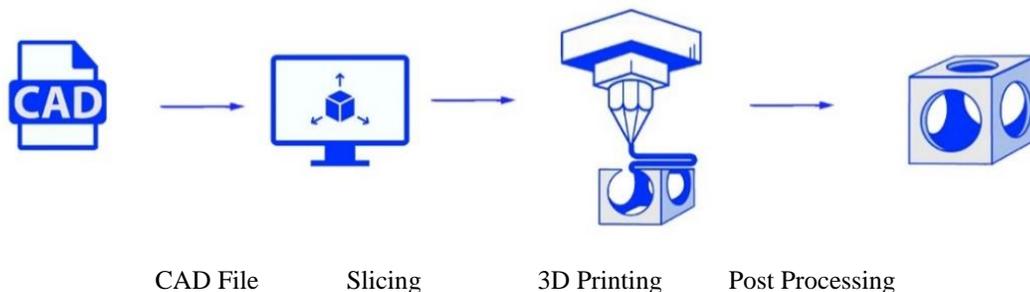CAD File   Slicing   3D Printing   Post Processing

Figure 3: AI integration in smart AM methods

Machine learning (ML) methods play a vital role in data communication to smart machines using prediction with minimal error. Most of the automation works will be based on artificial intelligence in form of machine learning techniques. Based upon the Insite learning process, machine learning techniques are classified as

supervised learning, unsupervised learning, and reinforcement-based learning. To attain the desired feature of the object, a supervised ML technique was employed that consists of both input and target or out data of the process. An Artificial Neural Network (ANN) that has a Multi-layer Perceptron model (MLP) was used to train the model. In the ANN model, there will be three important phases namely, training the model, validating the model, and testing the model. Unlike FEM tedious calculations ANN techniques identify the pattern of correlation between input and output values. This network is provided with a set of input values and its corresponding output set values and the neurons present in the hidden layer map the output value with some weights and either positive or negative bias value. Further, the trained ANN model is capable of finding the error between the desired value and predicted value, the error between both leads to the tuning of the network so the ANN model will predict near optimal desired value.

IV. Industry 5.0 and its Role in Manufacturing

Evolution of Industry 5.0 coin the terms Additive Manufacturing (AM) and smart machines along with simulation and virtual reality. The use of intelligent robots in collaboration with human beings with the aid of IoT technology transforms classical manufacturing into automated manufacturing. Automation in Manufacturing (AIM) employs digital data for production as in additive manufacturing. AM is renowned for its progressive and prospective potential aspects in several applications. The use of robots and smart machines with artificial intelligence delivers excellent precision with large-scale production without comprising the quality of the product where the product life cycle is integrated with the supply chain in form of digital data with the inclusion of cobats (Xia et al., 2020).
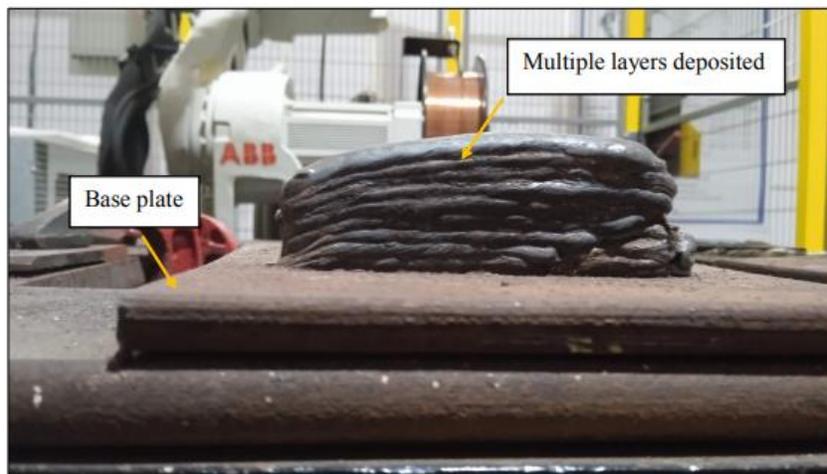

Figure 4: Layer-by-layer Deposition of Weld Bead Towards a Thin Wall

The potential benefits of AM have transformed its applications to functional part fabrication whereas earlier versions of AM are limited to the fabrication of prototype models. Metal AM methods are often used for producing complex and intricate customized 3D objects. Using the standard Rapid Prototyping (RP), cycle the original CAD data referred to as 3D metadata is transformed into a Standard Tessellation Language (STL) file, where 2D data is organized in a layered fashion. This file is fed to the motion controller which drives the material deposition layer-by-layer to fabricate the 3D object in figure 4. Depending on the material feed stock supply, AM techniques are classified into three main groups. They are Powder feed-based, powder bed-based, and wire feed-based systems. Wire feed based is extensively used in the manufacturing industry. The dimensional accuracy and material utilization technically known as the buy-to-fly ratio are the key parameters that distinguish AM from other classic manufacturing methods (Treutler & Wesling, 2021).

In wire arc additive manufacturing, initial weld bead deposition was very crucial and was a prominent factor to consider, because the later bead deposition has to take place with desired features. Process parameters such as wire feed, weld speed, the voltage supplied, current, the flow rate of shielding gas, tip distance of filler wire, nozzle to tip distance, base substrate position, fixtures, weld waviness, weld torch angle, deposition direction, the standard time between single layer multiple beads were treated as prominent enough to deposit the weld bead.
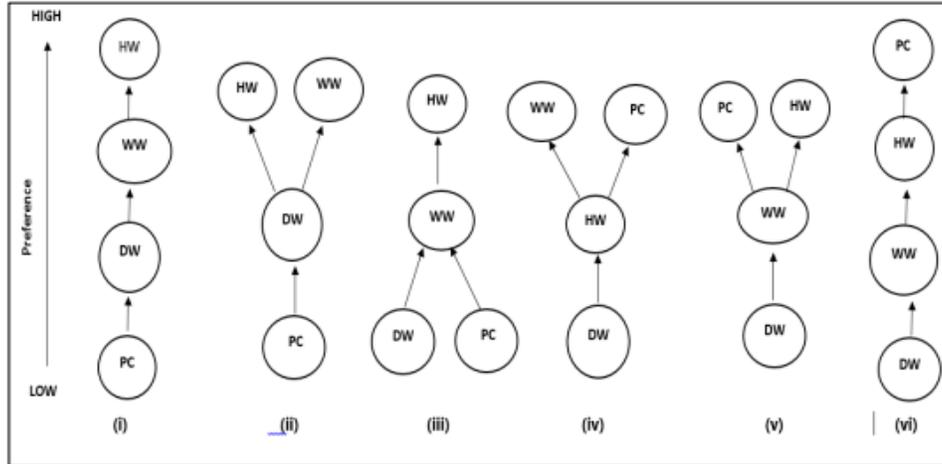
Figure 5: Graph Theory Matrix (GTM) Algorithm

The substrate also termed as base plate shown in figure.5, was made of low carbon steel and the plate thickness was 10mm., to run the design, and the experiments, the base plate was taken with a square shape of an area of 300 mm2. Gas Metal Arc Welding (GMAW) process-based wire arc additive manufacturing was performed. The filler wire of 1.2mm diameter, copper-coated mild steel of industrial grade ER70S-6 was used throughout the process. The main objective of the study is to determine the influence of process parameters on the bead quality and further the structural quality of the wall. Further, the power consumption associated with the process is also determined (Venkatarao, 2021). To optimize the process parameters a hybrid multi-objective optimization technique is used. Using the Graph Theory Matrix (GTM) algorithm the weights are calculated based on the preferences considered. With the weights calculated for each of the output characteristics, the multi-objective optimization technique h-TLBO is used for optimization.

V. Discussions

WAAM process is different from the other conventional manufacturing process in terms of the casting process, subtractive machining process, and post-processing process. The progressive advances of Wire arc additive manufacturing made the process beneficial compared to the conventional manufacturing process as WAAM offers high potential in all the manufacturing aspects. WAAM offers significant benefits that automate the production process. It offers a high degree of design freedom which has the potential for customization. It reduces material wastage, thereby it offers an excellent buy to fly ratio in the overall production process. The deposition rate of WAAM is high compared to that of other processes which are one big advantage. It offers almost zero spatters or reduced spatter in the process in contrast with the other methods WAAM is considered with less toxic emissions involved in the process (Derekar, 2018). Figure 6 displays the S/N Ratio with Better Utility below.
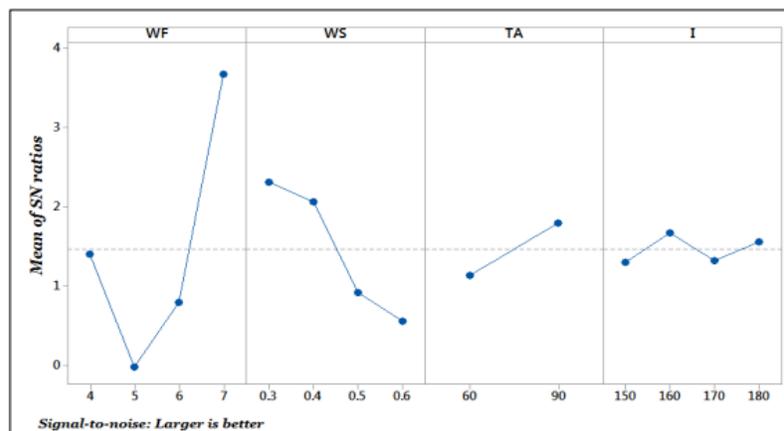

Figure 6: S/N Ratio with Better Utility

It can be observed from experiment with the process parameters, 123 A of current, with the weld torch angle 900 , at weld feed supply of 6.45 m/min with the welding speed 0.513 m/min, which consumes 3.8 kW power with arc force 10.20 N providing 0.611 microns of surface finish with the bead geometrical proportions HWB, DWB, WWB is 3.583 mm, 0.972 mm, 6.36 mm respectively is found to be optimal. Further, second optimum working conditions are found with experiment 5 with the 146 A of current, weld torch angle 79.70, weld feed 7.45 m/min, weld speed 0.513 m/min, power consumption 3.7kW, surface finish 0.647 microns with HWB, DWB, WWB, are 4.80mm, 1.192 mm, and 6.481 mm respectively.
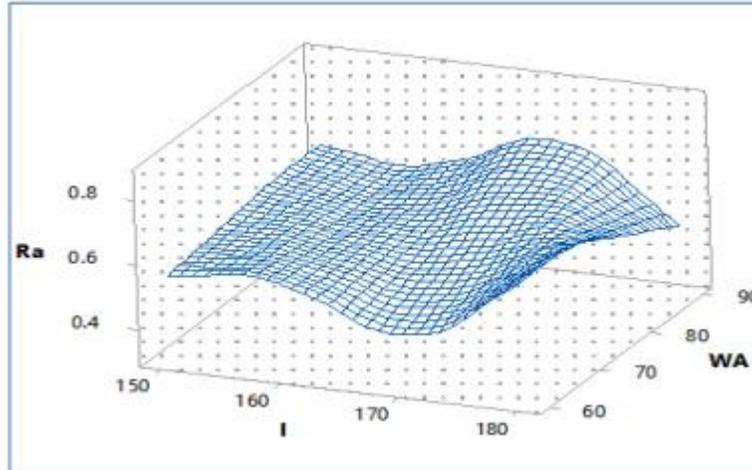

Figure 7: Influence of Current and weld Angle on the Surface Finish

From the interaction effect of process parameters on Power consumption as shown in figure 7, it is observed that a linear relationship exists among them and is associated with the net arc force. As discussed in the forces composition section, net arc force is the combination of gravitational, electromagnetic, and arc plasma drag forces. Among this composition, the electromagnetic force is dependent on the input current to the process. This force is proportionate to the supplied current. In this work, experiments are carried out with conventional industry power ratings and process parameters. The minimum net arc force generated is 10.93 N and the maximum force is 11.92 N.
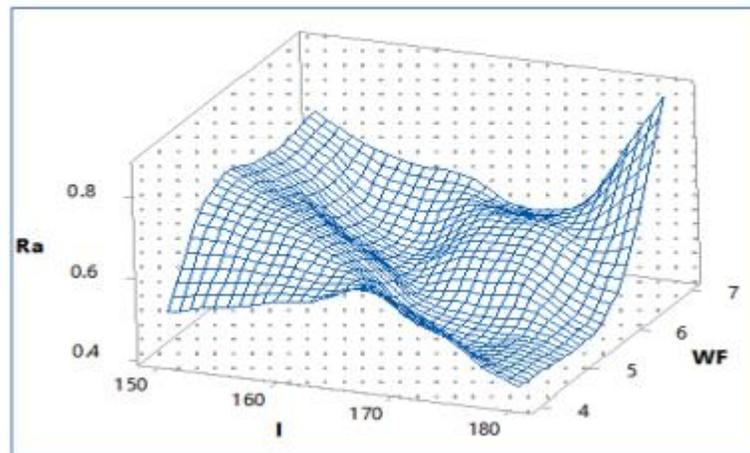

Figure 8: Influence of current and weld feed on the Surface finish.

The intensity of arc force results in a more penetrated depth of weld bead. As a resulting depth of the weld bead increases with an increase in current through arc force. It is also found that the depth of the bead is maximum at 900 torch angles. The interaction effect of process parameters on current is proportionate with the height of the weld bead at 170A, as shown in figure 8.
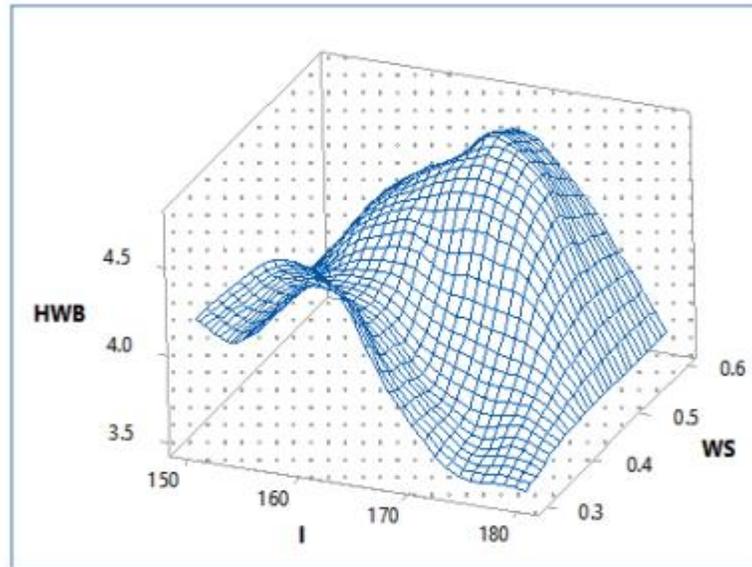
Figure 9: Influence of current and weld speed of weld bead

Further depth of the weld bead is much higher with maximum current and maximum torch angle. It can be observed from the interaction that the effect of process parameters on surface roughness is independent of process parameters as shown in figure 9, and nonlinear relation exists between them irrespective of the arc force and power consumption.

VI. Conclusions

Experiments were performed using the IRB 1520ID MIG welding robot, which was a six-axis industrial robot that works on rapid language. Using the robot, the experiments were performed and were investigated experimentally for the weld bead structure as well as the quality concern. The forces involved in the process were also determined along with the power consumption and surface roughness. The dimensional accuracy of the deposited weld bead relies on the quality of the deposition process with high accuracy. The accuracy concern was addressed by robot specifications and with strict compliance of the same. The heat-affected zone of each experiment was studied which influences the grains in the microstructure. The grain structure significantly affects the WAAM-deposited object's mechanical properties. The Power consumption and surface roughness were considered important for the current thesis aspect. As the process was having multi objectives to be focused on, it was selected to use an efficient multi-objective optimization technique that would not fall into the local optima and leads to a convergent solution. A hybrid TLBO optimization technique was employed for the present work yielding a corresponding optimal set of process parameters with a power consumption of 3.7 kW and 0.611 microns of surface roughness. The proposed optimization results are validated with the experimental results and were found to be in good agreement between the both. Further, to automate the WAAM process, an artificial neural network was proposed. In this aspect forward ANN model was used to predict the weld bead characteristics upon the training of input process parameters. The backward ANN model is the reverse mapping of the ANN model to predict the weld parameters for a specified bead geometry.

References

[1]   Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). The role of additive manufacturing in the era of industry 4.0. *Procedia manufacturing, 11*, 545-554. https://doi.org/10.1016/j.promfg.2017.07.148

[2]   Kumar, N., Bhavsar, H., Mahesh, P. V. S., Srivastava, A. K., Bora, B. J., Saxena, A., & Dixit, A. R. (2022). Wire arc additive manufacturing–a revolutionary method in additive manufacturing. *Materials chemistry and physics, 285*, 126144. https://doi.org/10.1016/j.matchemphys.2022.126144

[3]   Liberini, M., Astarita, A., Campatelli, G., Scippa, A., Montevecchi, F., Venturini, G., ... & Squillace, A. (2017). Selection of optimal process parameters for wire arc additive manufacturing. *Procedia Cirp, 62*, 470-474. https://doi.org/10.1016/j.procir.2016.06.124

[4]   Singh, S. R., & Khanna, P. (2021). Wire arc additive manufacturing (WAAM): A new process to shape engineering materials. *Materials Today: Proceedings, 44*, 118-128. https://doi.org/10.1016/j.matpr.2020.08.030

[5]   Jin, W., Zhang, C., Jin, S., Tian, Y., Wellmann, D., & Liu, W. (2020). Wire arc additive manufacturing of stainless steels: a review. *Applied sciences, 10(5)*, 1563. https://doi.org/10.3390/app10051563

[6]   Xia, C., Pan, Z., Polden, J., Li, H., Xu, Y., Chen, S., & Zhang, Y. (2020). A review on wire arc additive manufacturing: Monitoring, control and a framework of automated system. *Journal of manufacturing systems, 57*, 31-45. https://doi.org/10.1016/j.jmsy.2020.08.008

[7]   Treutler, K., & Wesling, V. (2021). The current state of research of wire arc additive manufacturing (WAAM): a review. *Applied Sciences, 11(18)*, 8619. https://doi.org/10.3390/app11188619

[8]   Derekar, K. S. (2018). A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium. *Materials science and technology, 34(8)*, 895-916. https://doi.org/10.1080/02670836.2018.1455012