A REVIEW PAPER ON METAL ARC ADDITIVE MANUFACTURING BY USING MIG WELDING

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Abstract - Wire arc additive manufacturing (WAAM) is a fusion manufacturing process in which an electric arc's heat energy is employed for melting the electrodes and depositing material layers for wall formation or simultaneously cladding two materials to form a composite structure. This directed energy deposition-arc (DED-arc) method is advantageous and efficient as it produces large parts with structural integrity due to the high deposition rates, reduced wastage of raw material, and low consumption of energy in comparison with the conventional joining processes and other additive manufacturing technologies. These features have resulted in a constant and continuous increase in interest in this modern manufacturing technique which demands further studies to promote new industrial applications. The high demand for WAAM in aerospace, automobile, nuclear, molds, and dies industries demonstrates compatibility and reflects comprehensiveness.

By using this process with the help of MIG welding, we are planning to create the 3D object using WAAM technology so that we can check the characteristics as well as mechanical and metallurgical behavior of the 3D object that is created by using MIG welding with the help of WAAM technology

Keywords: *Wire Arc Additive Manufacturing (WAAM), Fusion, Electric Arc, cladding, Deposition arc (DED-arc).*

1. INTRODUCTION *(Size 11, Times New Roman)*

Wire Arc Additive Manufacturing (WAAM) is a production process used to 3D print or repair metal parts. It belongs to the Direct Energy Deposition (DED) family of Additive Manufacturing processes. WAAM is executed by depositing layers of metal on top of each other until a desired 3d shape is created. It is a combination of two production processes: Gas Metal Arc Welding (GMAW) and additive manufacturing. GMAW is a welding process used for joining metal parts using an electric arc, and additive manufacturing is the industrial term for 3D printing. The production of parts using WAAM is carried out by a welding robot integrated with a power source. A welding torch attached to the robot is used to melt the wire feedstock to build 3D parts.

2. LITERATURE SURVEY

The Latest Research of Wire Arc Additive Manufacturing (WAAM). (Researched by Institute of Welding and Machining, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany). Wire arc additive manufacturing is currently rising as the main focus of research groups around the world. This is directly visible in the huge number of new papers published in recent years concerning a lot of different topics. This review is intended to give a proper summary of the international state of research in the area of wire arc additive manufacturing. The addressed topics in this review include but are not limited to materials (e.g., steels, aluminum, copper, and titanium), the processes and methods of WAAM, process surveillance, and the path planning and modeling of WAAM. The consolidation of the findings of various authors into a unified picture is a core aspect of this review. Furthermore, it intends to identify areas in which work is missing and how different topics can be synergetically combined. A critical evaluation of the presented research with a focus on commonly known mechanisms in welding research and without a focus on additive manufacturing will complete the review.

At present, additive manufacturing is the focus of industry and research due to a large number of new developments in processes and systems. This is further strengthened by the general trend toward resource efficiency, as additive manufacturing processes offer the possibility of near-net shape or net shape production. Particularly for cost-intensive materials like titanium or tungsten, additive manufacturing can be the manufacturing process of choice. The main factors influencing the selection of the additive manufacturing process are the complexity and resolution that can be achieved, as well as the deposition rate and component size. Furthermore, additive manufacturing grants a lot more degrees of freedom for product design than conventional manufacturing processes and opens up the possibility of load-optimized design.

The newly increasing interest in WAAM is based on the advances in robotic control and modern electronic control circuits for welding machines. They made modern controlled short arc welding processes with reduced energy input possible and very stable. The most known modified short arc process, “cold metal transfer” (CMT), has been developed by the company “Fronius” and is the most used process for WAAM based on Gas Metal Arc Welding (GMAW) in the literature. Furthermore, for controlled short arcs, the intention to lower the heat input is the focus of some research, increasing the potential applications. Aside from the common gas metal arc welding processes, Tungsten Inert Gas (TIG) welding processes or plasma welding processes have been used due to the separation of energy and mass input. Aside from standard welding processes, the combination of welding processes with others (e.g., laser-assisted welding) or with forming processes has been attempted as well. The basic literature about welding gives a good overview of the used welding processes.

Based on a large number of publications in recent years, it is clear that arc-based additive manufacturing, which also includes WAAM, is the focus of scientific attention. However, there is still no comprehensive and complete understanding of the effects and potential of it. In the context of the current state of research, and especially integrating product development into the process chain, manufacturing for WAAM components would enable a new generation of components with load-specific adjusted properties in research and thus may lead to full exploitation of the potential of WAAM.

A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminum. (This review was submitted as part of the 2018 Materials Literature Review Prize of the Institute of Materials) Wire-arc additive manufacturing (WAAM) is a common metal 3D printing technique that offers several benefits, including a high rate of deposition, cheap price, and efficacy for complex parts. Even though (WAAM) has demonstrated its ability to meet the demands of manufacturing components of medium-to-large size made of (Al) for the automotive and other related industries, WAAM cannot currently use as a complete production procedure due to practical issues such as mechanical properties that aren't matched and the presence of significant residual stresses. the AM technologies offer promising new benefits with the MMCs as a solution for some challenges. This article reviews the MMCs Mixing technique and their critical issues, AM classification, and WAAM process with advantages and challenges. also reviews WAAM of some AMCs with different reinforcements and power sources. The results of the study of the influence of reinforcement particles on the structure showed that they changed grains structure from the columnar dendrite to uniaxial dendrites after the solidification and improves hardness.

Although wire arc additive manufacturing (WAAM) has proven its capability of fulfilling demands of production of medium-to-large-scale components for automotive and allied sectors made up of aluminum, at present, WAAM cannot be applied as a fully-fledged manufacturing process because of practical challenges such as under-matched mechanical properties, the presence of large residual stresses and mandatory post-deposition operation for the formed component. This paper is a review of WAAM technology including a brief of WAAM's history, status, advantages, and constraints of the WAAM field. A focus is provided including the efforts directed towards the reduction of porosity, tensile properties, microstructural investigations, and other valuable advancements in the field of WAAM of aluminum.

A Review on Wire Arc Additive Manufacturing using CMT. (This review was submitted by Dr. B. Anandavel, Prof. N. Thenammai Dept. of Metallurgical Engineering, Government College of Engineering Salem-636011, Tamil Nadu India) Wire Arc Additive manufacturing is an upcoming method to replace the normal conventional machining process and also can reduce wastage and save raw material. This process can be used to produce small to large structures which can be complicated in other conventional machining processes. CMT is a modified variant of GMAW that can be suitable for Wire arc additive manufacturing; this paper reviews the technique which can be used in the WAAM and give information on a research paper that is useful for studying wire arc additive manufacturing.

Discussed the CMT unique specification like low thermal heat input which can produce spatter-free and excellent quality weld, metal transfer mode like Dip transfer in CMT pulsed and spray dip transfer in CMT pulsed advanced. ER2319 is deposited in both CMT pulsed and CMT PADV the result shows that CMT PADV has more efficient deposition and also eliminates porosity and also has perfect strength and excellent plastic elongation and also suggests interlayer cold rolling can produce a perfect layer and post-heat treatment can improve aluminum in WAAM.

Compared CMT and CMT Pulsed mode by depositing 8 multilayers of ER309LSi and analyzed the temperature cooling technique for depositing thick and strong tools for heavy applications. Taguchi method was used for DOE, for both methods welding parameters like wire feed rate, torch travel speed, current, voltage, and shielding gas flow are optimally selected and the Interval time for depositing minimum thickness wall is 9mins and for Maximum thickness is 42mins and the weaving frequency is 1Hz common for both processes, Result of the study reveals both CMT and CMT Pulsed produces same high-temperature zone and shows the CMT process is energy saving and has 60% smaller for high-temperature zone.

The authors investigated the combination of ER408S an alloys wire and MF6– 55GP hard-facing material which is deposit first four layers are deposited by ER408S and 5-8 layers are deposited by MF6-55GP which is a hard-facing material both are deposited in WAAM and their microstructure and mechanical properties are investigated to find out the wear-resistant compounded created by using CMT, The result shows a positive approach for creating a wear resistant materials can be produced, and also residual stress and defect in the surface are present more innovations are needed to improve the quality. UTS test shows fractures occurred in MF6-55GP and also have a high hardness value of 800HV.

A review on wire arc additive manufacturing: Monitoring, control and a framework of an automated system. (This review is submitted by the School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong, NSW, 2522, Australia) Wire arc additive manufacturing technology (WAAM) has become a very promising alternative to high-value large metal components in many manufacturing industries. Due to its long process cycle time and arc-based deposition, defect monitoring, process stability, and control are critical for the WAAM system to be used in the industry. Although major progress has been made in process development, path slicing and programming, and material analysis, a comprehensive process monitoring, and control system is yet to be developed. This paper aims to provide an in-depth review of sensing and control design suitable for a WAAM system, including technologies developed for the generic Arc Welding process, the Wire Arc Additive Manufacturing process, and laser Additive Manufacturing. Particular focus is given to the integration of sensor-based feedback control, and how they could be implemented into the WAAM process to improve its accuracy, reliability, and efficiency. The paper concludes by proposing a framework for sensor-based monitoring and control systems for the GMAW-based WAAM process. This framework provides a blueprint for the monitoring and control strategies during the WAAM process and aims to identify and reduce defects using information fusion techniques.

Wire arc additive manufacturing (WAAM) is an emerging technology in advanced fabrication. In contrast to other additive manufacturing (AM) technologies, WAAM makes use of an electric arc as a heat source to deposit metal material layer-by-layer, which makes up the final part. According to the type of heat source, WAAM commonly has three types: Gas Tungsten Arc Welding (GTAW)-based, Gas Metal Arc Welding (GMAW)-based and Plasma Arc Welding (PAW)-based. This method of depositing an entire component using welded metal has been in practice since 1925. Compared to laser additive manufacturing (AM) techniques, WAAM features many distinct advantages. Firstly, deposition rates of WAAM processes are typically much higher than laser-based AM, making WAAM more appropriate for the production of large-scale complex components. WAAM also features relatively low equipment costs, as it typically makes use of off-the-shelf industrial robotics and arc-welding equipment. When compared to laser powder AM methods, WAAM also features a better material utilization ratio and a more environmental-friendly production process.

A review on Wire arc additive manufacturing of aluminum alloys for aerospace and automotive applications. (This review is submitted by Babatunde Omiyage, the Federal University of Technology Akure) Wire arc additive manufacturing (WAAM) is suitable for printing medium-to-large complex parts with structural integrity while reducing material wastage, and lead time, improving the quality and customized design for functional components. Aluminum alloys are one of the most commonly used metallic materials in manufacturing parts for aerospace and automotive applications due to their lightweight, excellent strength, and corrosion resistance properties. Aluminum alloys have been employed in the WAAM process to produce parts for the aerospace and automotive industries. In this paper, various research works associated with the application of WAAM of aluminum alloys for aerospace and automotive industries, their metallurgical characteristics, and their mechanical properties have been reviewed and discussed in detail to identify the research gap and future research directions. This paper is patterned to provide a comprehensive review of WAAM of aluminum alloys for the production of parts in the aerospace and automotive industries.

The processing of aluminum alloys by wire arc additive manufacturing (WAAM) gained significant attention from industry and academia in the last decade. With the possibility to create large and relatively complex parts at low investment and operational expenses, WAAM is well-suited for implementation in a range of industries. The process nature involves the fusion melting of a feedstock wire by an electric arc where metal droplets are strategically deposited in a layer-by-layer fashion to create the final shape. The inherent fusion and solidification characteristics in WAAM are governing several aspects of the final material, herein process-related defects such as porosity and cracking, microstructure, properties, and performance. Coupled with all mentioned aspects is the alloy composition, which at present is highly restricted for WAAM of aluminum but received considerable attention in later years. This review article describes common quality issues related to the WAAM of aluminum, i.e., porosity, residual stresses, and cracking. Measures to combat these challenges are further outlined, with special attention to the alloy composition. The state-of-the-art of aluminum alloy selection and measures to further enhance the performance of aluminum WAAM materials are presented. Strategies for further development of new alloys are discussed, with attention on the importance of reducing crack susceptibility and grain refinement.

A Review on Arc Welding Processes for High Deposition Rate Additive Manufacturing. (This review was submitted at the 19th CIRP Conference on Electro-Physical and Chemical Machining, 23-27 April 2018, Bilbao, Spain)

Arc-welding-based additive manufacturing techniques are attracting interest from the manufacturing industry because of their potential to fabricate large metal components with low cost and short production lead time. This paper introduces wire arc additive manufacturing (WAAM) techniques, reviews the mechanical properties of additively manufactured metallic components, summarizes the development in process planning, sensing, and control of WAAM, and finally provides recommendations for future work. Research indicates that the mechanical properties of additively manufactured materials, such as titanium alloy, are comparable to cast or wrought material. It has also been found that twin-wire WAAM can fabricate intermetallic alloys and functionally graded materials. The paper concludes that WAAM is a promising alternative to traditional subtractive manufacturing for fabricating large expensive metal components. Based on current trends, the future outlook will include automated process planning, monitoring, and control for the WAAM process.

Although Additive Manufacturing implementation is rapidly growing, industrial sectors are demanding an increase in manufactured part size which most extended processes, such as Selective Laser Melting (SLM) or Laser Metal Deposition (LMD), are not able to offer. In this sense, Wire-Arc Additive Manufacturing (WAAM) offers high deposition rates and quality without size limits, becoming the best alternative for additive manufacturing of medium-large size parts with high mechanical requirements such as structural parts in the aeronautical industry.

WAAM technology adds material in the form of the wire using an arc welding process to melt both the wire and the substrate. Three welding processes are mainly used in WAAM: Plasma Arc Welding (PAW), Gas Tungsten Arc Welding (GTAW or TIG), and Gas Metal Arc Welding (GMAW or MIG). This paper studies these processes regarding their capabilities for additive manufacturing and compares the mechanical properties obtained by the different welding technologies applied in WAAM. Obtained results show the applicability of the technology as an alternative to traditional metallic performing manufacturing processes, such as casting or forging.

Up to now, GTAW and PAW-based arc welding technologies have been demonstrated to be more reliable processes for WAAM with fewer problems of sputtering, excessive heating, distortion, or porosity than GMAW. However, in these two technologies, the wire is not fed coaxially and this leads to process variations when changing the welding direction and extreme sensibility to arc length. Many robotic welding systems require a rotary axis to orient the wire-feeding nozzle and keep it matched with the welding direction which limits applicability.

The main results obtained from the development of the three processes for Additive Manufacturing. Results include not only mechanical properties values but also the capability of each studied process to be applied in High Deposition Rate Additive Manufacturing. Results are divided by WAAM technology (CMT, PAW, and Top TIG) and materials (AISI 316L and Ti6Al4V).

A review of process planning strategies and challenges of WAAM. (This review was submitted by Sagar Singh, Satish Kumar, Department of Mechanical Engineering, Thapar Institute of Engineering and Technology, Patiala, Punjab 147004, India)

Wire arc and additive manufacturing (WAAM) is coming out be a new promising economical technique for metal additive manufacturing. Custom-built large-volume metallic structures can be produced in relatively less time using WAAM techniques. A state-of-the-art setup of WAAM needs to control several parameters related to the process of additive manufacturing and welding process. Hence, the process planning of WAAM is a crucial aspect in the successful execution of WAAM. In the present study, the fundamentals of WAAM techniques, various important steps, and strategic process planning for WAAM have been elaborated. Furthermore, the challenges and cutting-edge developments in this prominent field of WAAM are focused on a better understanding of processes and technologies.

Process planning is an important task for the proper utilization and implementation of any manufacturing process. Therefore, process planning strategies used by researchers and practitioners for the application of the WAAM approach and those reported in the literature are reviewed in this manuscript to present it in such a way that it works as a guiding tool for beginners. Along with this, challenges of WAAM either in terms of its application or product quality are also complied with by reviewing the existing literature.

The aerospace and automobile sectors are employing the welding arc-based AM techniques against the traditional subtractive manufacturing and manufacturing techniques for multifaceted product structures. The heterogeneity of micro-mechanical properties in WAAM components/parts is a major concern owing to the residual stress, stair-step effect, solidification cracking, and porosity. Currently, the WAAM of most of the metals is at an initial stage, however several researchers undoubtedly.

In this review work, along with an introduction to WAAM techniques, all important steps and strategies of process planning are reviewed and presented. Current development trends and challenges in the field of WAAM are also discussed. From the extensive literature survey, the following conclusions are drawn.

1. Welding arc-based additive manufacturing is becoming popular as an economic alternative to metal additive manufacturing.
2. Process planning for WAAM is a very important task for success.

A review of the wire arc additive manufacturing of metals: properties, defects, and quality improvement. (This review was submitted by John Norrish, Dominic Cuiuri School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong NSW 2522, Australia). This article reviews the emerging research on WAAM techniques and the commonly used metallic feedstock materials, and also provides a comprehensive overview of the metallurgical and material properties of the deposited parts. Common defects produced in WAAM components using different alloys are described, including deformation, porosity, and cracking. Methods for improving the fabrication quality of the additively manufactured components are discussed, taking into account the requirements of the various alloys. This paper concludes that the wide application of WAAM still presents many challenges, and these may need to be addressed in specific ways for different materials to achieve an operational system in an acceptable time frame. The integration of materials and manufacturing processes to produce defect-free and structurally sound deposited parts remains a crucial effort into the future.

Due to the highly complex nature of WAAM, many different aspects of the process need to be studied, including process development, material quality and performance, path design and programming, process modeling, process monitoring, and online control [9]. Several WAAM review papers have been published by leaders in the field, covering state-of-the-art systems, design, usage, in-situ process monitoring, in-situ metrology, and in-process control. Nevertheless, there is still a need for a systematic review of the properties of various WAAM-processed materials, the defects associated with different alloys, and a summary of current and future research directions that are aimed at quality improvements for the alloy classes of interest.

In recent years, wire arc additive manufacturing (WAAM) has increasingly attracted attention from the industrial manufacturing sector due to its ability to create large metal components with high deposition rate, low equipment cost, high material utilization, and consequent environmental friendliness. The origin of the WAAM process can be traced back to the 1925s when Baker [1] proposed to use an electric arc as the heat source with filler wires as feedstock materials to deposit metal ornaments. Since then, consistent progress has been made in the development of this technology, particularly in the last 10 years.

This paper reviews the microstructure and mechanical properties of various metals, including titanium and its alloys, aluminum, and its alloys, Ni-based alloy, steel, and other intermetallic materials fabricated by the various WAAM processes. The common defects that have been found to occur for different materials are also summarized. The current methods for both in-process and post-process quality improvement and defect reduction are introduced. Finally, a discussion is given on improving the quality of WAAM fabricated parts through process selection, feedstock optimization, process monitoring and control, and post-process, including proposals for future research directions.

A review of WAAM for steel construction – Manufacturing, material and geometric properties, design, and future directions. (This review was submitted by Jian Qin, Paul Shepherd, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK) This paper provides a review of the capabilities of WAAM for manufacturing steel components for use in the construction industry, with a focus on the structural stability and design of WAAM builds. Manufacturing techniques that can be used for WAAM construction are first discussed. This is followed by a detailed review of the material and geometric properties and the resulting structural stability performance of WAAM steel structures to date. To exploit the advantage of WAAM in building free-form shapes, structural optimization techniques suitable for WAAM construction are discussed. Lastly, conclusions and future research directions are provided.

Initially developed for mechanical applications, WAAM is a material-efficient alternative to subtractive techniques. Whilst 52 % of global steel is used for construction as reinforcement bars, plates, and structural profiles which are traditionally rolled or welded into standard or universal prismatic shapes, on average, half of the steel in structures is not used to bear design loads because shear forces and bending moments aren't constant along the length of a member. By employing WAAM, more structurally efficient, non-prismatic, free-formed geometries are made possible. Additionally, combinations of alloys can be used to produce functionally graded materials, and parts can be produced with variable microstructures by controlling cooling rates, which can lead to advantageous material properties.

The use of WAAM in construction could increase automation, reduce physical workload, and improve workplace safety. Furthermore, it could allow safer construction in harsh environments such as war zones, areas affected by natural disasters, and extra-terrestrial sites. Trusses with optimized cross-sections and free-form joints have been realized using WAAM, and the design efficiency (using capacity-to-mass ratio) was found to be at least double that of conventional designs. This highlights how WAAM could be used to manufacture material-efficient designs that cannot be produced using conventional processes. Two steel footbridges (one in Darmstadt, Germany, and one in Amsterdam, The Netherlands have also been successfully manufactured using WAAM, with the former being manufactured in situ. However, there are still significant research gaps in establishing the optimal process parameters to be used, and whether the mechanical properties and structural stability of WAAM steel structures meet the design requirements for other civil applications. To this end, this paper provides a detailed review of the potential use of WAAM to produce steel members for use in construction and identifies the research gaps and areas of opportunities.

In the current paper, a description of the WAAM process and emerging technologies suitable for construction are first introduced. The material properties and types of geometric imperfections of WAAM structures, along with the effects of different manufacturing parameters on them, are then reviewed. This is followed by a discussion on topology optimization and structural form-finding methods that may benefit WAAM construction. The final section discusses the current inconsistencies in findings, identifies the research gaps, and provides suggestions for future research directions for the development of WAAM in the construction industry.

This review details the major research areas related to WAAM in construction, including manufacturing techniques, material properties, geometry, structural response, and design. These research areas have gained the attention of many research groups and companies alike. Although recent builds demonstrate the potential of WAAM in construction, there are numerous research gaps and areas for future investigation.

A Review on Effects of heat accumulation on the arc characteristics and metal transfer behavior in Wire Arc Additive Manufacturing of Ti6Al4V. (This review was submitted by Bintao Wu, Donghong Ding, School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong, NSW, 2522, Australia) Wire arc additive manufacturing (WAAM) offers a promising alternative to traditional subtractive manufacturing of metallic components, particularly in the case of large Ti6Al4V structures for the aerospace sector that features high buy-to-fly ratios. This study investigates the influence of heat accumulation on bead formation, arc stability, and metal transfer behavior during the manufacture of Ti6Al4V with the gas tungsten wire arc additive manufacturing (GT-WAAM) using localized gas shielding. An infrared pyrometer is used to measure the in-situ interpass temperature which is a key factor in determining heat accumulation. Arc stability and metal transfer behavior are monitored using a high-speed camera. The results show that due to the various thermal dissipation paths along the building height, there exists a significant difference in temperature variation between the substrate and in-situ layer. Owing to the influences of heat accumulation, the interlayer surface oxidation and bead geometries vary along the building direction, especially for the first few layers of the deposited wall, which lead to variation in an arc shape and metal transfer behavior. The research outcome provides a better understanding of the effects of heat accumulation on deposition stability during the WAAM process, which benefits future process optimization and control.

Heat accumulation is a critical factor that influences the stability of the WAAM process in terms of the geometrical accuracy, deposition defects, microstructural evolution, and material properties of as-fabricated parts. Ma et al. (2015b) carried out an experiment in which a simple Ti-Al part was fabricated using GT-WAAM. It was found that the alpha phase fraction in the microstructure decreases by nearly threefold when the interpass temperature changes from 100 °C to 500 °C, which results in a decrease in hardness values. Shen et al. (2016) investigated the fabrication of Fe-Al materials using a similar WAAM process and reported that poorly controlled interpass temperature is likely to produce longitudinal cracking and high residual stress in the first few layers. In addition, considerable research has focused on arc stability and metal transfer behavior of the WAAM process. Wang et al. (2016) claim that during the arc-wire deposition process, the distance between the trailing end and center of the molten pool was increased by 1.95 mm from 1st layer to 5th layer due to the increased heat accumulation. Similar results could also be found in earlier literature (Zhao et al., 2011) regarding the analysis of thermal behaviors during multi-layer rapid prototyping fabrication. Another study conducted by Denlinger et al. (2015) found that the distortion and residual stresses in as-fabricated titanium and nickel alloy parts were significantly affected by the inter-layer dwell time that is directly related to the thermal characteristics. Zhou et al. (2016) developed a three-dimensional model to simulate the arc shape and metal transfer behaviors occurring in the WAAM process. The distribution of thermal conductivities and molten pool characteristics for single-bead as well as overlap deposition were investigated. Their results show that the high-temperature region of the molten weld pool for overlapping deposition is narrower than that of single-bead deposition, due to the smaller net heat flux of overlapping deposition. Although these simulation and experimental studies have provided some useful information, the underlying mechanisms of arc characteristics and metal transfer behavior associated with heat accumulation are still poorly understood due to the complexity of the WAAM process.

This study investigates the influence of heat accumulation on process stability during the fabrication of Ti6Al4V parts using GT-WAAM with localized gas shielding. The difference in temperature variations between the substrate and in-situ layers is discussed. The results provide insight into how the interpass temperature is measured. Furthermore, the surface morphology, geometrical features, arc characteristics, and metal transfer behaviors in different layers during deposition are compared to identify variation trends associated with heat accumulation. Although the research outcomes are not a direct physical explanation of the thermal mechanism, this study offers a better understanding of the effects of heat accumulation on the process stability of the wire arc additive manufacturing process, which will benefit further process optimization and control.

In this study, Ti6Al4V alloy has been used as the build material for the GT-WAAM process using localized gas shielding. Based on the in-situ measurement of the temperature at each layer, the effects of heat accumulation on the stability of deposition, oxidation, geometrical shape, arc characteristics, and metal transfer behavior were investigated.

A Review of Thermo-mechanical Modelling and Analysis of Residual Stress Effects in Wire Arc Additive Manufacturing. (This review was submitted by Fakada Dabalo Gurmesa and Hirpa Gelgele Lemu, Department of Mechanical and Structural Engineering and Materials Science, Faculty of Science and Technology, University of Stavanger, N-4036 Stavanger, Norway). The wire arc additive manufacturing (WAAM) process is a 3D metal-printing technique that builds components by depositing beads of molten metal wire pool in a layer-by-layer style. Even though manufactured parts commonly suffer from defects, the search to minimize defects in the product is a continuing process, for instance, using modeling techniques. It focuses on thermo-mechanical modeling and analysis of residual stress, which has interdependence with the thermal cycle, mechanical response, and residual stress in the process during printing. This review also explores some methods for measuring and minimizing residual stress during and after the printing process. Residual stress and distortion associated with many input and process parameters that are in complement to thermal cycles in the process are discussed. This review study concludes that the thermal dependency of material characterization and process integration for WAAM to produce structurally sound and defect-free parts remain central issues for future research.

Thermo-mechanical modeling provides the description, methodology, and background of WAAM techniques to assist the production process and increase the quality of printed parts based on the concepts of thermal and mechanical analysis. Though most recent research on WAAM focused on modeling techniques, many studies merged both modeling and experimental works for the sake of validation. For instance, Ding et al. studied both the mechanical and thermal models with the finite element (FE) software package ABAQUS 6.10 using Eulerian and Lagrangian reference frames for a steady state and a transient thermal model, respectively, and validated them with experiments. The study also indicated that, in the WAAM, the higher power input of the welding process causes major RS and distortion of the manufactured components. Cambon et al. conducted experimental work on the thermo-mechanical model to separately explain the heat effect in the WAAM process and on a mechanical model to study the expansion and the solidification leading to shrinkage. The mechanical properties of parts produced using WAAM are affected by the thermal residual stresses when the stress results exceed the local yield stresses and experience plastic deformation. Other researchers, such as Li et al. conducted a coupled thermo-mechanical model to determine the thermal stresses and the distributions of RS using a GMA-based AM process in the MSC. Marc code. The hole-drilling method was used to measure the RS generated in the deposited layers and substrate to confirm the effectiveness of the model.

With geometrical consistency for the desired production by moderating the heat inputs. RS and distortions are considered to be the major obstacles against the more widespread application of WAAM. In particular, since WAAM involves significant amounts of heat input within the printed part, thermal management is the main important action needed to improve the quality of the part in cases of surface finish and induced internal voids. For these defects, thermal modeling can provide the basis for the thermal properties of the RS remaining in the products. As the moving localized heat source causes steep temperature gradients, which are inevitable in this process, accurate prediction of the thermally induced RS and distortions are of paramount importance. The properties of the thermally affected build-up part are due to the layer-by-layer molten pool deposits and process conditions such as the deposition patterns, energy input, and heat conduction during the printing process.

This review article presented the details of thermo-mechanical modeling and analysis of RS with a focus on how the thermal input effects are interrelated to the mechanical properties and RS associated with the WAAM process, as well as the characterization of the products. According to the literature reviewed, the mechanical performance of WAAM components is determined by defects that exist in the products, which are mostly affected by the thermal cycle performed during the manufacturing process.

A Review on Fabrication of iron-rich Fe–Al intermetallic using the wire-arc additive manufacturing process. (This review was submitted by Chen Shen and Zengxi Pan, Faculty of Engineering & Information Sciences, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia). A wire-arc additive manufacturing (WAAM) system is used to fabricate iron-rich Fe–Al intermetallic with 25 at% aluminum content. The alloy is produced in situ through the controlled addition of the elemental iron and aluminum components into the welding process. The properties of the fabricated material are assessed using optical microstructure analysis, hardness testing, tensile testing, X-ray diffraction phase characterization, and electron dispersive spectrometry. It is shown that the WAAM system is capable of producing iron-rich Fe–Al intermetallic with higher yield strength and similar room temperature ductility when compared to equivalent materials produced using powder metallurgy.

Iron-rich Fe–Al intermetallic is of interest for its excellent oxidation and corrosion resistance, low density, and low material cost. Systematic research on this material has been conducted since the 1980s when Oak Ridge National Laboratory (ORNL) produced iron-rich Fe–Al compounds by melting and drop casting, and also used microalloying and heat treatment methods to assess the effects on the mechanical properties of the material. According to the Fe–Al binary diagram, iron-rich Fe–Al intermetallic mainly contains a Fe_3Al phase with a DO_3 structure and FeAl phase with a B2 structure. To date, research has mainly focused on improving the mechanical properties, especially ambient temperature ductility and yield strength above 600 °C, by adding alloying elements to Fe_3Al or FeAl-based iron aluminides. Improvements in the conventional casting of iron aluminides have stalled. Instead, powder-based melting and mechanical hot pressing have become the preferred methods of producing these alloys. However, the manufacturing cost of these methods is relatively high therefore the innovative method of fabricating iron aluminides with lower manufacturing cost has been announced to be one of the main future research areas.

Considering the low ductility and machinability of Fe–Al intermetallic at room temperature, and also the current manufacturing trend of free-forming processes, the additive manufacturing (AM) processes may offer an effective alternative for fabricating full-density structural iron aluminides. AM processes have been increasingly successful since their first introduction into the manufacturing industry in 1986. While initially applied to non-metallic materials, AM has subsequently been adapted to fabricate complex, net-shaped metal components in successive layers. As a rapid prototyping technique, short lead times are obtained and design changes can easily be incorporated. It has proven to be very effective in accelerating product development by omitting extensive machining and thus reducing time-to-market for traditional machining approaches. Currently, deposition methods for metal AM processes can be divided into two categories: powder-based (laid down as a bead or continuously blown into the melt area by a gas stream) and wire-fed. The present research has chosen the wire-fed approach as the preferred deposition method. Although the powder-based AM process has more shaping accuracy and higher resolution, for certain materials it cannot directly produce functional parts of high structural integrity that can be used in operational systems. Powder-based AM processes produce parts that are close to full density but often require expensive processing such as hot isostatic pressing (HIP) to achieve the full density that is essential for highly loaded structural materials. Also, the wire-fed deposition method has significantly lower material supply cost and there is less potential for oxide contamination when compared to powder-based methods. The power source chosen for the present AM process is gas tungsten arc welding (GTAW) arc rather than laser or electron beam, due to a combination of advantages including low cost, no need for a vacuum chamber (when compared to electron beam), the ability to economically apply the process to a very large operating volume, and a much higher deposition rate.

Furthermore, compared to the GMAW process, the GTAW arc is more stable and less inclined to generate spatter when applied to a wide range of ferrous, and non-ferrous alloys and their combinations, which is more desirable to achieve the consistent chemical composition of the disposition. The GTAW process can be combined with industrial welding robots and multi-sensor control systems to achieve high arc placement accuracy in industrial applications where distortion or other small-but-unpredictable component placement errors are likely.

The purpose of this feasibility study is twofold. The first objective is to explore a cost-effective method for fabricating fully dense iron-rich Fe–Al intermetallic; the second is to prove that AM processes can be applied to directly fabricate iron-rich Fe–Al intermetallic with acceptable material properties if components made by the AM process had acceptable mechanical properties for aerospace structural components [25], [26], the method demonstrated in this study should have the potential to replace conventional powder-based casting or melting manufacturing methods.

It is feasible to produce Fe_3Al-based iron aluminide, exhibiting consistent composition and full density, by using the wire-arc additive manufacturing (WAAM) process incorporating in situ alloying of the elemental iron and aluminum components

A review on Generalized overlapping model for multi-material wire arc additive manufacturing (WAAM). (This review was submitted by Seyed Aref Banaee, Angshuman Kapil & Abhay Sharma, Faculty of Engineering Technology, Department of Materials Engineering, KU Leuven, Sint-Katelijne Waver, Belgium). The single-material overlapping models are incompatible with multi-material wire arc additive manufacturing (WAAM). A newly developed generalized model considers dissimilar adjoining beads in multi-material WAAM. The geometric model of dissimilar overlapping beads coupled with an algorithm identifies the process conditions for the two materials to maintain the same bead heights. The model, implemented for stainless-steel and creep-resistant-steel pair, yields significant scientific and practical findings. Compared to a fixed overlapping distance in single-material, e.g. 0.66 or 0.738 times the bead width, the multi-material overlapping distance is a complex function of individual bead widths. The bi-metallic interface fusion is affected by the molten metal flow, bead dimensions, and heat input. Contrary to the prevailing notion of a flat-top surface in the intermediate layer ideal for multi-layer deposition, a slight hill ensures a defect-free interface. The repeatable and defect-free bi-metallic walls and a matrix is expected to have a breakthrough in multi-material WAAM.

Multi-material additive manufacturing (MMAM) provides the unique ability to fabricate geometrically intricate shapes whilst satisfying the requirements of site-specific properties and desired property variations in a single operation. The components such as the engine block bi-metallic aero-engine turbine blade nozzle manifold, and bi-metallic channel wall nozzle have been successfully fabricated using WAAM. The growth of MMAM is evident from several recent reviews detailing the existing state-of-the-art. Among different AM processes (directed energy deposition (DED-powder/wire), powder bed fusion (PBF), laser engineering net shaping (LENS), and hybrid AM), wire and arc-based DED commonly known as wire arc additive manufacturing (WAAM) is the recent addition in the MMAM group. Compared to other options, WAAM is suited for the cost-effective fabrication of medium to large structural components, e.g. bridges owing to the unconstrained build volumes and significantly higher deposition rates than other competing processes like PBF and LENS. Moreover, the ability to use feedstock in the form of wire provides much higher material efficiency. It eliminates the need for additional powder recycling processes, reducing health and safety concerns and offering a significant reduction in price per kilogram compared to powder for a wide array of engineering materials.

Unlike single-material WAAM, in multi-material wire arc additive manufacturing, the differences in material properties can render the traditional single-material overlapping models ineffective. The present investigation provides a breakthrough in the context of MMWAAM by developing new overlapping models for the scenario wherein beads of different materials are deposited adjacent. The investigation conducted on a bi-metallic pair of SS-CRS draws several conclusions as follows:

a. Unlike single-material WAAM, where the height and width of adjacent beads are identical and can be consistently maintained, in MMWAAM, the widths of the adjacent beads are not equal for the same height, necessitating the formulation of new overlapping models. Maintaining equal height of adjacent beads requires an algorithmic identification of feasible deposition parameters.

b. The overlapping models for single-material WAAM apply to a wide range of process conditions. In contrast, due to the difference in fluidity of the different materials, the overlapping models in MMWAAM are feasible in a relatively narrow range of process conditions.

A Review on Acoustic feature-based geometric defect identification in wire arc additive manufacturing. (This review was submitted by Nowrin Akter Surovi & Gim Song Soh, Singapore University of Technology and Design (SUTD), Singapore, Singapore). In additive manufacturing of metals, numerous techniques have been employed to sense print defects. Among these, acoustic-based sensing has the advantage of low cost and shows the most potential to identify both external and internal defects as an in-situ monitoring system. Using acoustic signals, researchers have broadly investigated non-machine learning and machine learning-based approaches to identify defects like balling, micro defects, lack of fusion pores, keyhole pores, cracks, and porosity. While most of these works have shown promising results for laser-based AM systems, few have explored how acoustic signals can be used effectively for Wire Arc Additive Manufacturing (WAAM) defect detection. This paper proposes a methodology to construct machine learning (ML)-based models on identifying geometrically defective bead segments using acoustic signals during the WAAM process. A geometrically defective bead segment or geometric defect is a defect that causes voids in the final printed part due to incomplete fusion between two non-uniform overlapping bead segments. Such a defect is currently not explored in the literature. The proposed methodology uses a novel dataset labeling approach to identify good and bad bead segments based on an optimal threshold of the range of mean curvature. Furthermore, the methodology targets defective bead segments based on acoustic feature inputs like Principal Components (PC) or Mel Frequency Cepstral Coefficients (MFCC). To understand the resulting performance of the defect identification models constructed based on the proposed methodology, experiments are performed and tested on a variety of ML models (KNN, SVM, RF, NN, and CNN) based on the Inconel 718 material. The results show that the combinatorics of two acoustic input features and five ML models can be able to identify geometrically defective segments accurately with an F1 score that ranges from 80% to 85%.

Wire Arc Additive Manufacturing (WAAM) is a direct energy deposition process according to ASTM F2792-12a where weld beads are deposited layer-by-layer to form 3D metallic components. WAAM employs an electric arc as a heat source and a metal wire as a feedstock for material deposition. WAAM is recently becoming popular because of its low equipment cost, low buy-to-fly ratio, high deposition rate, and environmentally friendly approach. However, WAAM suffers from processing-related defects such as porosity, cracks, distortion, oxidation, etc. Sometimes these defects can propagate to the subsequent layer, which reduces the strength of the final printed part, shortens the product's lifetime, and sometimes cause a collapse of the structure that causes economic loss. Therefore, it is important to identify print defects as early as possible to take appropriate corrective measures during the printing process to save welding resources and material costs.

In this paper, a methodology for constructing the geometric defect detection model to identify defective bead segments using acoustic sensing for the WAAM process is proposed. The performance of ten of such models is evaluated, and the results have demonstrated they can able to identify geometrically defective segments accurately (80%80% to 85%85%) when tested on the Inconel 718 dataset. Among the various trained defect detection models, it is found that having MFCC acoustic features with support vector machine performs the best in terms of F1 score, and having principal components as an acoustic feature with K nearest neighbor performs the best based on the confusion matrix. The first novelty of this research lies in the defects that are targeted. Geometric defects are a unique problem in WAAM due to their sensitivity to process variation. A bead produced using a constant process parameter would produce bead segments of different geometrical shapes due to environmental factors. This would lead to voids and affect the final part performance if left untreated. The second novelty lies in the segment-wise geometric defect detection approach. By discretizing defect detection, it has the benefit of identifying a localized defect more accurately so that early intervention can be possible. The third novelty lies in the dataset labeling approach of geometric defects, where good and bad bead segments are separated based on a threshold of the range of mean curvature determined through a heuristic search. Currently, labeling for AM defects is based on a visual inspection approach, which is error-prone and timeconsuming when the dataset is large. Here an approach to determine an optimal threshold for labeling based on overlapping areas of KDE distribution is proposed to separate good and bad segments. For future work, the authors intend to explore the inclusion of other features, such as the WAAM process parameters, to further increase the defect detection performance. The goal is to implement this approach for defect detection during real-life printing.

A Review on Effects of milling thickness on wire deposition accuracy of hybrid additive manufacturing. (This review was submitted by Shuai Zhang & Yazhou Zhang, Wuhan National Laboratory for Optoelectronics (WNLO), Huazhong University of Science and Technology, Wuhan, People's Republic of China). A hybrid technique integrating wire arc additive manufacturing (WAAM) and milling was studied using Al5Si aluminum alloy. The results showed both the surface roughness and the machining

allowance of this hybrid additive/subtractive manufacturing were reduced in comparison with pure WAAM when the milling thickness was in the range of 0.4–1.2 mm. The accuracy improvement was discussed in terms of the melt flow. It was found that after the surface was milled to a plane, the melt flow changed from the downward along camber surface to the outward and backflow on the plane. This change slowed down the velocity of melt flow, and then reduces the fluctuation of the side profile of the deposited thin wall,

As one of the most promising techniques for large complex structure parts, wire arc additive manufacture (WAAM) possesses the advantages of a short production cycle, low running cost, high material utilization, high deposition rate, high flexibility of equipment, and excellent forming quality. However, the deposition realized by the droplet transfer at high temperatures leads to poor geometrical accuracy and rough surface. Further, post-processing is usually employed to meet the application requirement for these forming parts. For example, Ortega controlled the deviation of the deposited dimension of the WAAM within 0.3 mm by optimizing droplet transfer parameters, but the machining was unavoidable for the final application. Importantly, some closed or semi-closed areas of complex structural parts are difficult, or even cannot be machined after being deposited.

The current research verified the advantages of hybrid additive manufacturing by some scattered data, but the effect of milling on the deposition accuracy, especially for the robotic system, has not been addressed. To break through the bottleneck of hybrid manufacturing, the quantitative relationship between milling parameters and sample deposition accuracy is necessary to be established. In this paper, the effects of milling thickness on the deposition accuracy of Al5Si alloy thin-wall were studied with a robotic hybrid WAAM/Milling manufacturing, which integrated Cold Metal Transfer (CMT) WAAM and high-speed milling.

The accuracy improvement was achieved by the change in melt flow. After the surface of the WAAM layer was milled to a plane, the melt flow changed from the downward along camber surface to outward and backflow on the plane because of the increase of the liquid–solid contact angle at the edge of the previously deposited layer. This change slows down the flow velocity and then reduces the fluctuation of the side profile of the deposited thin wall.

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