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Insights into Functionally Graded Materials Fabricated by Wire Arc Additive Manufacturing: A Comprehensive Review

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This study reviews the mechanical and microstructural properties of components produced through various additive manufacturing techniques, including gas metal arc welding (GMAW), cold metal transfer (CMT), and wire arc additive manufacturing (WAAM). The findings indicate that these methods result in components with anisotropic mechanical properties, influenced by the orientation and thermal cycles experienced during fabrication. Techniques like inter-pass rolling significantly refine microstructures, improving strength and hardness by converting columnar grains to equi-axed grains. Elemental segregation and the formation of intermetallic phases in bimetallic and functionally graded materials (FGMs) play a crucial role in defining their mechanical performance.

Additionally, the optimization of process parameters, such as travel speed in CMT-WAAM, is essential for achieving enhanced microhardness and tensile strength. This review underscores the critical interplay between manufacturing conditions and material characteristics, guiding the development of advanced additive manufacturing processes.

Keywords: gas metal arc welding (GMAW), cold metal transfer (CMT), and wire arc additive manufacturing (WAAM).

1. Introduction

Functionally Graded Materials (FGMs) are specialized regions within a component that display a continuous variation in chemical composition, leading to distinctive and tailored mechanical and thermal characteristics. They were first proposed during the development of thermal restraint coating materials [1]. Because their properties can be tailored by incorporating selected reinforcements chronologically.

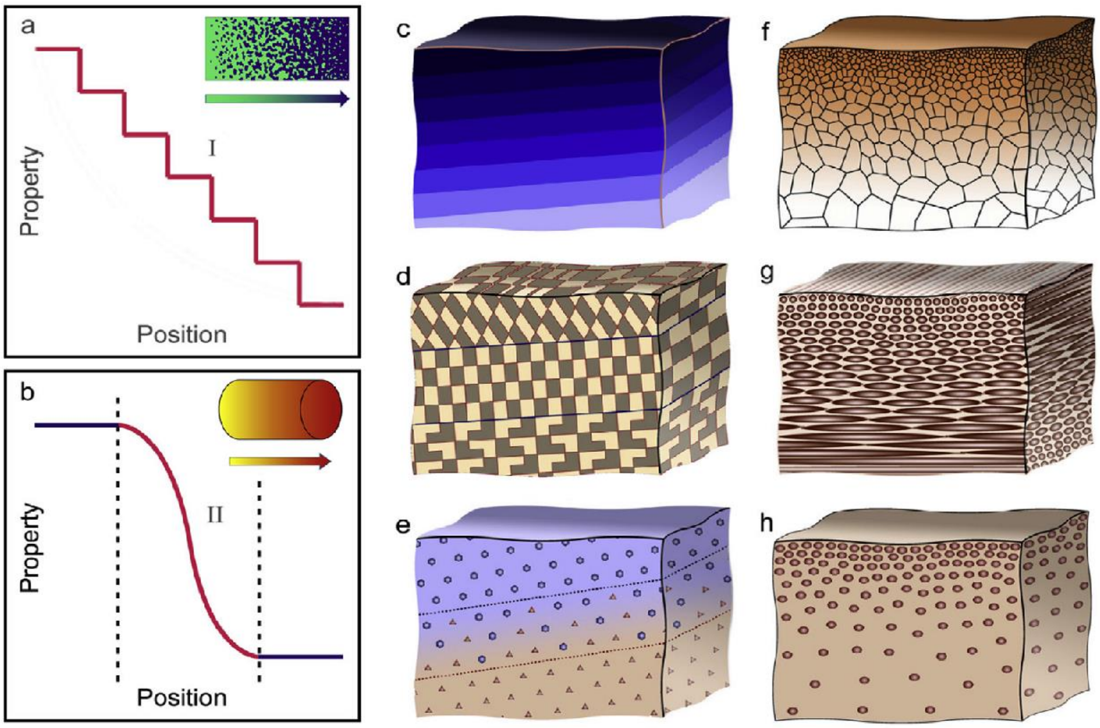
The utilization of FGMs is on the rise in the advanced industrial, aviation, and automotive industries. Microstructural characteristics and composition variations throughout the dimensions of a material are of highest relevance in some engineering applications, and FGMs come highly recommended. By altering the composition gradient inside an element, FGMs can improve the component's overall performance.

The number of technologies accessible to material engineers for producing these materials has also risen substantially over the past few decades, giving design engineers a much wider range of options for materials of different size and performance. The structure, composition, particle size, and density of FGMs diverge significantly from those of the base materials. This contributes significantly to the researcher's interest in FGMs. Furthermore, FGMs have superior properties to conventional composites. The FGMs find extensive applications as marine risers in offshore drilling and oil production systems, especially in deepwater operations. They are also utilized in the automotive and aerospace industries, where functionally graded composite panels and bearings contribute to improved performance. Furthermore, in military and defense applications, functionally graded armors featuring an outer layer resistant to penetration and inner layers designed to dissipate impact energy offer enhanced protection. In critical applications such as inner walls of the nuclear furnaces, and outer shell of the ballistic capsules, FGMs play a pivotal role in enhancing the functionality and durability.

1.1 Classification of FGMs

The utilization of FGMs is on the rise in the advanced industrial, aviation, and automotive industries. Figure 1.1 depicts the classification of FGMs into continuous and discontinuous graded materials [2-5]. FGMs can be categorized based on their dimension and composition. Gradients can be categorized into two distinct groups according to their dimensions: thin-section gradients, which resemble surface coatings, and thick gradients. Thick gradients can be continuous or discontinuous, depending on their structure. Materials that display abrupt changes in elemental composition or microstructure, leading to observable interfaces, are commonly referred to as exhibiting discontinuous gradients. Materials with continuous gradients display a gradual change in their elemental composition or microstructure throughout their structure, making it challenging to identify a distinct interface within the structure.

The schematic diagrams presented in Figure 1.1 depict a range of FGMs. Functionally graded structures can be observed either uniformly across the entire material or selectively in certain localized areas.



(Source: Liu et al. 2017)

Figure 1.1 Types of FGM(a) Discontinuous FGM (b) Continuous FGM (c-e) Discontinuous FGM interfaces with gradual changes in composition, grain orientation, and volume fractions of two types of second-phase particles (f-h) Continuous FGMs without interfaces and with gradual changes in grain size, fibre orientation, and volume fraction of second-phase particles

Figure 1.1(a & b) depicts schematic diagrams of two types of FGMs, namely discontinuous and continuous FGMs. Furthermore, the aforementioned illustration depicts three schematic representations denoted as (c), (d), and (e) of discontinuous FGMs that encompass interfaces with small changes in composition, grain orientation, and volume fractions of two distinct types of second-phase particles. The diagrams designated as (f), (g), and (h) illustrate FGMs that are continuous and lack interfaces. These materials display a gradual variation in grain size, fibre orientation, and volume fraction of second-phase particles [2].

Various techniques have been employed for the production of FGMs, including but not limited to centrifugal methods, powder-based methods, and vapour deposition methods [6]. The centrifugation method has the capability to generate continuous FGMs. However, it is important to note that this method is restricted to FGMs that possess radial gradients [7].

1.2 Applications of FGMs

- Continuous FGMs which are known for their smooth transition in properties can be found in components like jet engine blades and rocket nozzles, thermal barrier coatings for gas turbine engines, and heat exchanger components.
- Discontinuous FGMs which are known for their sudden change in properties includes cutting tools like drills and milling cutters, armoured vehicles, and turbine blades, which have a sudden change in material properties from the blade's root to its tip.
- In addition, discontinuous FGMs, known as heat shields, are used in aerospace applications to guard against extremely hot temperatures.

2. Processing of FGMs

The various processing procedures of FGMs are:

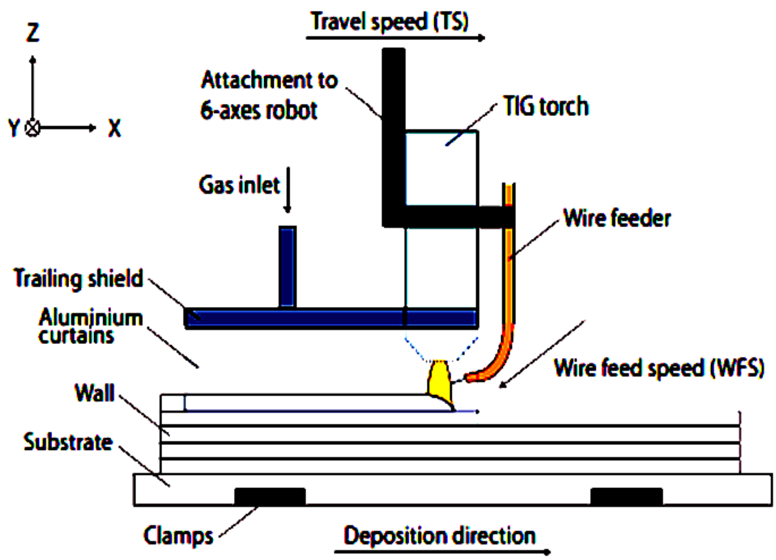
1. Liquid state processes
   i. Centrifugal casting
   ii. Infiltration
   iii. Gravity setting
2. Deposition processes
   i. Vapour deposition
   ii. Laser deposition
   iii. Spray deposition
3. Solid state processes
   i. Powder metallurgy
   ii. Diffusion Bonding
   iii. Additive manufacturing

According to previous studies, it has been observed that FGMs created through powder metallurgy techniques tend to have a minimal amount of pores. The existence of these pores has a detrimental effect on various properties, such as thermal conductivity, mechanical strength, physical characteristics, wear resistance, magnetic behaviour, and corrosion resistance [8]. The emergence of additive manufacturing (AM) techniques has garnered significant interest due to the limitations associated with existing approaches for producing functionally graded materials (FGMs).

Additive manufacturing holds a distinct advantage over traditional manufacturing methods due to its capacity for functional integration, use of multiple materials, accommodation of complex geometries, and suitability for low-volume production. This advanced technique empowers the creation of intricately designed parts while simultaneously reducing material wastage. The use of Additive Manufacturing (AM) technology is deemed appropriate for the production of FGMs owing to the capability of layer-by-layer fabrication and facile modification of elemental composition in different layers [9]. Using digitally aided Wire Arc Additive Manufacturing (WAAM), the FGM parts can be created by layering materials one by one. The Wire Arc Additive Manufacturing (WAAM) technique enables the production of FGMs by employing different input wire materials during the deposition process.

2.1 Wire Arc Additive Manufacturing of FGMs

WAAM is a metal 3D printing process that utilizes an electric arc to melt and deposit metal wire in a sequential layering manner, resulting in the creation of three-dimensional objects. The WAAM process typically involves several key components. These include a robotic arm or motion control system, which is responsible for guiding the welding torch. Additionally, a spool of metal wire, often consisting of a specific alloy or combination of alloys, is used. Finally, an electric arc welding system is employed to complete the process [10]. The schematic arrangement of WAAM process in shown in figure 2.1.



(Source: Addison et al.2015)

Figure 2.1 Wire Arc Additive Manufacturing process

WAAM, has attracted interest from industries due to its high deposition rate that speeds up fabrication (reduces processing time by 40–60 % compared with the conventional method), low equipment cost (and ability to operate in any environment), and high material utilization rate (up to 90 %–100 % that lowers the expense). WAAM techniques have a number of benefits over powder-bed based systems, which is the most popular metal AM technique. Because of the increased deposition rate, it processes information faster. According to [11], the deposition rate for Ti_6Al_4V alloy using the laser powder bed fusion method is roughly 0.1-

0.18 Kg/h, while it is 0.26-0.36 Kg/h using the electron beam powder bed fusion method. However, the pace might increase to 0.5–10 kg/h with WAAM.

WAAM contributes to the production of nickel-stainless steel FGMs by facilitating the customization of mechanical properties, minimizing material wastage, enabling the creation of intricate geometries, and reducing lead times. WAAM is increasingly being considered for industrial Additive Manufacturing (AM) applications due to its ability to achieve faster part production rates compared to other AM techniques. WAAM is a fabrication process that exhibits superior material utilization efficiency compared to powder-based techniques. WAAM manufactures parts by serially depositing molten metal over a substrate. Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW) are the heat sources that melt the metallic filament. The wire-feed direction is a critical factor in the fabrication of parts using GTAW and PAW processes, but it does not hold the same level of importance in the case of parts fabricated using the GMAW process. As a result, GMAW has the potential to boost output and facilitate greater levels of automation in industrial settings. Residual stress, porosity, solidification fractures, and distortion are only some of the issues with the WAAM method. The limitations associated with WAAM can be circumvented by utilizing cold metal transfer (CMT) as the underlying technology.

The Wire Arc Additive Manufacturing (WAAM) methodology was employed as a means of overcoming the constraints associated with the deposition rate, equipment, and powder cost limitations of powder-based additive manufacturing. Numerous researchers have utilized WAAM to produce free-form parts. Throughout the years, (Metal Inert Gas) MIG welding has been the standard technique for the WAAM process. It has been demonstrated, however, that (Tungsten Inert Gas) TIG-based WAAM offers superior deposition quality, no spattering, and autonomy over the heat source and wire conveying. Recent research has focused on plasma arc welding, which is similar to TIG. Using a plasma arc to dissolve the wire as opposed to a TIG arc has numerous advantages, including a higher energy density, greater arc stability, a smaller heat affected region, and greater control over the power source parameters [12]. Ramkumar et al. examined the structural properties, mechanical properties, and susceptibility to corrosion of dissimilar weldments involving Inconel 718 and SS 316L [13]. The aforementioned joints were fabricated using the GMAW process without activated flux. According to the report, dissimilar weldments exhibited superior ultimate tensile strength in comparison to similar weldments, with parent metal failure being observed in all instances. The results of the bend test indicate that dissimilar weldments exhibit superior strength in comparison to SS316L weldments. Furthermore, the weld zone exhibited complete regulation of the Laves phase, thereby facilitating enhancement of the mechanical characteristics. The investigation on corrosion has verified that the SS316L exhibited a lower degree of weight loss in comparison to the other weldments. Sayiram et al. conducted an examination of the microstructural features of dissimilar welds involving Incoloy 800H and SS321. The findings indicate the existence of Ti (N, C) precipitates within the austenitic matrix, specifically located at the grain boundaries [14]. The extent of grain boundary migration in the weld metal of Incoloy 800H was found to be significantly greater in comparison to that observed in the weldment of SS321. The SS321weldment exhibited epitaxial growth, resulting in enhanced strength and ductility of the weld metal. A demarcated region devoid of intermixing in close proximity of the fusion boundary separating SS321 and Incoloy 800H weld metal has been detected.

Sasikumar et al. a functionally graded Inconel 625-SS316L wall was produced using wire arc additive manufacturing. It was found that the microstructure of the SS 316L layers was predominantly austenitic with a reduced proportion of ferrite. The Inconel 625 layers exhibited precipitates within the austenitic matrix. The investigation ascertained that the Yield Strength (YS) and tensile strength (UTS) exhibited by SS 316L and IN625 are similar to those demonstrated by forged materials [15]. The use of electrical arc and filler wire in the Wire Arc Additive Manufacturing (WAAM) process has led to noteworthy cost reductions by obviating the requirement for costly thermal sources and metallic powders in the production of FGM [16].

2.2 Cold Metal Transfer Based WAAM of FGMs

CMT-WAAM works by short-circuiting the metal transfer mechanism, in contrast to the more common metal powder AM methods. When making WAAM with GMAW, issues like residual strains, porosity, spatter, solidification cracks, and distortion can arise. To deal with these problems, WAAM employs a process called cold metal transfer.
In 2004, Fronius, an Austrian company, developed the CMT-WAAM process. CMT-WAAM works on short-circuit metal transfer mechanism. The utilization of electronic control systems in conjunction with a welding gun featuring an integrated servomotor facilitates the retraction of the wire upon contact with the melt pool, thereby mechanically transferring the molten metal droplet with minimal heat input [17]. The block diagram of CMT-WAAM process in shown in figure 2.2.

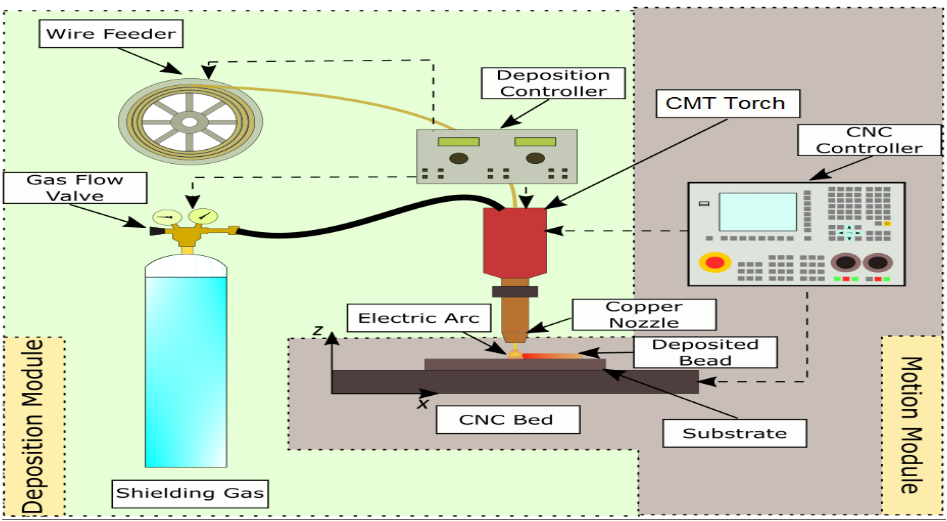


Figure 2.2 Block diagram of CMT-WAAM process

The consumable electrode, in the form of a wire reel, is consistently fed through the feed rollers, while the welding torch is linked to the gas supply cylinder to provide the required inert gas. The electrode and the workpiece are both connected to the welding power supply, which consistently maintains a constant voltage. The welding machine modulates the current by adjusting the rate at which the electrode wire is fed. The implementation of CMT-based WAAM results in a reduction of spatter and distortion, leading to an improvement in the quality of the produced parts.

Chandrasekaran et al. utilised wire arc additive manufacturing to fabricate marine risers and noted that the implementation of the CMT-WAAM technique resulted in a decline in heat input due to the decrease in current in each cycle. Additionally, it is evident that the FGM material displays comparable yield strength and percentage elongation values to those of the X-52 material. However, the ultimate strength of the FGM material demonstrates a slight increase. The increase in strength that was observed can be attributed to the refinement and absence of defects in the solidified microstructure. Element diffusion takes place at the interface of two materials, resulting in the formation of a region of convergence. As a result, there is an enhancement in the mechanical strength of the materials [18].

The CMT welding cycle is commonly characterized as the duration necessary for the deposition of a molten droplet of filler wire into the weld pool. The examination of current and voltage waveforms is a crucial aspect in investigating the allocation of energy among distinct phases during the transfer of droplets [19]. The CMT process is utilized in diverse industrial applications as a means of addressing the limitations of existing welding methodologies, owing to its exceptional arc length management and higher edge coupling tolerances [20]. In addition to enhancing the deposition rate, this method facilitates expedited production while minimizing material waste. The Wire Arc Additive Manufacturing (WAAM) process utilising Cold Metal Transfer (CMT) technology has the capability to achieve a deposition rate of approximately 10 $kgh^{-1}$for steel material [21, 22], which is much faster than powder-based additive manufacturing approaches, which have a deposition rate of 600 gh^{-1}[23]. Wire arc additive manufacturing may make advantage of a wide range of melting energies such as Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), Plasma Arc Welding (PAW) [24-30]. A fully automated robotic CMT-WAAM set up fabricating a FGM wall is shown in figure 2.3

(Source: Senthil et al.2021)

Figure 2.3 Automated-robotic CMT-WAAM set up

3. Characterization of FGMs made by WAAM process:

Mechanical parameters like as micro-hardness, microstructure [31], induced residual stress levels, and tensile strength have all been tested and studied for parts made by GMAW-based additive manufacturing. Pramod et al. investigated the tensile strength and hardness of additively produced metallic parts. A 7.6% and 4.8% variation in average and ultimate tensile strength was found. Furthermore, it has been established that the hardness values are consistent, with some variation in the surface layers of mild steel components being the only exception [32]. The microstructure and mechanical properties of components produced through an additive manufacturing process utilizing MIG welding were analyzed by Liu et al. [33]. It was reported that the yield strength was lower in the direction parallel to the build axis (461-618.5 MPa) than in the direction perpendicular to the axis (519.5-693.5 MPa). The study conducted by Xu et al. [34] aimed to investigate the mechanical and microstructural properties of maraging steel components fabricated through the process of wire arc additive manufacturing. It was observed that the mechanical properties of the alloy in its as-fabricated state exhibited a decrease from the bottom to the top. This can be attributed to the unsteady state thermal cycles, which caused ageing and the formation of precipitates along the build direction. Furthermore, it was observed that the alloy in its as-deposited state exhibited enhanced strength compared to the wrought alloy. However, the strength of the former was found to be lower than that of the latter in an aged condition. This is because of the microstructure of the low-angle columnar grains, which exhibited a less pronounced ageing response. Rajkumar et al. conducted an investigation into the microstructural characteristics, mechanical properties, and corrosion resistance of Incoloy 825 fabricated via wire arc additive manufacturing. The observed microstructure exhibited a prevalence of dendritic morphology, accompanied by the existence of intermetallics and laves phases. The microhardness measurements demonstrated a variation of 226-262 HV across the lower and upper regions [35]. Yangfan et al. used Cold Metal Transfer (CMT)-based Wire Arc Additive Manufacturing (WAAM) to investigate the mechanical and microstructural properties of the inconel 625 wall. The study revealed that the hardness and tensile properties of the specimens exhibited a positive correlation with the travel speed. Specifically, the average microhardness of the manufactured specimens demonstrated a modest increase from 248 HV to 253 HV as the travel speed increased. The results indicate that there was an increase in the tensile properties of the material. Specifically, the UTS increased from 647 MPa to 687 MPa, while the YS increased from 376 MPa to 400 MPa. The findings of the study indicate that the mechanical efficacy of the components produced through the CMT-WAAM technique surpassed that of the Inconel 625 alloy casting parts, with the exception of Ultimate Tensile Strength (UTS). The results indicate that Inconel 625 alloys can be efficiently manufactured using CMT-based WAAM [36].

The microstructure of Ti-6Al-4V components manufactured through interpass rolled-wire + arc additive manufacturing was examined by [37]. Rolling action has been found to cause significant refinement of β grains, reduction in α-phase lamellae, and conversion of columnar grain microstructure to equiaxed grain microstructure. The observed phenomenon can be attributed to the process of recrystallization. This process occurred due to the heating of the previously deformed stratum during the deposition of the subsequent stratum.

Domack et al. employed three discrete fabrication methods in order to produce FGMs made of Inconel 718 and Ti-6Al-4V alloy. It was reported that the components produced by laser direct metal deposition were found to have considerable segregation of elements, and the microstructure was characterized by coarse dendrites [38]. The mechanical characteristics of the dissimilar alloys, Titanuim-Aluminium (Ti-6Al-4V and $AlSi_5$) were investigated through the utilization of cold metal transfer welding [39]. The results of the study revealed the presence of a crack in the FGM interface. Wang et al. fabricated Inconel 625 utilising the Gas Tungsten Arc Welding (GTAW) technique and subsequently analysed the tensile properties throughout the build height. The study determined that a rise in the height of deposition resulted in a proportional augmentation of the primary dendrite arm spacing, while the segregation behaviour exhibited a consistent strengthening trend. Analogous patterns were noted in the mechanical characteristics as the deposited height was raised [40].

Niendorf et al. reported the utilization of Selective Laser Melting (SLM) for the production of stainless steel components featuring diverse localized functionalities. A significant microstructural variation was identified as the root cause of discernible differences in local-level mechanical characteristics [41].

Senthur Prabhu et al. fabricated SS904L-Inconel 625 weld joints. The study examined the mechanical properties and microstructural characteristics of the FGM interface, revealing the presence of micro-segregated phases rich in niobium and molybdenum [42]. The feasibility of constructing functionally graded Inconel 625-SS304Lwall through directed energy deposition was investigated by Carroll et al. [43]. Furthermore, the microstructural features and thermodynamic models were investigated.

Senthil et al., studied the mechanical behavior of the functionally graded Inconel 825 - SS316L wall fabricated using the Cold Metal Transfer (CMT) based Wire Arc Additive Manufacturing (WAAM) process. It was observed that the tensile fracture morphology revealed that all the specimens failed after sufficient plastic deformation, indicating ductile fracture. A change in microhardness was observed at the FGM interface region. A continuous and discontinuous cellular–dendritic region was found in the Inconel 825 region, whereas the SS316L region was comprised of δ ferrite in the primary austenitic (γ) dendrites [17].

Motwani et al. investigated the mechanical and microstructural characteristics of bimetallic SS316LSi-Inconel 625 walls fabricated by CMT-WAAM. It was reported that the microstructure of the bimetallic wall at various regions of the wall indicated the presence of a columnar solidification structure. In addition, epitaxial grain growth was observed between the layers. The interdendritic regions of the alloy 625 deposits exhibited segregation of niobium and molybdenum, resulting in the emergence of the NbC and Laves phases. Microhardness evaluations were performed across the bimetallic interface, indicating that the 316LSi exhibited a hardness spectrum of 160 to 190 HV, whereas the alloy 625 deposit exhibited a range of 220 to 245 HV. Tensile testing revealed that, on average, the material had an ultimate tensile strength of 660 MPa, a yield strength of 412 MPa, and an elongation of 49.3%.The results of the fractographic analysis indicated the presence of ductile fractures in every instance [44].

Ayan et al characterized the functionally graded dissimilar steels (ER70S-6 and 308LSi) fabricated by Wire Arc Additive Manufacturing (WAAM). According to the report, the FGM interfaces exhibited no defects and demonstrated a tensile strength increase of up to 46% in comparison to the fabrication of a single material. The FGM structure has been found to exhibit varying properties based on the alterations in its layers, as observed during hardness measurements and microstructure investigations. The research findings indicate that the FGM component exhibits a fatigue limit that is 25% greater in the horizontal orientation compared to the vertical orientation [45].

In a study, RajKumar et al. produced Incoloy 825 through wire-arc additive manufacturing. The resulting microstructure was predominantly dendritic, with the inclusion of intermetallics and laves clusters [35]. According to several recent studies on functionally graded bi-metallic structure, The microstructural composition comprises of dendrites that are elongated and equiaxed, accompanied by secondary arms and intermetallics [46-52].

4. Discussions:

The studies reviewed collectively emphasize the significant advancements in understanding the mechanical and microstructural properties of components produced through various additive manufacturing techniques, particularly focusing on Gas Metal Arc Welding (GMAW), Cold Metal Transfer (CMT), and Wire Arc Additive Manufacturing (WAAM). Key conclusions drawn from these investigations include:

4.1 Mechanical Properties Consistency and Variability:

Components fabricated using GMAW-based additive manufacturing exhibit consistent hardness values, with minor variations observed in surface layers of mild steel components. The tensile strength and hardness of additively produced metallic parts show variability, with a 7.6% and 4.8% difference in average and ultimate tensile strength, respectively.

4.2 Directional Mechanical Properties:

Components fabricated through additive manufacturing techniques exhibit anisotropic mechanical properties, with notable differences in yield strength depending on the orientation relative to the build axis. For example, yield strength is generally lower parallel to the build axis than perpendicular.

4.3 Impact of Thermal Cycles:

The mechanical properties of components, such as maraging steel produced by wire arc additive manufacturing, show variation from bottom to top due to unsteady thermal cycles during fabrication. These cycles cause ageing and precipitate formation, affecting strength and hardness.

4.4 Microstructural Refinement and Recrystallization:

Processes like interpass rolling in wire arc additive manufacturing can significantly refine microstructures, converting columnar grains to equiaxed grains and reducing α-phase lamellae through recrystallization. This refinement improves mechanical properties, such as strength and hardness.

4.5 Elemental Segregation and Intermetallic Phases:

Bimetallic and functionally graded materials (FGMs) often exhibit elemental segregation and the formation of intermetallic phases such as Laves and NbC, impacting their mechanical performance. These microstructural features are critical in defining the hardness and tensile properties of the fabricated components.

4.6 Correlation Between Process Parameters and Properties:

Process parameters, particularly travel speed in CMT-WAAM, directly influence the microhardness and tensile strength of materials like Inconel 625. Higher travel speeds result in enhanced mechanical properties, demonstrating the importance of optimizing manufacturing parameters to achieve desired material characteristics.

5. Conclusion:

This review highlights that additive manufacturing techniques like GMAW, WAAM and CMT-WAAM produce components with distinct anisotropic mechanical properties, influenced by directional orientation and thermal cycles during fabrication. Processes such as inter-pass rolling enhance microstructural refinement, converting columnar grains to equi-axed grains, thereby improving mechanical strength and hardness. The elemental segregation and intermetallic phase formation in bimetallic and functionally graded materials significantly impact their overall performance. The optimization of process parameters, particularly travel speed in CMT-WAAM process, plays a crucial role in achieving superior microhardness and tensile strength, emphasizing the intricate relationship between manufacturing conditions and material properties.

Conflict of interest

There is no conflict of interest in the submission of this work, and has been agreed by all the authors for the publication of the manuscript.

Credit Author Statement

J. Kavitha - Investigation

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R.S.Srikanth Varma - Formal Analysis.

P Sreenivas - Writing - review & editing.

M. Ravichandran - Writing - review & editing

M. Manohara - Writing - review & editing

T. S. Senthil - Methodology, Conceptualization, Original drafting (corresponding author)

R Rajaprasanna - Writing - review & editing

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Joshi R K, Alwarappan S, Yoshimura M, Sahajwalla V and Nishina Y 2015 Graphene oxide: the new membrane material Appl. Mater. Today 1, 1–12.
2. Liu, Z, Meyers, MA, Zhang, Z & Ritchie, RO 2017, 'Functional gradients and heterogeneities in biological materials: design principles, functions, and bioinspired applications', Progress in Materials Science, vol. 88, pp. 467-498.
3. Verma, RK, Parganiha, D &Chopkar, M, 2021, 'A review on fabrication and characteristics of functionally graded aluminum matrix composites fabricated by centrifugal casting method', SN Applied Science, vol. 3, p.227.
4. Valmik B, Prakash K, Sandeep T, Sachin P & RKP Singh 2017, 'A Review on Functionally Gradient Materials (FGMs) and Their Applications', IOP Conf. Ser.: Mater. Sci. Eng. vol. 229, pp. 012021.
5. Reza, G & Homam, NM 2021, 'Additive manufacturing of functionally graded metallic materials: A review of experimental and numerical studies', Journal of Materials Research and Technology, vol. 13, pp. 1628-1664.
6. Lei, Y, Yitao, C & Frank, L 2020, 'Additive manufacturing of functionally graded metallic materials using laser metal deposition', Additive Manufacturing, vol. 31, pp. 100901.
7. Kieback, B, Neubrand, A & Riedel, H 2003, 'Processing techniques for functionally graded materials', Materials Science and Engineering: A, vol. 362, no. 1-2, pp. 81-106.
8. Samal, P, Newkirk, J, 2015, Powder Metallurgy Methods and Applications, vol. 7, ASM Handbook of Powder Metallurgy.
9. Jin, X, Wu, L, Sun, Y &Guo, L 2009, 'Microstructure and mechanical properties of ZrO2/NiCr functionally graded materials', Materials Science and Engineering: A, vol. 509, pp. 63-68.
10. Cunningham, CR, Wikshaland, S & Xu F 2017, 'Cost Modelling and Sensitivity Analysis of Wire and Arc Additive Manufacturing', Procedia Manufacturing, vol. 11, pp. 650-657.
11. Raut, LP &Taiwade, RV 2022, 'Microstructure and mechanical properties of wire arc additively manufactured bimetallic structure of austenitic stainless steel and low carbon steel', Journal of Materials Engineering and Performance, vol. 31, pp. 8531-8541.
12. Sasikumar, R, RajeshKannan, A, Mohan Kumar, S, Pramod, R, Pravin Kumar, N, Siva Shanmugam, N, Yasam, P &Sakthivel, S 2022, 'Wire arc additive manufacturing of functionally graded material with SS 316L and IN625: microstructural and mechanical perspectives', CIRP Journal of Manufacturing Science and Technology, vol. 38,
13. pp. 230-42.
14. Ramkumar, T, Selvakumar, M, Narayanasamy, P, AyishaBegamd, A, Mathavand, P &Arun Raj, A 2017, 'Studies on the structural property, mechanical relationships and corrosion behaviour of Inconel 718 and SS 316L dissimilar joints by TIG welding without using activated flux', Journal of Manufacturing Processes, vol. 30, pp. 290-298.
15. Sayiram, G & Arivazhagan, N 2015, 'Microstructural characterization of dissimilar welds between Incoloy 800H and 321 Austenitic Stainless Steel', Materials Characterization, vol. 102, pp. 180-188.
16. Sasikumar, R, RajeshKannan, A, Mohan Kumar, S, Pramod, R, Pravin Kumar, N, Siva Shanmugam, N, Yasam, P &Sakthivel, S 2022, 'Wire arc additive manufacturing of functionally graded material with SS 316L and IN625: microstructural and mechanical perspectives', CIRP Journal of Manufacturing Science and Technology, vol. 38,
17. pp. 230-42.
18. Martina, F, Mehnen, J, Williams, SW, Colegrove, P & Wang, F 2012, 'Investigation of the benefits of plasma deposition for the additive layer manufacture of Ti-6Al-4V', Journal of Materials Processing Technology, vol. 212, (6), pp. 1377-1386.
19. Senthil, TS, Ramesh Babu S, Puviyarasan, M & Dhinakaran, V 2021, 'Mechanical and microstructural characterization of functionally graded Inconel 825 - SS316L fabricated using

wire arc additive manufacturing', Journal of materials research and technology, vol. 15 pp. 661-669.

20. Chandrasekaran, S, Hari, S & Murugaiyan, A 2020, 'Wire arc additive manufacturing of functionally graded material for marine risers', Materials Science and Engineering: A, vol. 792, pp. 139530.
21. Akash, P., Puviyarasan, M., Senthil, T. S., Rathinasuriyan, C., & Sindhiya, S. (2023). Microstructural characterization and mechanical properties of Inconel 625 wall fabricated by GTAW-based WAAM using stringer bead and circular weave pattern. Engineering Research Express, 5(3), 035020. https://doi.org/10.1088/2631-8695/ab1234.
22. Lorenzin, G &Rutili, G 2009, 'The innovative use of low heat input in welding- experiences on 'cladding' and brazing using the CMT process', Welding International, vol. 23, no. 8, pp. 622-632.
23. Wei, G, Yunbo, Z, Devarajan, R, Karthik, R, Yong, C, Christopher, BW, Charlie, CLW, Yung, CS, Song, Z & Pablo, DZ 2015, 'The status, challenges, and future of additive manufacturing in engineering', Computer-Aided Design, vol. 69, pp. 65-89.
24. Donoghue, J, Antonysamy, AA, Martina, F, Colegrove, PA, Williams, SW &Prangnell, PB 2016,'The effectiveness of combining rolling deformation with wire-arc additive manufacture on β-grain refinement and texture modification in Ti-6Al-4V', Materials Characterization, vol. 114, pp. 103-114.
25. Williams, SW, Martina, F, Addison, AC, Ding, J, Pardal, G &Colegrove, P 2016, 'Wire + Arc Additive manufacturing', Materials Science and Technology', vol. 32, pp. 641-647
26. Williams, SW, Martina, F, Addison, A & Ding, J 2016, 'Wire+arc additive manufacturing', Materials Science and Technology, vol. 32, pp. 641-647.
27. Senthil, T.S., Puviyarasan, M., & Babu, S. R. (2022). Mechanical characterization of wire arc additive manufactured and cast Inconel 825: A comparative study. Materials Today: Proceedings, 62(Part 2), 973-976. https://doi.org/10.1016/j.matpr.2022.03.537.
28. Xiong, J, Liu, G & Pi, Y 2019, 'Increasing stability in robotic GTA-based additive manufacturing through optical measurement and feedback control', Robotics and Computer-Integrated Manufacturing', vol. 59, pp. 385-393.
29. González, J, Rodríguez, I, Prado-Cerqueira, JL, Diéguez, JL & Pereira, A2017, 'Additive manufacturing with GMAW welding and CMT technology', Procedia Manufacturing, vol. 13, pp. 840-847.
30. Hu, Z, Qin, X, Li, Y, Yuan, J & Wu, Q 2020, 'Multi-bead overlapping model with varying cross-section profile for robotic GMAW-based additive manufacturing', Journal of Intelligent Manufacturing, vol. 31, pp. 1133-1147.
31. Lin, J, Lv, Y, Liu, Y, Sun, Z, Wang, K, Li, Z, Wu, Y &Xu, B 2017, 'Microstructural evolution and mechanical property of Ti-6Al-4V wall deposited by continuous plasma arc additive manufacturing without post heat treatment', Journal of the Mechanical Behavior of Biomedical Materials, vol. 69, pp. 19-29.
32. Artaza, T, Bhujangrao, T, Suárez, A, Veiga, F &Lamikiz, A 2020, 'Influence of Heat Input on the Formation of Laves Phases and Hot Cracking in Plasma Arc Welding (PAW) Additive Manufacturing of Inconel 718', Metals, vol. 10, no. 6, pp. 771.
33. Senthil, T.S., Babu, S. R., Puviyarasan, M., & Balachandar, V. S. (2023). Experimental investigations on the multi-layered SS316L wall fabricated by CMT-based WAAM: Mechanical and microstructural studies. Journal of Alloys and Metallurgical Systems, 2, 100013. https://doi.org/10.1016/j.jams.2023.100013
34. Pramod, R, Kumar, SM &Girinath, B 2020, 'Fabrication, characterisation, and finite element analysis of cold metal transfer based wire and arc additive manufactured aluminium alloy 4043 cylinder', Welding in the World, vol. 64, pp. 1905-1919.
35. Liu, L, Zhuang, Z, Liu, F & Zhu, M 2013, 'Additive manufacturing of steel-bronze bimetal by

shaped metal deposition: Interface characteristics and tensile properties', The International Journal of Advanced Manufacturing Technology, vol. 69, pp. 2131-2137.

36. Xu, X, Ganguly, S, Ding, J, Guo, S, Williams, S & Martina, F 2018, 'Microstructural evolution and mechanical properties of maraging steel produced by wire+arc additive manufacture process', Materials Characterization, vol. 143, pp. 152-162.
37. Rajkumar, V, Vishnukumar, M, Sowrirajan, M & Rajesh Kannan, A 2022, 'Microstructure, mechanical properties and corrosion behaviour of Incoloy 825 manufactured using wire arc additive manufacturing', Vacuum, vol. 203, pp. 111324.
38. Senthil, T.S., Puviyarasan, M., Babu, S. R., & Prabhu, T. R. (2022). Pitting corrosion studies on functionally graded Inconel 825-SS316L wall manufactured by wire arc additive manufacturing. Engineering Research Express, 4(3), 035013. https://doi.org/10.1088/2631-8695/ac8148.
39. Martina, F, Colegrove, PA, Williams, SW & Meyer, J 2015, 'Microstructure of Interpass Rolled Wire + Arc Additive Manufacturing Ti-6Al-4V Components', Metallurgical and Materials Transactions A, vol. 46, pp. 6103-6118.
40. Domack, MS & Baughman, JM 2005, 'Development of nickel titanium graded composition components', Rapid Prototyping Journal, vol. 11, pp. 41-51.
41. Tian, YB, Shen, JQ, Hu, SS, Wang, ZJ & Gou, J 2019, 'Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V and AlSi5 dissimilar alloys using cold metal transfer welding', Journal of Manufacturing Processes, vol. 46, pp. 337-344.
42. Wang, JF, Sun, QJ, Wang, H, Liu, JP &Feng, JC 2016, 'Effect of location on microstructure and mechanical properties of additive layer manufactured Inconel 625 using gas tungsten arc welding', Materials Science and Engineering: A, vol. 676, pp. 395-405.
43. Niendorf, BT, Leuders, S, RiemeR, A &Brenne, F 2014,'Functionally graded alloys obtained by additive manufacturing', Advanced Engineering Materials, vol. 16, pp. 857-861.
44. SenthurPrabu, S, Ramkumar, KD &Arivazhagan, N 2019, 'Investigation on the fusion zone microstructures and mechanical integrity of AISI 904L and Inconel 625 weld joints', Materials Research Express, vol. 6, no. 8, pp. 1-23.
45. Senthil, T.S., Babu, S. R., & Puviyarasan, M. (2023). Mechanical, microstructural, and fracture studies on Inconel 825–SS316L functionally graded wall fabricated by wire arc additive manufacturing. Scientific Reports, 13, 5321. https://doi.org/10.1038/s41598-023-32141-7.
46. Motwani, A, Kumar, A, Puri, Y &Nitin KL 2022, 'Mechanical characteristics and microstructural investigation of CMT deposited bimetallic SS316LSi-IN625 thin wall for WAAM', Welding in the World, vol. 67, pp. 967-980.
47. Ayan, Y & Kahraman N 2022, 'Fabrication and characterization of Functionally Graded Material (FGM) structure containing two dissimilar steels (ER70S-6 and 308LSi) by wire arc additive manufacturing (WAAM)', Materials Today Communications, vol. 33, pp. 104457.
48. Rajesh Kannan, A, Mohan Kumar, S, Pramod, R, Pravin Kumar, N, Siva Shanmugam, N &Yasam, P 2021, 'Microstructure and mechanical properties of wire arc additive manufactured bi-metallic structure', Science and Technology of Welding and Joining, vol. 26, pp. 47-57.
49. Sasikumar, R, RajeshKannan, A, Mohan Kumar, S, Pramod, R, Pravin Kumar, N, Siva Shanmugam, N, Yasam, P &Sakthivel, S 2022, 'Wire arc additive manufacturing of functionally graded material with SS 316L and IN625: microstructural and mechanical perspectives', CIRP Journal of Manufacturing Science and Technology, vol. 38,
50. pp. 230-42.
51. Raut, LP & Taiwade, RV 2022, 'Microstructure and mechanical properties of wire arc additively manufactured bimetallic structure of austenitic stainless steel and low carbon steel', Journal of Materials Engineering and Performance, vol. 31, pp. 8531-8541.
52. Lu, X, Zhou, YF & Xing, XL 2017, 'Open-source wire and arc additive manufacturing system: formability, microstructures, and mechanical properties', The International Journal of

Advanced Manufacturing Technology, vol. 93, pp. 2145 2154.
53. Mohan Kumar, S, Rajesh Kannan, A, Pravin Kumar, N, Pramod, R, Siva Shanmugam, N, Vishnu, AS & Channabasavanna, SG 2021, 'Microstructural features and mechanical integrity of wire arc additive manufactured SS321/inconel 625 functionally gradient material', Journal of Materials Engineering and Performance, vol. 30, pp. 5692-5703.
54. Tian, Y, Shen, J, HuS, Chen, X, Cai, Y & Han, J 2022, 'Effect of deposition layer on microstructure of Ti-Al bimetallic structures fabricated by wire and arc additive manufacturing', Science and Technology of Welding and Joining, vol. 27, pp. 22-32.
55. Singh, S, Jinoop, AN, Palani, IA, Paul, CP, Tomar, KP &Prashanth KG 2021, 'Microstructure and mechanical properties of NiTi-SS bimetallic structures built using wire arc additive manufacturing', Materials Letters, vol. 303, pp. 130499.