A review on Additive Production of Functionally Graded Materials Based on Titanium

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Abstract. Functionally graded materials (FGMs) are heterogeneous structures that are advantageous in a wide range of applications due to their varied composition, microstructure, and site-specific characteristics, yet traditional manufacturing poses limitations. Additive manufacturing (AM) has surged in research interest over two decades, offering intricate part production with minimal waste, ideal for FGMs. AM advancements enable complex FGM designs, fostering their widespread use. Due to a number of advantages, the processing of functionally gradient materials was made feasible by the advent of modern additive manufacturing technology, which created a significant potential for the advancement of this class of engineering materials. When parts are subjected to different mechanical or thermal stresses within a focus area, these materials offer a sophisticated solution. Because of this, FGMs have found uses in the mining, aerospace, military, and marine manufacturing sectors etc., providing solutions for varied stresses. Notably, AM, particularly Directed Energy Deposition (DED), facilitates FGM fabrication, often using titanium and nickel alloys combined with other materials. The article explores an advanced conceptual understanding of additively manufactured FGMs, providing an overview of the Directed Energy Deposition (DED) technique. The focus is on enabling the production of FGM parts, with a brief examination of limitations in certain additive manufacturing (AM) technologies.

Keywords: Functionally gradient materials (FGMs), Additive manufacturing (AM), Direct energy deposition (DED).

1. Introduction

Materials are a fundamental building block for human advancement in science, technology, and society, and the creation and production of novel materials forms the basis of contemporary industry (Wu, S. et al.2021). Traditional homogenous materials have not been able to keep up with the sophistication and diversity demands of component structure and function due to the manufacturing industry's fast expansion. For instance, a structure may require many components with varying densities, strengths, ferromagnetism, thermal expansion coefficients, crystal structures, etc (Hofmann et al.2014), In FGM, characteristics move smoothly and gradually from one side to the other as a result of either the microstructure or the chemical content progressively shifting in one or more desired directions.FGM was extensively favoured over monolithic components because of advantages including affordability and less weight without compromising strength (Yin et al. 2018, Ahsan et al.

ICAMDMS 2024, February 23-24, Coimbatore, India

DOI 10.4108/eai.23-2-2024.2346987

2018). In Functionally Graded Materials (FGMs), the characteristics of the end product are determined by its position, resulting from deliberate alterations in composition or microstructures facilitated through particular production methods.The idea of FGMs originates from materials that are found in nature, include bamboo, teeth, bone, and wood (Henson, 2018; Inagaki et al., 2014; R.M. Mahamood and E.T. Akinlabi, 2017).The idea of FGMs originates from materials that are found in nature, include bamboo, teeth, bone, and wood (Henson, 2018; Inagaki et al., 2014; R.M. Mahamood and E.T. Akinlabi, 2017).The original industrial usage concerning FGMsgoes Return to Japan in the 1980s, where the major objective was to solve the difficulty of producing a surface-applied thermal barrier coating for aerospace or re-entry vehicles that can enduretemperatures ranging from 1500 to 1800 degrees Celsius (Koizumi. 1997). FGM gained widespread preference overmonolithic components owing to advantages such affordability and reduced weight without impacting strength (Yin et al.2018, Ahsan et al. 2018). FGMs have diverse potential applications in fields such as automotive, biomedical, marine, pharmaceutical, nuclear, petrochemical, and aerospace (Wang Shakerin et al., 2020; Shen et al., 2021.2019). Materials produced through traditional manufacturing methods exhibit significant alterations in characteristics such as strength, modulus of elasticity, and thermal expansion coefficient. The growth of brittle intermetallic phases (IMCs), cracking, and residual stress developmentare the results of this abrupt change in properties, which is ascribed to variations in thermo-physical properties, differences in atomic structure, and the inability to control the thermal history of materials.(Shi et al. 2018, Wu et al. 2021). When selecting materials for aerospace components, reducing weight is a crucial consideration to achieve fuel efficiency, manage material costs, and attain the desired strength. Titanium aluminides, such as γ-(Ti-Al), are commonly employed in aerospace components due to their low weight, outstanding stability at high temperatures, and extraordinary mechanical strength. While Ti2AlNb exhibits strong and resistant to fractures, Due to the higher Nb content, its preference is lower than that of γ-(Ti-Al), which negatively impacts the thrust-to-weight percentage(Ma et al. 2020, Liu et al. 2018). Selecting heat sources for combining different materialsdepends regarding the solidus temperature(Li et al. 2018, Khodabakhshi et al. 2019). Despite the ability of fusion welding to fabricate Functionally Graded Materials (FGMs), the process can lead to alterations in microstructure could result in serious difficulties such deformation, residual cracking under pressure. Variations in thermal expansion coefficients (CTE) and the generation of brittle intermetallic compounds (IMCs) create distortion and residual strains in fusion-welded structures. (Ahsan et al. 2021) Traditional manufacturing techniques face limitations due to constraints in manufacturing, material form, and associated costs (Durakovic. 2018). The diverse applications of FGMs across Table 1 shows a number of fields, and the potential uses for them are numerous.

Table 1. Applications of FGM in various fields

Area	FGM applications	References
Energy	Piezo electric Nano generators, Spacers in Gas insulated Bus Duct for efficient energy transmission, Fuel cells, Solar plates, high voltage Insulators, Li-Ion Batteries, Energy Saving Building windows, Gaseous Insulated switch gears and Pipelines for wind, solar energy transport, Fins, Plasma Facing components in nuclear fusion applications, Submersible pumps in Geothermal power plants, Pressure vessels, and spherical containers, Heat Exchange tubes	(Malakooti et al. 2018, P. Janaki et al. 2021, Mahamood RM and Akinlabi ET. 2017)

Manufacturing Industry	Tools and dies for Casting, Forging, cutting tools, Grinding wheels	(Schaper et al. 1999, El-Galy et al. 2019)
Aerospace	Heat exchange panels, Camera Housings, Reflectors, and Solar Panels, Engine Parts, Heat and Acoustic insulations of walls, Space shuttles	(Mahamood RM and Akinlabi ET. 2017, Schaper et al. 1999, El-Galy et al. 2019, Akshaya SL et al. 2020, Danesh and Ghadami. 2019)
Medical Application	Dental Strut Implants, Orthopedic Implants, Surgical Instruments	(Mahamood RM and Akinlabi ET. 2017, Sola et al 2016.)
Automotive	Car brakes, Flywheels, Cylinder Liners, Leaf springs, Drive Shafts, Shock absorbers, Engine combustion chamber	(Mahamood RM and Akinlabi ET. 2017, Miyamoto. 1996)
Defense Application	Firing Pins, Bullet proof vests, Armor Plates	(Mahamood RM and Akinlabi ET. 2017, Yadav A et al. 2021)
Marine Applications	Maine Riser, Sonar Domes, Piping system, Propulsion Shaft, Engine Components	(Mahamood RM and Akinlabi ET. 2017, Udupa et al. 2014)
Opto-Electronics	Lens, Sensors, semiconductors, Electronic Substrates, Buffer Layers, Fiber telecommunication, Photo detectors	(Mahamood RM and Akinlabi ET. 2017, Besisa DHA and Ewais EMM . 2016)

Over time, various manufacturing methods have been embraced in the creation of Functionally Graded Materials (FGMs). The utilization of powder metallurgy in the production process of FGM appears in current trends. (Nemat-Alla et al. 2011, SASAKI and HIRAI. 1991). FGMs are made possible by powder metallurgy with straightforward shapes and sizes. Additional processes may be necessary to eliminate porosity from the fabricated parts. In situations where cylindrical components with functionally graded properties are required, the centrifugal casting technique is employed (Watanabe et al. 2009). However, this method has limitations on the type of gradient it can produce, relying on the centrifugal force difference resulting from density variation between molten metal and solid components (Yoshihiko Watanabe et al. 1998, El-Hadad et al. 2010). Beyond these functionally graded surface coatings, and bulk process methods have gained widespread use, offering excellent surface protection withstand high levels of temperature, oxidation, wear, and corrosion. For example, coatings such as alumina-SiC on 316L stainless steel are suggested for uses in biomaterials, environmental barrier coatings (EBC), and thermal barrier coatings (TBC). (Sathish et al. 2021). Functionally graded surface coatings are generated using a variety of vapor deposition methods, such as sputter deposition, chemical vapor deposition (CVD), physical vapor deposition (PVD), and plasma-enhanced CVD. (Groves and Wadley. 1997, Mahamood et al. 2012). However, these processes have drawbacks, being energy-intensive and producing harmful gases (Knoppers et al. 2004).

Research indicates that a diverse range of materials can be utilized to develop components with functional property gradation through various techniques discussed earlier. For instance, Kawase et al. (1999) developed C/SiC FGM by the use of the CVD method. Using chemical vapor infiltration (CVI), other material combinations, such as WC/Co/diamond, were used for FGM with remarkable toughness and wear resistance. (Jain et al. 2001). Furthermore, a broad array of FGMs (ZrB2-SiC/ZrO2, Al2O3-Ti3SiC2, W-Cu, and SiC-Al3BC3) were made utilising spark plasma sintering (SPS) to obtain desirable mechanical features (Hong (2008), Lee et al. (2009), Tang et al. (2014), Luo Yongming et al. (2003)). (Raj et al. 2010) created rapidly cast Al-SiCp functionally graded metal matrix (FGMM) composites with exceptional toughness. Furthermore, FGM systems such as Ti-TiB2 and Ti-TiB were successfully prepared using the powder metallurgy (PM) technique (Ma and Geok Chin Tan. 2001, Gooch et al. 1999).

Among the various materials explored earlier and many others under investigation, titanium stands out as a crucial engineering material with significant applications in diverse fields. Notably, titanium has found widespread use in the biomedical sector for implants, scaffolds, and bone plates, as well as in aerospace for airframe and engine components, space launch vehicles, and the automobile industry for aerospace and for automobiles. This widespread utilization is attributed to titanium's favorable attributes, including a strong strength-to-weight ratio, high heat resistance, and resistance to corrosion. The exploration of Titanium-based Functionally Graded Materials Research on (FGMs) has been pursued for a number of years due to these desirable properties. Various methods have been employed for the manufacturing of Titanium-based FGMs, each with its own set of advantages and limitations. Although certain methods, such as chemical solution deposition, have shown successful implementation, they generate toxic waste. Selective plasma sintering and powder metallurgy, while effective, are constrained to producing simple shapes, and the latter is economically viable solely for big-scale production. Limits are set forth by reaction sintering, when components react during the sintering process. Spectrum of suitable materials becomes narrowed. The same applies to Spark Plasma Sintering (SCS), in which a series of chemical reactions spread layer by layer, ending in the burning of compressed powder for FGM creation. Achieving exact control over these chemical processes is tough, lowering the precision in reaching the target property gradation in such approaches. Nevertheless, the appropriateness of various approaches endures depends on how closely they satisfy the criteria of certain applications (see Table 2)

Table 2. Literature on additive manufacturing of Ti-based FGMs

S.No	FGMs	AM Process	No Of layers (Zones)	Composition/ grading, vol% or Wt%	Tensile strength Mpa	Hardness	Study	Ref
1	Ti6Al4V/ ZrO2	LP-DED	28	Compositions of 100% Ti6Al4V, 80% Ti6Al4V+20% ZrO2, 60% Ti6Al4V +40% ZrO2		390-790 HV	Mechanical, microstructure and Wear analysis of FGM was studied	(Zhao et al. 2020)
2	Ti-6AI-4V/ V	LP-DED	195 layers with 35 Individual compositions	100 vol% Ti64 to 100 Vol% V with 3% increment	828-776	47-2 HRC	A roadmap for fabricating FGMs that generally cannot be obtained using standard metallurgy techniques was provided	(Hofmann et al. 2014)
3	Ti-6Al-4V/ V	LP-DED	13	100wt.%TitoTi-25wt.%V	-	205-420VHN	Microstructure evolution in α /β Ti-V alloy FGM	(Banerjee et al. 2003)

4	Ti6Al4V/ ZrO2	LP-DED	142	Composition1: 100vol.%Ti64to75vol.%V Composition2: 25%SS/75%Vto50%SS/V	-	490 ± 48 to 713 ± 220 HV	Characterization of phase Composition and properties	(Bobbio et al. 2018)
5	TC4/TiAl	EBM		Sample 1- 100wt%TiAlto0% In 2 increments Sample 2- 0wt% TiAlto60% In 3 increments	-	Microhardness-350-450 Mpa	The chemical compositions, Microstructure and micro-Hardness of the dual material Samples were investigated	(Ge et al. 2015)
6	Ti6Al4V/ TiCp	LW-DED	51	From 100 vol. % Ti64 alloy to 50 vol.% TiCp with an increment of 5%	820	375-730HV	Effect of TiCp addition on microstructure and mechanical properties	(L. Li et al. 2017)
7	Ti6Al4V/ AlSi10Mg	LP-DED	5	From 100 wt.% Ti6Al4V to 100 wt.% AlSi 10 Mg with an increment of 25%	-	214-619 HV	Effect of process parameters on microstructure, tensile and microhardness	(Liu et al. 2018)
8	Ti-6Al-4V	LPBF		34.11 and 26.62% gradient in elastic modulus and hardness, respectively was obtained	Up to 100Mpa	Up to 4GPa	Gradient in material defects (ref pores, cracks) developed due to variation in proces parameters was observed	(Geng et al. 2021)
9	Ti6Al4V/ Mo	LP-DED	5	0 to 100 wt.% Mo with 25 wt % increments	-	190-450 HV	Microstructure and micro-hardness analysis	(Schneider-Maunoury et al. 2017)

A recent advancement in Functionally Graded Materials (FGMs) production involves the application of additive manufacturing (AM) techniques, addressing some limitations associated with traditional methods. Additive manufacturing stands out as a leading technology that enables the direct production of physical objects from computer-generated component data. Its noteworthy outcomes stem from the capacity to control internal geometric features, significantly minimize total product development and production time, obtain near-net form components, increase material consumption, and create sophisticated shapes and designs (Reichardt et al. 2020). Among many AM processes, laser-based technologies are frequently exploited for FGM fabrication. These methods include directed energy deposition (DED) and powder bed fusion (PBF). Nevertheless, it is not feasible to produce compositional or constitutional gradients in more than one orientation when using laser powder bed fusion (L-PBF). In contrast, directed energy deposition (DED) methods similar to laser powder DED (Low-DED) provide a solution, since through point-to-point deposition, the layer is formed. This technology enables various particles to be directed into a particular point with various feed rates, melted using laser heating, and quickly solidified (Zhang et al. 2019).

2. DED (Direct Energy Deposition) Process

One kind of additive manufacturing is Directed Energy Deposition (DED), in which a substance in the form of wire or powder is supplied on-site and using a concentrated heat source, such as an electric arc, laser, or electron beam. In this way, it is possible to fabricate parts layer by layer or repair or clad in many layers simultaneously using sequential melting. This subset includes three distinct processes: The processes of electron beam freeform fabrication (EBFF), wire and arc additive manufacturing (WAAM), and directed energy deposition using laser powder (LP-DED) (Yang et al. 2017). The creation of components with a form similar to a net makes heavy use of these methods.

Due to its many benefits, Direct energy deposition using lasers (LP-DED and LWDED) has been extensively studied. These include the ability to fabricate complicated and customized components, coat and fix valuable metal parts, and fabricate and restore in logistically difficult places.

The inventions of Harter and Kratky reveal that additive manufacturing has its origins in the welding AM period (I. Harter. 1942, A. Kratky. 1937), namely in the simultaneous supply of energy and material that is seen in contemporary DED. Innovations in the private sector, most notably the patent by Brown et al. (1982), expanded upon DED principles by outlining layer-wise additive deposition using a combination of laser and wire or powder metallurgy. Mehta et al. obtained a patent in 1988 for their method of using screamed powder and a laser to repair metallic items. Their method focused on ensuring a steady, uninterrupted supply of powder for further melting, although in the 1980s, DED-based technology saw little development. W. Konig, T. Celiker and H.-J.H. (1993) and Klocke et al. (1996) published successful implementations of the direct laser deposition (DLD) method, also known as "Controlled Metal Build-Up," throughout the 1990s in Germany. Deposition heads and other combined laser/powder delivery systems were developed by Buongiorno (A. Buongiorno. 1995) and Hammeke (A.W. Hammeke. 1988) to increase the technique's efficiency.

Laser-based DED includes the direct deposition of metals and alloys either wire or powder onto a substrate, synchronous with laser beam irradiation and the movement of the substrate. While powder usage leads in reduced the wire-fed DED technology can achieve up to 90% efficiency in deposition. (Jafari et al. 2021). This mismatch This may be related to the fact that just some of the powder melts and makes a bond with the substrate. Furthermore, the use of powder promotes the complexity and resolution of the manufactured parts, whereas the wire-fed process helps better for producing larger components because of its faster deposition rates. (Gibson et al. 2015, Xue and Islam. 2006). As shown in Fig. 1(a, b), powder DED and wire DED work together to make a pool of molten metal that effectively moves through space and time, forming a 3D component from a zero medium.

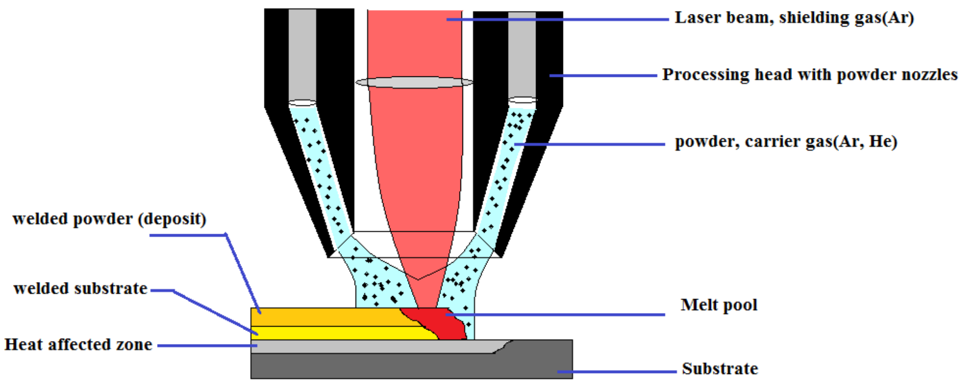

Fig.1. (a) Direct Energy Deposition with Power Fed,

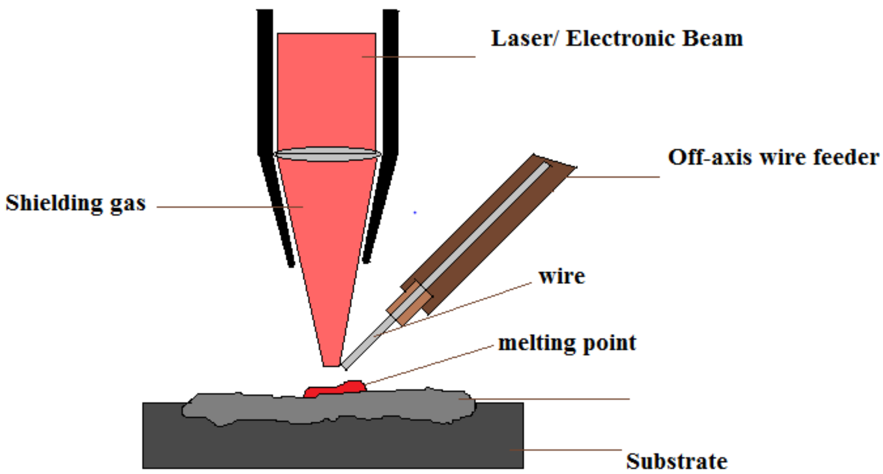

Fig.1. (b) Direct Energy Deposition with Wire Fed,

In the LP-DED (Laser Powder Directed Energy Deposition) technique, A emphasized laser beam links up with the deposition head, which could include one or more nozzles for spraying powder. On the other side, wire-DED applies a wire feedstock combined with an arc (electric or plasma) or laser beam (LW-DED) to produce heat energy. (Mazzucato et al. 2017). Typically, in With LP-DED, the laser beam provides enough heat energy to melt the powder particles into the melt pool when they are deposited. Extreme high-speed laser material deposition (EHLD) technology is one example of an advanced LP-DED technology that produces a focus zone for supplied powder, melting it before reaching the melt pool in the direction of deposition (Schopphoven et al. 2017).

Powder DED machines commonly combine the provision of inert gas, accompanying covering the pool of molten metal with powder from the nozzles and lower oxidation rates Z

(Ahn. 2021). This results in a molten metal pool above a zone influenced by heat (HAZ) with different penetration depths. Once a single layer has been deposited, the procedure is repeated, with the build plate moving in accordance with CAD or CNC data and the deposition head moving in the build direction. Research indicates that, occasionally, the wire-based DED technology provides enhanced efficiency and superior surface quality, albeit its applications are comparatively fewer compared to DED supplied in powder form. This could be caused of the simpler real-time control of blown powder dynamics and its appropriateness for precision manufacture of complicated geometries, together with the cost benefit of powder recycling. However, in situations with uneven deposition surfaces, strong residual stress, decreased surface roughness, and low surface roughness, wire-fed DED is susceptible to instability (Raut and Taiwade, 2021; Ding et al., 2015).

LP-DED is adaptable for producing many stainless steels, titanium alloys (Ti-Ni, Ti-Al, Ti-Nb, etc.), Inconel 625, H13 tool steel, chromium, tungsten, and a variety of other materials are examples of metals and ceramics (Griffith et al. 1999, Bian et al. 2015). Ongoing technical improvements have led to research concentrating on enhancing LP-DED efficiency, especially in areas like the adjustment of various process variables that vary depending on the material being used, including laser power, powder feed rate, scan speed, hatch spacing, and layer thickness. Given the wide range of appropriate materials, finding an acceptable process window becomes critical for intended outcomes (Arshad Harooni et al. 2016).

In LP-DED, fluctuations in laser absorption owing to variables including surface shape, pre-heating effects, and powder feed rate need real-time parameter control for processes,as addressed by Sorn et al. (Ocylok et al. 2014). Temperature monitoring and in-situ imaging allow the evaluation of flaws like fractures and the absence of fusion, as well as the geometry measurement in LP-DED (Garmendia et al. 2018). By adjusting the component's cooling rate, the LP-DED process can change mechanical and structural features through parameter control (Huang et al. 2019).

A new advance in the production of active components with integrated sensors for remotely monitoring bodily features like temperature and pressure is done by LP-DED. Integrated optical fiber sensors are used in cutting tools created using the combination of LP-DED and molding, delivering advantages such as lower size, low weight, great durability, and resistance to outside electromagnetic fields (Grandal et al. 2018, Alemohammad et al. 2007).The specified grain development, microstructure, and intermetallic phases are all significantly impacted by processing parameters (laser power, scan speed, powder feed, etc.) during component fabrication. These factors ultimately have a significant impact on the part's final qualities.

3. Additive Production of Functionally Graded Materials Based on Titanium Materials

Materials with functional grades provide an avenue for tailoring mechanical and thermal properties by managing microstructural and compositional variations throughout the material's bulk (Noda, 1999). As previously mentioned, titanium ti is a desirable engineering material because of its high strength-to-weight ratio, resistance to corrosion, and ability to endure high temperatures (Brandl et al. 2010, Ermachenko et al. 2011).Ti finds significant applications in airframes, gas turbine engines, rocket engines, and hypersonic aircraft thermal protection (Williams and Boyer. 2020) (Afanas'ev et al. 2020), and as construction components for space launch vehicles.

Integrating elements such as steel, Mo, Nb, Al, and Ni alloys (Inconel 625, Inconel 718, and Monel), researchers have investigated the possibility of developing functionally graded materials (FGMs derived from titanium or its alloys as a result of Al's low production costs, aerospace and automotive companies often use Ti-Al-based systems. The final structure may break due to the huge disparity in thermal characteristics between Ti and Al, even though Ti-Al systems are efficient. Scientists have tried to solve this problem by creating functionally graded Ti-Al structures. To generate a gradation in physical characteristics and prevent crack formation, in their 2012 study, Shishkovsky et al. employed the direct metal deposition (DMD) approach to build Ti-Al system structures with functional grading. The goal was to regulate the development of intermetallic phases. Intermetallic phases, such as TiAl and Ti3Al, are brittle and may cause cracks to occur (Shishkovsky et al. 2012).It was proposed that during DMD processing, reducing cracking might be achieved by preheating the substrate to temperatures between 450 and 500 degrees Celsius.

Hotz et al. (2021) and others have demonstrated that in the Ti-Al system, graded composition transition (gradation of AlSi10Mg on AlMg3 substrate to Ti6Al4V, with AlSi10Mg deposited first) causes more cracks than step transition (direct deposition of Ti6Al4V on AlMg3 substrate) (Hotz et al. 2021).On a Ti6Al4V substrate, another study used laser powder-directed energy deposition (LP-DED) to create cylindrical structures with a compositionally graded Ti6Al4V+Al12Si.On a Ti6Al4V substrate, another study used laser powder-directed energy deposition (LP-DED) to create cylindrical structures with a compositionally graded Ti6Al4V+Al12Si.

In addition to their usefulness in the medical field, research suggests that Ti-Nb alloys may find a place in the aerospace industry for certain uses (Martins et al. 2010Variations in cytocompatibility, mechanical properties, and microstructure with variations in Nb% have been investigated in studies on Ti-Nb alloys, such as those by Fischer et al. (2016, 2017) and Han et al. (2015). Various phases formed, which led to changes in hardness and a decrease in elastic modulus as Nb% increased. Binary as-melted alloys Ti-Nb, with Nb% ranging from 10 to 50 wt.%, showed greater microhardness values than Cp-Ti, according to Thoemmes et al. (2016).Employing 0, 15, 25, and 45 weight percent Nb, Wang et al. (2017) reported the minimal Young's modulus for 25 weight percent Nb, highlighting the existence of non-melted Nb in the inventory (Q. Wang et al. 2017). After finding that the hardness decreased with increasing Nb wt.% owing to larger grains and more porosity, Cheung (2015) created Ti-6Al-4V to Nb gradient alloys. The rise in porosity was thought to be caused by the fact that a lot more power was needed to melt the powder as the weight percent of Nb went up (Cheung, 2015).

Ti-SS (Titanium-Stainless Steel) FGM systems have been researched owing to the difficulty in bonding Ti alloys and stainless steel utilizing conventional thermal fusion procedures, resulting in the production of brittle intermetallic phases. To counteract this, in order to prevent the formation of intermetallic phases, an interlayer metal or transition composition is added. Studies, such as those by Sahasrabudhe et al. (2015) and Li et al. (2019), employed Ti64 will be deposited on SS410 substrate using LP-DED, adding intermediate bond layers to avoid delamination and cracking (Sahasrabudhe et al., 2015; W. Li et al., 2017).

Another material combination under research is the Ti-Ni (Titanium-Nickel) FGM system. Despite their different features, Ti-Ni-based FGMs are of interest for their ability to effectively generate graded materials with a combination of desired qualities. Challenges exist in Ti-Ni-based FGMs owing to thermo-physical property mismatch, resulting to cracking in particular compositions. Solutions entail employing a compositional bond layer (CBL) or intermediate layers to resolve the mismatch and avoid cracking, as established in research by Onuike and Bandyopadhyay, Meng et al. (Onuike and Bandyopadhyay. 2018, Meng et al.2020).

4. Summary

Functionally graded materials (FGMs) are produced using advanced manufacturing techniques, especially additive manufacturing (AM), which has grown in favor recently for a variety of aerospace and aircraft applications. An overview of studies on the use of lasers in additive manufacturing to produce titanium-based FGMs is given in this study, concentrating on Ti-Ni FGM systems. Mechanical features, microstructure, and processing defects related to Directed Energy Deposition (DED) for Ti-based FGMs are included in the discussion. The use of directed energy deposition (LP-DED) using laser powder in manufacturing FGMs is particularly promising for diverse engineering applications, opening up new possibilities across industrial sectors, including applications in biomedicine, automotive, aerospace, defence, and the navy.

The primary section delves into the idea, fundamental principles, and conventional methods traditionally used for developing FGMs based on titanium. The following is a brief overview of AM techniques' advantages and potential, and then the setup, guiding principles, and latest LP-DED technologies are explored in detail. The subsequent sections provide a concise review of various LP-DED techniques employed for developing Ti-based FGMs. FGMs represent an advanced material with remarkable stability, strength, resistance to corrosion, and lightweight properties useful for applications in a wide temperature range, including space, aircraft, and nuclear power facilities.

The comprehensive review indicates that LP-DED is a prominent method among various AM technologies for producing a diverse range of FGMs. This process allows for the ability to deliberately manipulate compositional variations to produce directional qualities and design complex pieces layer by layer. When compared to alternative procedures, LP-DED proves to be an effective way to produce gradient structural properties in complicated parts. In order to guarantee faultless, metallurgically sound qualities in Ti-based FGMs customized for particular applications, effective manufacturing procedures are essential. These to provide desirable mechanical qualities, components should show traits like equiaxed microstructure in all directions, lack of fusion, independence from porosity flaws, and consistent microhardness properties.

4.1 Expectations for the Future

The literature review confirms a growing application of Additive Manufacturing (AM) technology in Fabrication of Functionally Graded Materials (FGMs). Laser Directed Energy Deposition (DED) stands out for fabricating complex geometries with spatially varying phase distributions, enabling tailored thermo-mechanical properties. Despite the advantages of AM, several issues remain, necessitating further research to provide comprehensive information and prediction models to enable efficient process control in the development of FGM using AM methods.

Addressing the challenges requires improved process control, feedback mechanisms, online monitoring systems, and in situ analysis to enhance the reliability, reduce costs, and optimize the performance of the process of additive manufacturing. Particularly, Michigan Tech University used the DED technology to achieve economical metal deposition on a moving surface, showcasing potential cost reductions. However, the problem of FGMs based on Ti-Ni having cracks at specific Ni concentrations (60–80%) persists, requiring additional research on processing conditions, including preheating the substrate.

Further studies are needed to explore the impact of reducing the gradient (< 10 weight or volume%) on the properties and, using computer modelling, create an integral database for different FGM systems. Thermomechanical analysis of DED process parameters, such as paths, cooling rates, and preheating temperatures, is crucial. Advances in machine learning (ML) and artificial intelligence (AI) offer potential remedies for addressing challenges, enhancing design aspects, predicting equipment failures, and optimizing parameters to minimize print failures.

Additionally, the design and development of AM techniques for fabricating multifunctional, intricate, and application-specific FGMs suitable for extreme conditions should be explored. In conclusion, despite existing challenges, the application of AM to FGMs holds significant potential, warranting further detailed exploration and research.

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