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Additive Manufacturing of Metal Functionally Graded Materials: A Review

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Abstract

Functionally graded materials (FGMs) have attracted a lot of research interest due to their gradual variation in material properties that result from the non-homogeneous composition or structure. Metal FGMs have been widely researched in recent years, and additive manufacturing has become one of the most important approaches to fabricate metal FGMs. The aim of this paper is to review the research progress in metal FGMs by additive manufacturing. It will first introduce the unique properties and the advantages of FGMs. Then, typical recent findings in research and development of two major types of metal additive manufacturing methods, namely laser metal deposition (LMD) and selective laser melting (SLM), for manufacturing different types of metal FGMs will be discussed. Finally, the major technical concerns in additive manufacturing of metal FGMs which are closely related to mechanical properties, and industrial applications of metal FGMs will be covered.

Keywords: Additive Manufacturing; Functionally Graded Materials; Mechanical Properties; Laser Metal Deposition; Selective Laser Melting

Introduction

Functionally graded materials (FGMs) are advanced materials characterized by a gradual change in properties with respect to spatial positions [1]. The idea of FGM originated from composite materials, which combine two or more different constituents and exhibit good material properties [2]. However, sharp transitions between dissimilar constituents often exist in composite materials, which are stress concentrators that can lead to delamination, which is a detrimental material failure [1]. To avoid this disadvantage and eliminate sharp transitions, the concept of FGM was suggested to introduce a gradient zone between dissimilar constituents. Fig. 1 illustrates the difference between composite materials and FGMs. As shown in Fig. 1(a), in composite materials, due to the abrupt switch from material A to material B, the material property function $F(x)$ undergoes a sharp stepwise transition. Sharp transition in material properties at the interface will result in very different responses to the environment at the interface and cause damage. Instead, if we change from material A to material B with a compositional gradient in the middle as Fig. 1(b), then $F(x)$ can be a continuous function, thus relieving the significant difference. FGM was invented by Japanese scientists in the 1980s to design a thermal barrier with a temperature difference as high as 1000 K [5]. Later on, FGMs have been designed to be used in many other areas such as automotive, aerospace engine, implant, etc. [1,6].

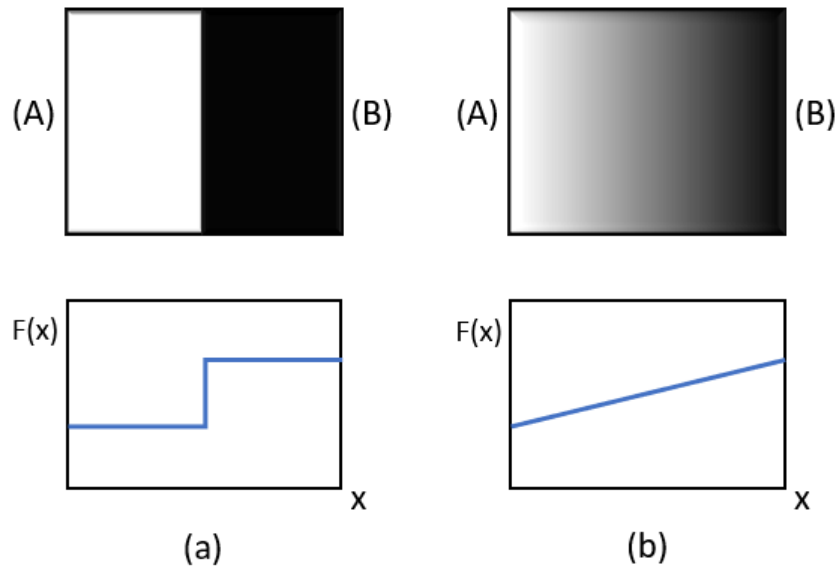


Fig. 1. (a) Composite materials combined with material A and material B: material property $F(x)$ is a step function which changes abruptly at the interface, (b) FGM which gradually varies from material A to material B: material property varies smoothly along the dimension.

There are several ways to classify FGMs. According to the type of grading, FGMs can be classified as stepwise graded FGMs or continuous graded FGMs. FGMs can also be classified into compositionally graded FGMs and structurally graded FGMs [61]. In compositionally graded FGMs, the grading is created by the gradual variation in chemical compositions, while for structurally graded FGMs, the grading comes from graded spatial structure, such as graded porosity and lattice. In Fig. 2, FGM “A” is an example of FGM with graded porosity and here the pores vary gradually in size along the grading direction. FGM “B” is graded in lattice structure and in this case, the thickness of lattice structure increases gradually from the top to the bottom.

Conventional methods for manufacturing FGMs include vapor deposition [9], powder metallurgy [7], centrifugal casting [10], etc. Vapor deposition is used for thin-coating FGMs. Due to its high energy consumption and toxic by-products, vapor deposition is not an environmentally friendly approach to produce bulk FGMs [3]. Powder metallurgy and centrifugal casting are used to produce bulk FGMs. Manufacturing FGMs by powder metallurgy involves preparation of the mixture of powder materials according to a predesigned dispersion formulation, stacking, and final sintering [8]. Since the stacking and powder mixing should be prepared before the final sintering process, powder metallurgy can only deal with stepwise grading. Centrifugal casting can realize continuous grading. However, due to the limitation in hardware, only cylindrical sections of FGMs such as tubes can be obtained [11]. The traditional methods mentioned above all need quite a lot of manufacturing tools and assembly processes, which makes the entire procedure time-consuming. Nowadays, a new approach called additive manufacturing (AM) is attracting a huge amount of interest. AM is defined by ASTM as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [15]”. A 3D computer model of a 3D object can be constructed and sliced into thin layers by computer-

aided design (CAD) tools. Then the AM system will form each layer under the guidance of the tool path and join all the layers together to make a 3D part.

AM is regarded as having major advantages over traditional processing such as its ability to fabricate complex geometries and customized parts, its shorter lead time, less tooling, less assembly required, and overall less waste generated [16]. Due to the important role of metals and their alloys in our everyday life, numerous research works have been done over AM of metal. The two major types of AM for fabricating metallic components are laser powder-fed (LPF) AM and laser powder-bed (LPB) AM [17]. LPF belongs to direct energy deposition (DED) in the seven categories of AM according to ASTM standard, and it is also regarded as laser metal deposition (LMD). In the LPF process, a focused laser beam is applied to create a melt pool on a metal substrate. At the same time, a stream of powder particles is blown into the melt pool by powder feeders. The moving is controlled by CNC for each layer. This process will repeat layer by layer until finally a 3D metal part is achieved. The whole process is carried out in an inert gas atmosphere to avoid metal oxidation. In LPB, a laser beam is used to selectively melt a layer of powder on the powder bed. Thus, LPB is also known as selective laser melting (SLM). The melted powder particles join together and become solid immediately. Once a layer is solidified, the roller spreads a new layer of metal powder to the fabrication zone and the laser melting process will be repeated layer by layer [18]. As this goes on, an as-built 3D part will be generated, along with other unmelted powder particles that can be recycled for future use. That explains why AM generates less waste than conventional subtractive manufacturing.

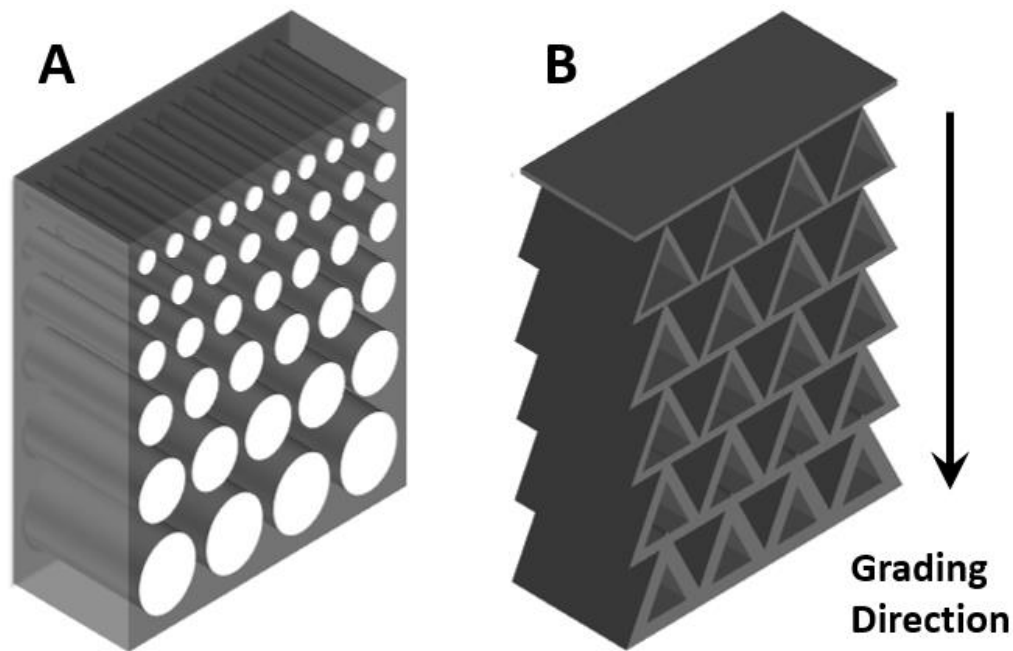


Fig. 2. Structurally graded FGMs with grading in porosity (A) and grading in lattice structure (B).

Due to the fast growth of metal AM and metal FGMs, additively manufactured metal FGMs have become a big topic. LMD and SLM are utilized for different types of metal FGMs. The LMD process is good at controlling chemical composition by changing the feeding rate for different

types of powder, but is weak in controlling structures such as pores or lattice. Thus, LMD is a better choice to manufacture FGMs that are graded in chemical composition. For FGMs that are graded in spatial geometry, such as functionally graded lattice structure or scaffold, SLM is the better approach to precisely control the spatial distribution of materials and meet the special structural design requirements [61]. Although there are now numerous review articles on FGMs [1, 3, 4, 8, 12, 13], there is still a lack of comprehensive understanding on additive manufacturing of metal FGMs. This paper presents research work in LMD and SLM to produce metal FGMs with gradings in composition and structure. Critical issues of manufacturing metal FGMs are discussed in detail.

FGMs Fabricated by LMD

LMD can flexibly control the chemical composition at different deposition positions by gradually varying the ratio of different metal powders. It creates a graded mixing ratio of metal powders from layer to layer. After the fabrication, the graded ratio will result in a graded chemical composition and graded mechanical properties. This technology is especially useful in many industrial areas such as automotive and aerospace industry [14], where multiple types of outstanding mechanical properties are required within one metal component [3]. For instance, a cutting tool needs high hardness and wear resistance at the edge and sufficient toughness at the root. Sometimes two good mechanical properties, such as high hardness and high ductility, are not able to coexist within a part made by homogeneous materials. Therefore, LMD can be used to make new designs of metal components by merging two or more materials together to make metal FGMs according to the special requirements in different portions. This section will review recent important findings in manufacturing metal FGMs by LMD.

One of the important aims of designing metal FGMs by LMD is to gradually add a strengthening phase. Titanium alloys, especially Ti-6Al-4V, are widely used because of their low density, high strength-to-weight ratio, and biocompatibility. A decent number of research efforts have focused on the feasibility of manufacturing Ti-based FGMs reinforced by TiC to improve hardness and wear resistance of titanium alloys. Early successful work in fabricating Ti/TiC FGM was done by Liu and Dupont [20]. Later the hardness study was performed by [21] and [22]. Zhang et al. [22] deposited functionally graded Ti-6Al-4V/TiC by LMD with stepwise gradient: 10% TiC, 20% TiC and 30% TiC. The variation of hardness along the compositional gradient was studied. Vickers hardness changed from 300 HV1.0 at the Ti-6Al-4V bottom substrate to 600 HV1.0. Zhang et al. [21] fabricated Ti-40vol.%TiC FGM by the LMD process. Different laser parameters were applied in different layers according to the variation of material composition. The hardness of the Ti-40vol.%TiC FGM increased smoothly with the TiC concentration, and no obvious interface was observed. Mahamood et al. [23] fabricated Ti-6Al-4V/TiC FGM with composition from 100% Ti-6Al-4V to 50% Ti-6Al-4V/50% TiC. Wear volumes for samples made by fixed parameters and optimized parameters were tested and compared. It was discovered that the optimized parameters can result in better wear resistance. The relationship between tensile properties and TiC volume fraction was studied by Li et al. [24]. The ultimate tensile strength (UTS) of Ti-6Al-4V/TiC FGM with 5% TiC volume fraction is enhanced by about 12.3%. However, when the TiC volume fraction exceeded 5%, the tensile strength of FGM started to decrease. Those representative research works in combining titanium alloy and TiC by LMD are summarized in Table 1.

Table 1. Typical reported research in functionally graded titanium alloy/TiC by LMD

Composition/Grading	Deposition effects/Mechanical properties	Ref.
From 100% Ti-6Al-4V to 30% TiC with 10% gradient increment	<ul style="list-style-type: none"> • Hardness changed from 300 HV1.0 at the Ti-6Al-4V bottom substrate to 600 HV1.0; • Crack free. 	[22]
From 100% Ti to 40vol.% TiC	<ul style="list-style-type: none"> • Hardness HV5 increased smoothly from the substrate along the grading. Hardness doubled at about 20 mm from the substrate; • The composition of unmelted and resolidified TiC increased with TiC composition. 	[21]
From 100% Ti-6Al-4V to 50% Ti-6Al-4V/50% TiC	<ul style="list-style-type: none"> • Optimized functionally graded sample showed the lowest wear volume; • Microhardness was as high as 1200 VHN. 	[23]
From 100% Ti-6Al-4V to 50vol.% TiC	<ul style="list-style-type: none"> • UTS improved by 12.3% with 5% TiC volume fraction. UTS decreased when TiC volume fraction exceeded 5%; • No crack. 	[24]

If two different metals with disparate properties can be combined by LMD, more exotic alloys with novel properties will be generated. Ti-6Al-4V was also used to merge with molybdenum (Mo). Ti-6Al-4V/Mo FGM was deposited by Catherine Schneider-Maunoury [26]. Good metallurgical bonding was found between the deposited wall and the substrate, and also between adjacent deposited layers [26]. Ti/Invar FGM was deposited by Bobbio et al. [27]. Apart from titanium alloys, stainless steel was also investigated to combine with other alloys. The 304L/Inconel 625 FGM, whose composition varied from 100% 304L on one side to 100% Inconel 625 on the other side, was successfully fabricated without a sharp interface by Carroll [28]. Joining dissimilar materials may create different types of intermetallic compounds at the interface that result in properties that are hard to predict. Liu et al. [25] studied lightweight Ti/Al graded material for combining excellent properties of both Ti alloy and Al alloy. The composition of Ti/Al varies from pure Ti-6Al-4V to pure AlSi10Mg, with a complex phase change in the middle. Along the composition gradient, the hardness increased and then decreased [25]. Sometimes the aim is to apply functionally graded method to create a high-strength intermetallic phase, such as Ti-Al [19, 29]. In other cases, brittle intermetallic phase, such as Ti-Fe, needs to be avoided which may cause cracks or even fracture such as the joining between Ti-6Al-4V and 304L [30]. Typical combinations between two dissimilar metal alloys which change from 100% of one alloy to 100% of the other alloy are listed in Table 2 in accordance to [25, 26, 27, 28, 30]. From Table 2, it can be found that in most cases, the resultant powder mixing and element composition can be accepted, while cracking often occurs due to unmelted particles or interaction between different types of phases with distinct thermal properties generated during melting and solidification. More details on the brittle intermetallic phase and cracking will be covered in the discussion.

Table 2. Summary in combining dissimilar metal alloys by LMD

Materials	Composition/Grading	Deposition effects/Properties	Ref.
Ti-6Al-4V & AlSi10Mg	<ul style="list-style-type: none"> • From 100% Ti-6Al-4V to 100% AlSi10Mg • 5 gradient regions with 25wt.% increment 	<ul style="list-style-type: none"> • Element composition gave a nearly linear relationship along the gradient; • The maximum hardness reached 619 HV0.1 at the middle section of the deposition; • Zig-zag region in tensile stress-strain curve due to crack; • Fracture surface showed a transition from ductile to brittle along the graded direction. 	[25]
Ti-6Al-4V & Mo	<ul style="list-style-type: none"> • From 100wt.% Ti-6Al-4V to 100wt.% Mo • 5 gradient regions with 25wt.% increment 	<ul style="list-style-type: none"> • Homogeneous powder mixing; • Satisfactory metallurgical bonding; • Unmelted Mo resulted in the composition of Mo different from expected; • Minimum hardness 265 HV at 25wt.% Mo region, maximum hardness 450 HV at 75wt.% Mo region. 	[26]
Ti & Invar	<ul style="list-style-type: none"> • From 100 vol.% Ti to 100 vol.% Invar 	<ul style="list-style-type: none"> • Actual element composition did not significantly deviate from expected; • In the gradient region there was a large fluctuation in element composition due to segregation; • Major crack through the gradient due to the presence of secondary phase FeTi and Fe₂Ti; • High hardness plateau at the region of 15~33 vol.% and 36~48 vol.% Invar. 	[27]
304L & Inconel 625	<ul style="list-style-type: none"> • From 100% 304L to 100% Inconel 625 	<ul style="list-style-type: none"> • A gradient zone without sharp distinction; • No major deviation in composition; • Cracks of several hundred microns in length were found in a region composed of approximately 79 wt.% SS304L and 21 wt.% Inconel 625. 	[28]
Ti-6Al-4V & 304L	<ul style="list-style-type: none"> • From 100 vol.% Ti-6Al-4V to 100 vol.% 304L • V was added in 25 vol% increments 	<ul style="list-style-type: none"> • Process stopped at the region of 50% 304L/50% V; • The transition from 25% SS304L/75% V to 50% SS304L/50% V resulted in major cracking at the interface and build failure due to the formation of the σ-FeV phase. 	[30]

Properties other than mechanical properties of FGMs were also studied. For instance, copper can be deposited on steel molds to improve the thermal behavior of steel molds. Since copper and iron are very different in their thermal expansion coefficient, depositing copper directly on steel is very likely to cause failure at the sharp interface. Thus, graded copper was deposited on the H-13 tool steel by Noecker and DuPont [32]. Karnati et al. [33] combined copper and nickel

to make Cu/Ni FGM, which possesses both the high thermal conductivity of copper and the strength in high temperature of nickel to create multifunctional alloy in a high-temperature regime. The graded magnetic property was achieved by Heer and Bandyopadhyay [34]. A magnetic compositionally graded bimetallic structure was built via LMD by combining two different types of stainless steel: SS430 and SS316, and the selective magnetic function was then proved to be achievable.

For properties in the biomedical area, titanium alloy is a good candidate due to its biocompatibility. People tend to combine titanium alloys with ceramics or other metal elements with special functions to make Ti-6Al-4V a perfect choice for implants. Novel biomechanical properties were achieved through fabricating graded Ti-TiO₂ structures by LMD. The addition of TiO₂ ceramics in titanium not only improved the hardness but also enhanced the surface wettability [35]. Hard and wear-resistant coating consisting of Co-Cr-Mo was deposited on Ti-6Al-4V. All the deposited materials are nontoxic. Living cell density was tested and it was shown that 50% Co-Cr-Mo surface possessed the best combination of biocompatibility and wear resistance [36]. For artificial implants, one important concern is whether the material used for manufacturing implants is safe for human body in the long run. In Ti-6Al-4V, the Al and V elements can cause health issues over a long period of time. Therefore, the nontoxic element molybdenum can be added into Ti-6Al-4V. In addition, molybdenum has a lower Young's modulus than α -Ti, which can also contribute to the decrease of the overall Young's modulus in order to match with human tissues and reduce the risk of health concerns [26].

In the process of LMD, the low powder capture rate is an issue. Using wire to replace powder can be a potential solution. Wang et al. deposited Ti-6Al-4V/TiC FGM by feeding Ti-6Al-4V wire and TiC powder simultaneously [37]. Copper powder and nickel wire were used by Li et al. to manufacture Cu/Ni FGM [38]. They compared powder-wire deposition with dual powder deposition and proposed that to deposit two different types of metallic materials by the powder-wire method, it is better to use the material with a higher melting point in wire form and the material with a lower melting point in powder form. Similarly, wire arc additive manufacturing (WAAM) was also tried in fabricating metal FGMs. Shen et al. [39] used a WAAM system to fabricate Fe-FeAl wall with desired mechanical properties. It has similar mechanisms to powder deposition, and it also possesses high deposition efficiency, low cost in material supply, and higher part density.

The FGMs mentioned above are all graded in a single direction. Apart from the grading in one direction, other types of gradient can be achieved by adding a new degree of freedom to the AM system. In [40] and [41], metal FGMs with radial grading were fabricated. A functionally graded tube with grading along the tube radius was developed by Durejko et al. [41]. An amended data matrix code (DMC) file was generated to guide the manufacturing system to generate a gradient along the radius rather than the tube axis. Two types of functionally graded 316L/Fe₃Al tubes were fabricated. Type A varied from pure 316L at the inner surface to pure Fe₃Al at the outer surface, while Type B varied in the opposite way. Hofmann et al. [40] developed an AM system with a combination of rotation and linear motion to deposit 304L stainless steel to Invar 36 gradient cladding on an A286 steel rod. The addition of new degrees of freedom can make a more functional LMD system to achieve more flexible deposition.

FGMs Fabricated by SLM

SLM is a powder bed based manufacturing process; thus, SLM is not flexible enough to do real-time controlling of composition. Hence, SLM is not a proper way to fabricate FGMs with graded chemical compositions. Thanks to the extremely high precision of SLM, researchers take this merit in another area of FGMs: functionally graded cellular materials. Functionally graded cellular materials often exist in a cellular form with grading in lattice structure or porosity in 3D space.

SLM is a powerful tool to manufacture components incorporating complicated lattice structures that are difficult for traditional machining. Due to the complex 3D geometry, it is too time-consuming to make molds for the casting process, and the assembly is also troublesome. However, SLM can selectively and precisely control the melting and solidification in each layer and finally make differences in solid layers. Apart from periodic cellular structures, which simply repeat a unit cell across the 3D space, cellular structures with gradient have more attractive properties. They are different from compositionally graded FGMs fabricated by LMD, which usually need fully dense manufacturing to avoid major defects under extreme loading conditions, and cellular materials will be used in certain areas where specific lightweight or hollow structures are required.

One important area for research and development on cellular solids is the mechanical response under quasi-static loading and dynamic impact. Fabrication of lightweight lattice structures for energy absorption has also become popular in these years. Previous research has proved the unique mechanical behaviors and capabilities in energy absorption of lattice structures [42]. Recently, researchers have started to add gradients onto these intriguing structures and find more novel mechanical behaviors. There have been many cellular structure designs in the past but with no gradient. Thanks to the intrinsic high degree of design freedom and rapid development of manufacturing precision that SLM can provide, we can not only fabricate lattice structures without the constraint of molds but also import gradient to those materials by controlling the volume fraction in different manufacturing layers. By using SLM, we can manufacture graded lattice structures by controlling the 3D geometric design and graded porosity parts by adjusting the building parameters such as laser power, scanning speed, and hatch space, etc.

Graded lattice structures are often seen in controlling the 3D geometric design to achieve density gradient. Researchers have reported different types of gradient lattice structure with different unit cells and alloys by SLM. Maskery et al. [42] studied mechanical properties of graded Al-Si10-Mg body-centered cubic (BCC) lattice structures manufactured by SLM. They linearly decreased the diameter of struts from the bottom to the top to create a grading. Heat treatment was applied after the SLM process to eliminate the thermal stress and homogenize the microstructure. Both the mechanical behavior of functionally graded lattice and uniform lattice were studied. A uniaxial compression test with a rate of 3×10^{-2} mm/s was applied to the heat treated uniform sample and the heat treated graded sample [42]. Different mechanical behaviors were found after the comparison test. For the compression of the uniform lattice sample, abrupt structure collapse occurred with an angle of 45° when the lattice strain reached 12%. As the lattice strain kept increasing, the collapse effect became more severe and formed a 45° shear band, which was regarded as abrupt shear failure. By contrast, for the compression of the graded sample, the

collapse started from the top layer with the thinnest struts to the lower layers with the thickest struts. From the comparison, it is believed that functionally graded lattice has a more reliable and predictable crushing behavior. Thus, it is a more favorable design for structural engineers [42].

Choy et al. [44] studied both Ti-6Al-4V cubic lattice and honeycomb lattice in the density gradient made by SLM. The graded structure was also realized by linearly changing the diameter of the struts. Comparison between the uniform lattice structure and the graded lattice structure was also made and a similar compressive phenomenon was observed. Additionally, the difference in lattice orientation was covered. The test results showed that FGMs with vertical struts were better at energy absorption [44]. Al-Saedi et al. [43] studied the mechanical properties of uniform and functionally graded structures in the F2BCC unit cell, which consisted of one body-centered cubic (BCC) unit cell and two face-centered cubic (FCC) unit cells. The entire structure was made of Al-12Si and manufactured by SLM. The strut diameter increased gradually from top to bottom. Experimental work and numerical analysis were performed to understand the novel behavior of additively manufactured functionally graded F2BCC lattice structures under compressive loading. For the functionally graded structure case, the layer-by-layer crushing was successfully modeled by finite element method. However, due to the difficulty in modeling collapse behavior, the finite element result of the uniform case still needs further study [43]. Another type of lattice gradient consists of gradually varying the strut distribution but keeping the strut diameter as a constant value. A typical example work is in [45]. A density graded lattice structure made of Ti-6Al-4V, based on a rhombic dodecahedron unit cell, was fabricated by SLM. Both static loading with a strain rate of 0.001/s and dynamic loading with a strain rate of 1000/s were applied during testing, which showed the strain rate sensitivity for the bulk structure.

As it has the specific capability to customize manufacturing products, it is worth mentioning the important role of SLM in the biomedical field. Metal materials such as titanium alloy and cobalt chromium are both biocompatible and load-bearing resistant, which attract more attention from researchers who work in designing artificial implants. Due to the large difference in Young's modulus between solid metals and natural biomaterials, stress shielding may occur during the service period. Thus, porous or lattice structures are preferred to reduce the overall Young's modulus of implants and also improve osseointegration in the biological point of view. Moreover, for tissues and organs in human body such as teeth and bones, they are actually natural FGMs with cellular grading [16]. Thus, if metal artificial bones and teeth can be produced with functional grading that can effectively mimic the real biomaterials, the reliability of implants will be raised to a higher level. Controlling the Young's modulus and yield strength via adjusting the structure gradient of FGM to match the mechanical properties of natural bone structure was mentioned in [49]. The effective elastic modulus of the titanium alloy scaffold was in the range of 0.28~0.59 GPa. Literature [50] reviewed the state-of-art and applications of additively manufactured FGMs in orthopedic departments. Case studies in designing orthopedic implants by numerical optimization were listed, in which Co-Cr alloy was proposed to produce porosity graded femoral stem by SLM [57, 58]. Both experimental and numerical method proved that the overall stiffness was reduced if the porosity graded design was adopted. Thanks to the rapid development of 3D scanning technology, reverse engineering also contributes to the medical engineering area. In [49], the CT reconstruction was applied to prove a good reproduction for additively manufactured metal implants.

Another type of structurally graded structures called porosity graded metal FGMs can be made by controlling building parameters such as laser power, hatch space, etc. As shown in Fig. 3, changing the melt pool size and the distance between melt pools in a graded way in SLM can realize a metal part with gradient porosity. A large porosity can decrease the strength of metals. Then, fabricating porous metal parts with gradient porosity can relieve this problem [46]. Li et al. [46] developed an approach to manufacture steel parts with graded porosity. They verified that the gradient level of porosity can be realized by gradient changed laser scanning speed since when scanning speed increases, the melt pool size will decrease which will lead to controllable pores between melt pools or scanning tracks.

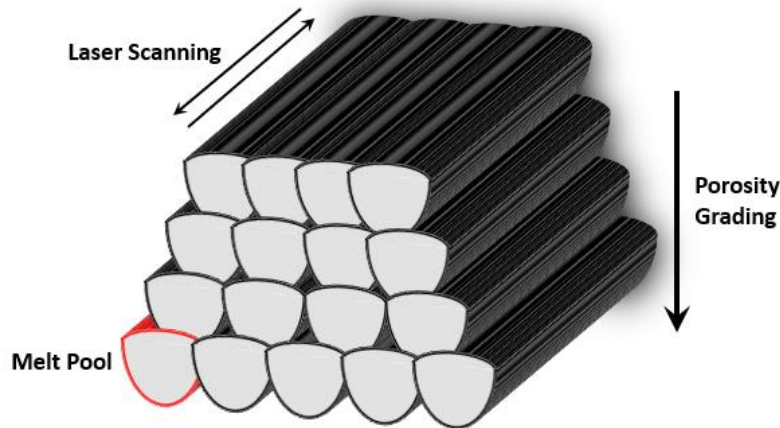


Fig. 3. Porosity grading can be controlled by controlling the melt pool size and the distance between adjacent melt pools.

Although SLM is mostly used for fabricating FGMs with a grading in lattice structure or porosity, attempts of metal FGMs with other types of gradient by SLM were also made in [48, 54], which may provide new ideas for more diverse design of FGMs. Literature [48] and [54] demonstrated that a graded grain size and texture was achieved by SLM. The graded microstructure was realized by a controllable laser scanning strategy that could maintain both fine grains and coarse grains with clear orientations within one single metal part. Thus, metal parts with flexibly tailorable properties can also be made possible by SLM. The metal FGM graded in microstructure is not commonly seen; however, it may suggest a novel direction in producing multifunctional metal components.

Discussion on Concerns and Challenges

The LMD process is still a new manufacturing approach, and the mechanisms still need to be understood so that the properties of the produced part made of FGMs can be understood as well [56]. Currently, there is research need for a comprehensive database of additively manufactured metal FGMs [1]. A clear understanding of the material selection and the relationship among chemical composition, phase transition, and mechanical properties is of great importance. As seen in Table 2, when joining dissimilar alloys, unmelted component was often detected which might cause deviation in composition and defects in structure. Optimizing laser processing parameters for depositing two or more different types of powder is critical in order to reach the best joining effect since the key is the interaction between LMD systems and as-deposited FGM parts.

In particular, cracking is a common issue if the combination is not merged in an appropriate way. For particle reinforced graded alloys, though it is proved that higher particle concentration can result in higher hardness and wear resistance, a limit should be controlled to reduce the amount of unmelted particles and to avoid the crack source [37]. In [35], when the concentration of TiO₂ changed from 0 to 100%, cracks were observed. The maximum TiO₂ concentration was then reduced to 90% to produce a non-cracked specimen. In some cases, intermediate transition route can be applied between two dissimilar materials to avoid specific intermetallic phases that easily cause cracks or even fractures. In [31], a Ti-6Al-4V/V/Cr/Fe/SS316 multi-metallic structure was fabricated to join Ti-6Al-4V and stainless steel 316 in a successful way without generating brittle Fe-Ti phase. In LMD, another important factor that may affect the manufacturing quality is the powder feeding which is a complex process. In this step, due to the difference in powder size and density, the behavior under argon gas flow can be different. There could be powder separation, which will break the predesigned powder ratio and cause a large deviation from the expected metal composition. In [60], the premixed powder flow under the carrier gas was studied numerically and experimentally to provide a guideline for dealing with this manufacturing error. Currently, the majority of FGM parts fabricated by LMD are still test samples. Moving the simple test samples to the real functional components need the comprehensive development of system control. Thus, a global method for LMD path planning should be studied to manufacture functional complex parts rather than single walls [55].

SLM is the most commonly used metal powder-bed AM technique. Apart from SLM, other powder-bed based methods can also exhibit their capability in metal FGMs. For generating graded porosity, selective laser sintering (SLS) is a reasonable method as well, especially for FGMs graded in porosity. The main difference between SLS and SLM is that in SLS, powder particles are only partially melted. Due to the partial melting, there will be more pores generated among powder particles. Erdal et al. [59] applied SLS in manufacturing functionally graded porous polyamide. The application of SLS in metal FGMs is still waiting for more exploration. Electron beam melting (EBM) is also a powder-bed based AM process. The main difference between EBM and SLM is that the energy source used in EBM is an electron beam rather than a laser beam. EBM can be as accurate as SLM, and recently it has also been used for fabricating complex graded lattice structures with high strength and energy absorption [51, 52, 53, 61].

In SLM, the key issues mostly lie in material processing, solid mechanics, and design. For SLM processing, surface roughness and residual stress are major issues. In particular, for cellular graded FGMs made by SLM, a large amount of surface roughness and residual stress can greatly affect and even change the deformation behavior since microscale struts or pores are major constituents. Compared with bulk solid materials, graded lattice structures with fine details can be more sensitive to the size dimensions. Heat treatment processing is necessary for SLM parts. In [44], lattice structures with heat treatment and without heat treatment were compared, and it was found that the compressive response was different between lattice structures with and without heat treatment. It is beneficial to make the step of heat treatment efficient since if the post-treatment takes too long, AM will lose part of its merit of rapid manufacturing. Both surface finish and residual stress can reduce the fatigue life of metal parts. For graded lattice structures used for long-time service, understanding how much those factors can affect the fatigue behavior is essential.

Until now, there have been different types of unit cell design for graded lattice structures, such as BCC [42], F2BCC [43], rhombic dodecahedron [45], etc. Most of them are based on experimental methods. With the rapid development of computational methods, numerical modeling is becoming an important tool to reduce material consumption. Topology optimization can be used to find a reasonable unit cell and density distribution design [47]. Topology optimization also has potential applications in designing better support for structurally graded materials with a complicated overhang structure or a multidirectional grading. Finite element modeling is the principal way to predict the mechanical response under different loading conditions. Unlike solid bulk parts, many more possible responses exist in cellular structures, and some behaviors still cannot be accurately simulated. In addition, SLM accuracy is believed to be a factor which results in a gap between experimental results and numerical results [50]. In a word, the development of additively manufactured metal FGMs calls for joint effort among many areas, including development of AM systems, phase transformation, solid mechanics in cellular structures, and numerical modeling.

Conclusion

FGMs are emerging advanced materials with tailorable material properties that can be used under complex service conditions. Metal FGMs and metal AM are attracting lots of research interest during recent years. Typical research works in different types of metal FGMs manufactured by two major metal AM technologies, namely LMD and SLM are summarized in this paper. As additively manufactured metal FGMs are still in the early stage, design concerns and challenging technical issues are discussed in order to provide future research directions and arise new topics which can be beneficial to both areas of metal AM and metal FGMs.

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