International Journal of Frontiers in Engineering Technology
ISSN 2706-655X Vol. 7, Issue 2: 96-107, DOI: 10.25236/IJFET.2025.070213

Research progress and prospect of additive manufacturing technology for the preparation of functionally graded materials

Zhu Weiguang[1, a], **Wang Kun**[1,b,*], **Yan Chaowei**[1,c], **Li Yifan**[1,d], **Jiang Yanlin**[1,e]

[1]*College of Mechanical Engineering, Inner Mongolia University of Technology, Hohhot, China*
[a]*2794695815@qq.com*, [b]*2256833546@qq.com*, [c]*1539634793@qq.com*, [d]*1971683478@qq.com*,
[e]*1961465791@qq.com*
[*]*Corresponding author*

Abstract**:** *Functionally graded material (FGM) is a new type of heterogeneous engineering material composed of two or more materials with gradient composition, which is widely used in the engineering field due to its light weight, excellent physical properties and forming flexibility. The traditional production process is often limited by the long production cycle and customization problems when preparing FGM, and it is difficult to quickly respond to the high standard needs of modern engineering. The rise of additive manufacturing technology has opened up a revolutionary path for the manufacture of FGM. This technology has greatly contributed to the development of FGM due to its simplified production process, high design flexibility, and easy to achieve gradient continuity. In this paper, we systematically review the latest research results of FGM preparation using different additive manufacturing technologies at home and abroad, deeply analyze the process characteristics of these technologies and the performance of the prepared materials, and discuss the wide application of FGM in many engineering fields. Finally, based on the in-depth analysis of the current situation, this paper looks forward to the future development trend of additive manufacturing technology in the field of FGM, and emphasizes the key role of basic science research, high-tech integrated application, and special environment service needs in promoting the sustainable development of this field.*

Keywords: *functionally graded materials; additive manufacturing technology; gradient type; Trajectory planning*

1. Introduction

Functional gradient materials (FGM) refer to a new type of composite heterogeneous engineering material in which two or more materials are compounded in one or more dimensional directions, and their composition and structure change continuously in a gradient manner. They were developed to meet the needs of modern aerospace and other high-tech fields, aiming to ensure normal operation under extreme conditions[1]. Compared with conventional composite materials, FGMs have design requirements that their functions and properties vary with the internal position of the parts, and their overall performance is optimized to meet these requirements. Therefore, FGMs have the characteristics of light weight, excellent physical properties, and easy processing and forming. As a result, FGMs have been widely applied in aerospace[2], transportation engineering[3], biomedical engineering[4], flexible electronics[5], soft robotics[6], nuclear industry, semiconductor optoelectronics, defense and military industries, and other fields[7]. Traditional manufacturing methods for FGMs include vapor deposition[8], plasma spraying [9], powder metallurgy[10], temperature gradient method[11], centrifugal method[12], non-equilibrium swelling method[13], electric field induction method[14], and injection molding[15]. Despite the continuous expansion of the application scope of FGMs, the current manufacturing techniques, although they can meet basic requirements in specific fields, still encounter many limitations in a wide range of practical applications. For instance, components prepared by the centrifugal method often have high porosity problems; the temperature gradient method faces issues such as inaccurate temperature control and cooling rate. Additionally, these traditional preparation methods also have limitations such as long preparation cycles, difficulty in customizing processes, and the inability to quickly prepare complex-shaped components, which greatly hinder the development of FGMs. The 3D printing technology developed in recent years provides a new forming method for the preparation of FGMs, featuring simple forming processes, high design freedom, the ability to prepare multi-component and complex-shaped composite materials and FGMs, and the realization of continuous gradient changes[16], offering new methods and ideas for the preparation of FGMs.

2. Development history and classification of functionally graded materials

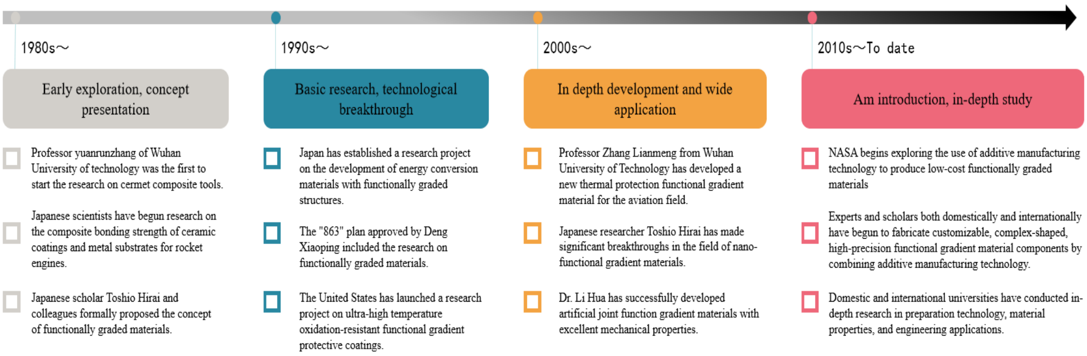

Figure 1: Development history of functionally graded materials

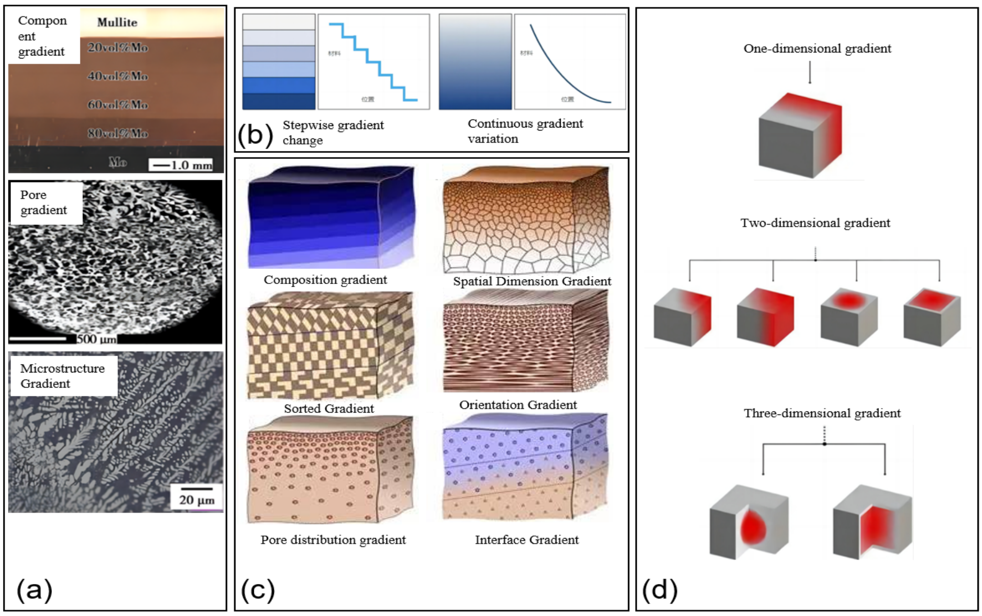

Figure 2: Classification of functionally graded materials. a) Classify by gradient type; b) Classify according to the form of change; c) Classify by transitional form; d) Classify by dimension

As shown in Figure 1, it was professor yuanrunzhang of Wuhan University of technology in China who started the research on metal ceramic composite tools. Since then, in 1987, Japanese scholars Masako Shinano, minao Hirai and ryosami Watanabe formally proposed functional graded materials (FGM) By 2025, FGM has gone through the stages of concept presentation, technological breakthrough, extensive application and in-depth research. More and more experts and scholars from enterprises and universities have combined additive manufacturing technology with the preparation of FGM to develop high-performance FGM[17], such as the Massachusetts Institute of technology[18] and Nanyang Technological University[19] in foreign countries, as well as Tsinghua University[20], xi'anjiaotong university[21], Northwestern Polytechnic University[22], Huazhong University of science and technology[23], sublimation three-dimensional and other universities and enterprises in China have conducted in-depth research in this area. According to the gradient type, functionally graded materials have expanded from the initial component gradient to three gradient types: component gradient, pore gradient and microstructure gradient (Fig. 2a)[24]. Functionally graded materials with component gradients are the most widely used functionally graded materials in the current field, with the longest development time[25]. The two key parameters of the component gradient are the number of gradient layers and the gradient index. The optimization of these two parameters can help reduce the interlaminar cracking, reduce the interlaminar stress and improve the performance of the material [26]. The pore gradient refers to the gradient change of the shape or size of the pores in the material, and the microstructure gradient refers to the gradient change of the size and shape of the grains in the material. How to accurately control the size and shape of pores and grains has always been the research focus of these two FGMs[26]. With the continuous expansion of application fields, porous and microstructure functionally graded materials are gradually applied in engineering practice. Functionally graded materials with pore gradients are used in material weight reduction, vibration absorption, biomedicine and other fields[27], while microstructure gradients have achieved good results in improving material strength, such as high wear resistance, hardened surface and corrosion resistance [28].

Functionally graded materials are mainly divided into composition gradient, porosity gradient, and microstructure gradient as shown in Figure 2(a). Composition gradient achieves synergistic optimization of mechanical properties and functionality by precisely controlling the spatial distribution of the material's chemical composition, typically applied in tool coating. Porosity gradient, by controlling the continuous change in porosity, balances load-bearing capacity with biocompatibility, promoting vascularization and cell adhesion in bone tissue engineering scaffolds. SLM technology can achieve precise control of porosity from 5% to 80% by adjusting the laser energy density. Microstructure gradient focuses on the gradient design of grain size, phase distribution, or fiber orientation. For example, in aerospace engine blades, a gradual change from a surface fine-grained strengthening layer to an internal columnar crystal structure can simultaneously enhance fatigue resistance and high-temperature creep strength. Electron beam melting wire deposition (EB-PBF) technology can achieve cross-scale structural control from millimeter to nanometer levels through temperature field control.

Functionally graded materials can be divided into stepped gradient change (discontinuous) and continuous gradient change from one end of the material to the other according to the change form, as shown in Fig. 2(b). Stepped gradient change means that the composition, structure and performance of materials show obvious segmented or hierarchical changes in a certain direction, and there are obvious boundaries between each segment. This form of change can be achieved by using materials or composites with different properties in different positions of the material. In the aerospace field, in order to deal with the thermal stress problem under extreme temperature changes, materials with different thermal expansion coefficients can be used in different parts of the structure, and the thermal stress can be relieved at the interface through stepped design. Continuous gradient change means that the composition, structure and performance of the material change continuously and smoothly in a certain direction without obvious mutation point. This change can be achieved by gradually changing the composition and structural parameters of the material (such as grain size, porosity, etc.) or adding different reinforcement phases. In metal ceramic functionally graded materials, the thermal expansion coefficient, thermal conductivity and other parameters of the material can be smoothly transferred at the interface by continuously changing the relative content of metal and ceramic, so as to reduce the thermal stress and improve the overall performance of the material.

According to the transition form of gradient, functionally graded materials are mainly divided into composition gradient, arrangement gradient, hole distribution gradient, spatial dimension gradient, orientation gradient and interface gradient, as shown in Fig. 2(c). Composition gradient refers to the transition from one material to another by changing the material composition step by step. The arrangement gradient usually refers to the gradient change of the arrangement of the internal microstructure of the material (such as grains, fibers, molecules, etc.) in space. In composites, the mechanical properties of the material can be optimized by designing the arrangement gradient of fibers or particles, such as improving the strength, toughness or fatigue resistance. In addition, in electronic materials, specific functions of electronic devices can be realized by controlling the arrangement gradient of conductive materials. The hole distribution gradient refers to that the material properties are generally changed by adding reinforcement phase in the material, and the performance of the gradient material is changed by adjusting the distribution of reinforcement phase, such as adding ceramic particles to the metal to enhance the high temperature and wear resistance of the metal. The spatial dimension gradient refers to changing the grain size/morphology from one end to the other, or changing the porosity of the material to meet the performance requirements of different positions. The orientation gradient can change the mechanical properties of the material in different directions by changing the microstructure orientation or the direction of the reinforced phase such as fibers. Interface gradient usually refers to the continuous or step-by-step change of a certain physical quantity (such as composition, structure, properties, etc.) in the interface area between two or more materials. By designing the gradient interface structure, good bonding and performance complementarity between materials can be achieved, so as to improve the performance and service life of the overall material. In the biomedical field, interface gradient technology is used to prepare implants such as artificial joints to improve their compatibility and stability with surrounding tissues.

Functionally gradient materials can be divided into one-dimensional, two-dimensional and three-dimensional according to dimensions. As shown in Figure 2(d), one-dimensional gradient materials only have component changes in one direction, which can be completely described by linear coordinates. For example, for a material gradually transiting from metal to ceramics, the components of metal and ceramics change continuously in one direction, forming a one-dimensional gradient structure. The two-dimensional and three-dimensional gradient materials can completely describe the gradient transition direction with the surface (two-dimensional coordinates) and the volume (three-dimensional coordinates), which can be applied to more special and complex engineering fields.

3. Research progress of functionally graded materials prepared by additive manufacturing technology

3.1 Research progress in preparation of functionally graded materials by melt deposition molding (FDM)

Melt deposition (FDM) is one of the most commonly used additive manufacturing technologies today. Its principle is that thermoplastic polymer materials are melted and extruded, and deposited on the platform to build 3D objects layer by layer. The principle of preparing functionally graded materials is shown in Figure 3(a). FDM technology realizes the pore gradient of materials by controlling the filling rate, the number of contour layers, the filling method, the printing layer and other parameters, while the component gradient is achieved by adjusting the feed of different component extrusion wires. In recent years, it has been studied to use particles or powders instead of filaments. FGM can be prepared by designing and modifying the print nozzles used in FDM technology. The specific method is to set up an extruder with multiple material feeding channels to adjust the feed ratio of different materials in real time to realize the gradient change of material composition.

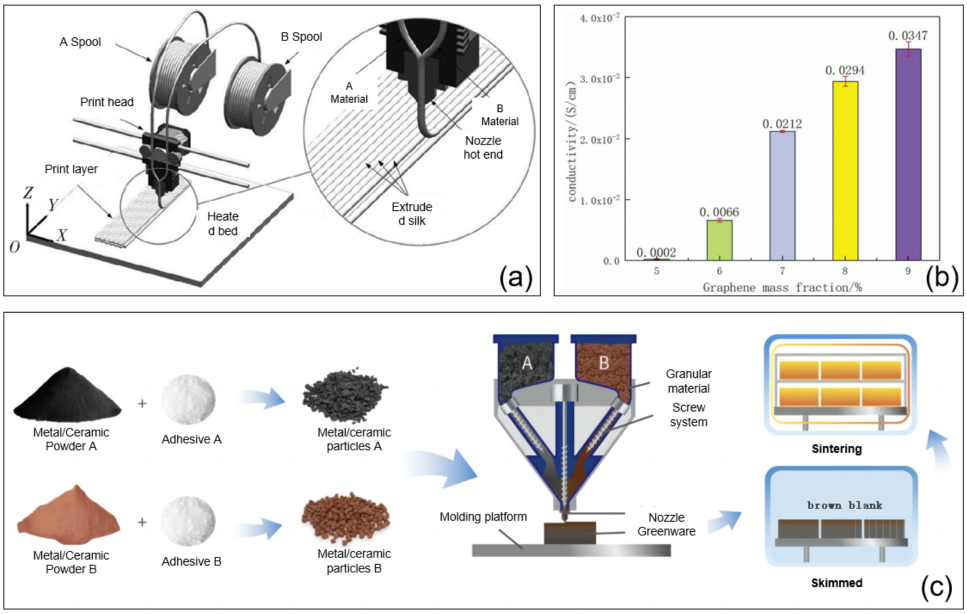

Figure 3: a) Schematic diagram of preparing functionally graded materials using fused deposition modeling (FDM) technology; b) Graphene content and conductivity; c) Schematic diagram of UPR-241 functional gradient material 3D printing equipment

In 2019, garland[29] used FDM technology to prepare functional gradient materials with component gradient by combining nylon and PLA with dual nozzle printer. The mechanical properties of the material show unique gradient variation characteristics in the three spatial dimensions of X, Y and Z. In 2020, wuhaihua and others from Three Gorges University[30] developed a gradient composite material based on graphene oxide (RGO) and polylactic acid (PLA). The influence of graphene content change on the electromagnetic properties of the material was explored, and the optimization interval of the thickness of the functional layer was accurately defined by using the reflection loss model. The experimental data show that when the mass ratio of graphene is 5%, 7% and 9%, compared with the traditional uniform structure absorber, this gradient structure material shows significant advantages in electromagnetic absorption performance (Fig. 3b). In 2024, sublimation 3D released the newly developed upr-241 functionally graded material 3D printer. The new three-screw two-component single nozzle system realizes the real-time control of composition, mixing and extrusion material composition through three stages. According to the composition design requirements, the double side feeding system can automatically adjust the feed screw speed in real time to realize the composition control of two kinds of feeds. The granular material is used to replace the fine wire, and the mixed printing molding is automatically adjusted according to the gradient design, realizing the gradient continuity change of the material (Fig. 3c).

3.2 Research progress of functionally graded materials prepared by direct writing molding (DIW)

DIW is an advanced additive manufacturing technology. It uses a movable nozzle to eject the printing slurry layer by layer through air pressure, piston, screw and other mechanisms to build a three-dimensional geometric structure (FIG. 4a). The printing slurry here has a broad definition, which can cover colloid, paste, slurry, even the material mixed by adhesive and powder, or the combination of solvent and solute. In order to ensure the printing performance of the printing paste, the rheological properties of the printing paste can be adjusted by adding thickener or diluent to meet the printing requirements. The advantage of DIW technology is its universality, which can be applied to a variety of different materials, including hydrogel, ceramics, metal, concrete and elastomer. Similar to FDM technology, DIW can also realize the gradient change of material composition in the process of 3D printing. By adjusting the process parameters and slurry ratio of different materials, it can realize the manufacture of functionally graded materials with pore gradient and component gradient, so as to meet the diversified material requirements[31-32].

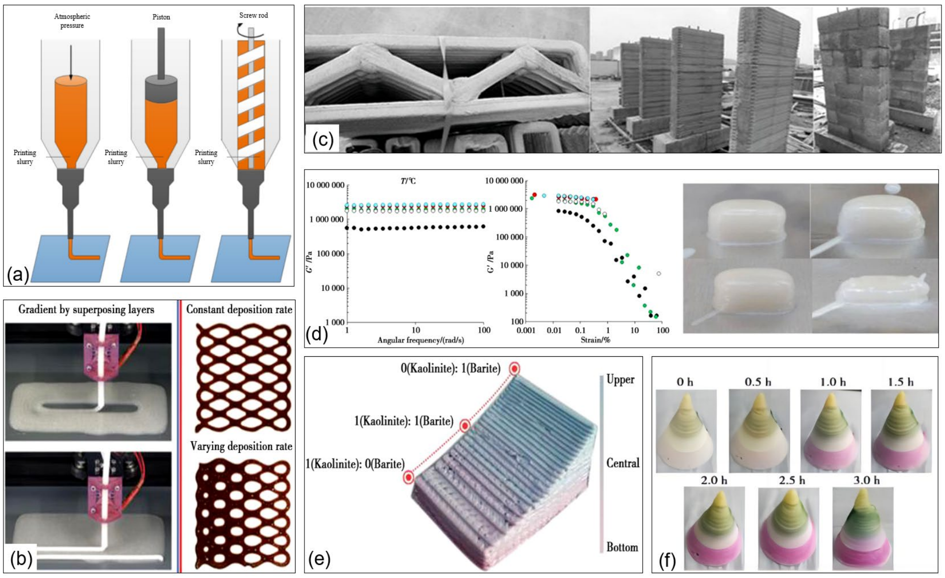

Figure 4: a) Schematic diagram of forming gradient materials using direct writing molding technology; b) Printing photos of samples with multiple layers of gradient materials and different material deposition rates for reinforcing ribs in the middle layer; c) 3D printing of reinforced masonry wall sections and reinforced masonry walls; d) Rheological properties and printing tests of materials prepared with 20% Mg and different contents of plant sterols (M20-20 M20-30、M20-40、M20-50); e) Gradient printing process and model printing effect diagram of kaolin and barite ceramics. f) Multi material 3D printing of purple mashed potatoes/mashed potatoes with different pH values

In the construction field, yangqianrong et al.[33] studied the effect of polymer additives on the rheological properties of 3D printing building mortar in 2020. The results show that the combination of HMC and KHC, FX and KHC in a specific proportion, and the joint incorporation of the three (HMC, FX, KHC) can produce a significant synergistic effect and improve the 3D printing performance of mortar. In the same year, Gejie et al.[34] used a composite slurry containing cement, fiber and organic adhesive, and fused with industrial by-products such as slag and fly ash, and built a shell with cavity structure through 3D printing technology. The vertical reinforcement was inserted into the shell and concrete was poured, and the reinforced masonry wall was successfully made. The experimental results show that the reinforced masonry wall manufactured by this 3D printing technology performs well in structural integrity, and its bearing capacity is twice that of the traditional block reinforced masonry wall under the same conditions (Fig. 4c). In the field of food, Nida et al.[35] transformed the rice husk powder that had no printing ability into a form suitable for 3D printing in 2020 and applied it to the manufacture of biodegradable food packaging materials. By adjusting and adding the optimal amount of guar gum (GG, 1% by mass) as adhesive, the printing stability and supply reliability of the material were enhanced. In the same year, he et al.[36] explored the printing adaptability of mashed potato under different formula adjustments and pH environment changes, implemented the double nozzle collaborative extrusion 3D printing test of purple mashed potato and mashed potato, and created 4D instant food with spontaneous color change characteristics (Fig. 4f). In 2022, cotabarren et al.[37] explored the rheological properties of the mixture of monoglyceride oil base (mg) and phytosterol (PS) with different proportions during the printing process and its impact on the quality of the final product to evaluate the production of nutritional oral preparations (Fig. 4d).

Giachini et al.[38] designed cellulose based materials with similar composition but different mechanical and rheological properties, and achieved the preparation of cellulose based adjustable viscoelastic materials with continuous transition, high contrast and multidirectional stiffness gradient through extrusion type multi material additive manufacturing technology. In addition, the preparation of micro scale pore gradient materials was achieved by using the changes of pores after sintering of different components (Fig. 4b). In 2020, Tang[39] created kaolin barite based ceramic functionally graded materials by using static mixing tube combined with direct writing molding (DIW) technology (Fig. 4e). This study analyzed the key effects of core process parameters such as printing speed, slurry flow rate and layer thickness on the final green body forming quality. The unique evolution of pore structure in sintered samples was revealed by scanning electron microscope observation, that is, from macro scale macropores (pore size more than 1 μ m) to micro scale nanopores (pore size less than 50nm).

3.3 Research Progress on Functionally Graded Materials Prepared by Selective Laser Melting (SLM) Technology

Selective laser melting (SLM) is an additive manufacturing technology that uses laser beam to scan, melt and process the powder on the surface of the powder bed layer by layer according to the model (Fig. 5a). The difference from selective laser sintering is that selective laser melting technology can completely melt the powder, and the green body does not need to be re sintered[40].

In 2020, Zhang et al[41]. used SLM technology to regulate the powder composition in each printing layer to build a composition gradient transition layer between pure copper alloy and glass, realizing a stable connection between the two (Fig. 5b). In the same year, Wei et al[42]. used SLM to prepare ti-5al-2.5sn/ti-6al-4v dissimilar titanium alloy materials. In the deposited and fully annealed States, there is a 70 μ m wide element diffusion zone between the ti-5al-2.5sn layer and the Ti-6Al-4V layer, and the metallurgical bonding quality of the interface is excellent (Fig. 5C). Chen et al[43]. prepared the steel bronze bimetallic structure using SLM and found that insufficient laser energy input density would lead to incomplete melting of the interface layer, resulting in holes and horizontal cracks. On the contrary, too high laser energy input density will lead to vertical microcracks and pores. Shiyusheng et al. [44] used selective laser melting technology to produce gradient lattice structure parts with continuous gradual change of structure and composition by replacing aluminum matrix composite powders with different proportions layer by layer, and the composition gradient showed the characteristics of vertical transition. Wei et al[42]. prepared ti-5al-2.5sn/ti-6al-4v dissimilar titanium alloy materials by SLM. Under the deposition and complete annealing conditions, there is a 70 μ m wide element diffusion zone between the ti-5al-2.5sn layer and the Ti-6Al-4V layer, and the metallurgical bonding quality of the interface is excellent.

In 2023, Li Xingran et al[45].achieved defect-free integrated forming of Ti6Al4V/NiTi bionic functionally graded materials using SLM technology, obtaining a defect-free interface structure and excellent mechanical properties. It was found that the heterogeneous metal materials exhibited a non-uniform structure composed of various grain morphologies and irregular eutectic structures, mainly consisting of titanium-rich and nickel-rich solid solutions and (Ti, Ni) compounds. The evolution law of the microstructure of different deposition layers in bionic functionally graded materials was revealed (Figure 5e).

In 2024, He Xin et al[46]. prepared CuSn10/AlSi10Mg functionally graded materials using SLM and studied the effect of material composition ratio on the microstructure of the CuSn10/AlSi10Mg transition layer. The results showed that the main reason for macroscopic cracking in the transition area is the high volume change (4.4%) caused by the directly generated Al4Cu9 phase, which tends to form stress concentration first in the 0-20% AlSi10Mg area, initiating microcracks; the high volume change

(4.3%) caused by the transformation of Al2Cu phase and excess copper in the matrix into Al4Cu9 phase (indirectly generated) further aggravates stress concentration and causes macroscopic cracking in the 80% AlSi10Mg area (Figure 5d).

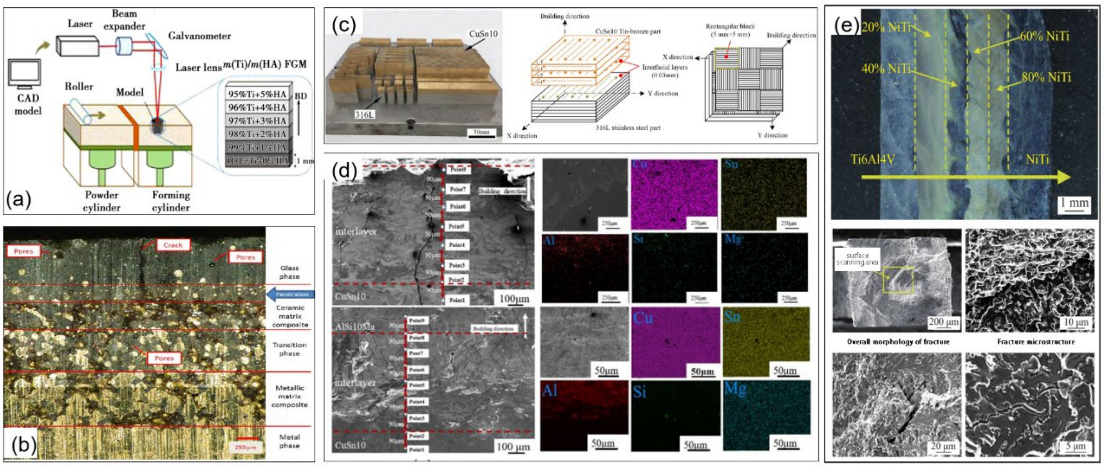

Figure 5: a) Schematic diagram of gradient material formed by selective laser melting; b) Observe the cross-sectional view of the gradient structure using a VHX-500F optical microscope; c) Schematic diagram of 316L/CuSn10 multi material bimetallic structure formed by Dimental-300 and interlayer staggered scanning strategy and island scanning strategy; d) Schematic diagram of EDS point scan position in the transition zone and EDS surface scan element distribution map in the fusion zone of the sample interface]; e) Cross sectional morphology of Ti6Al4V/NiTi BFGM and SEM morphology of tensile fracture of Ti6Al4V/NiTi BFGM

3.4 Research Progress on the Preparation of Functionally Graded Materials Using Electron Beam Melting (EBM) Technology

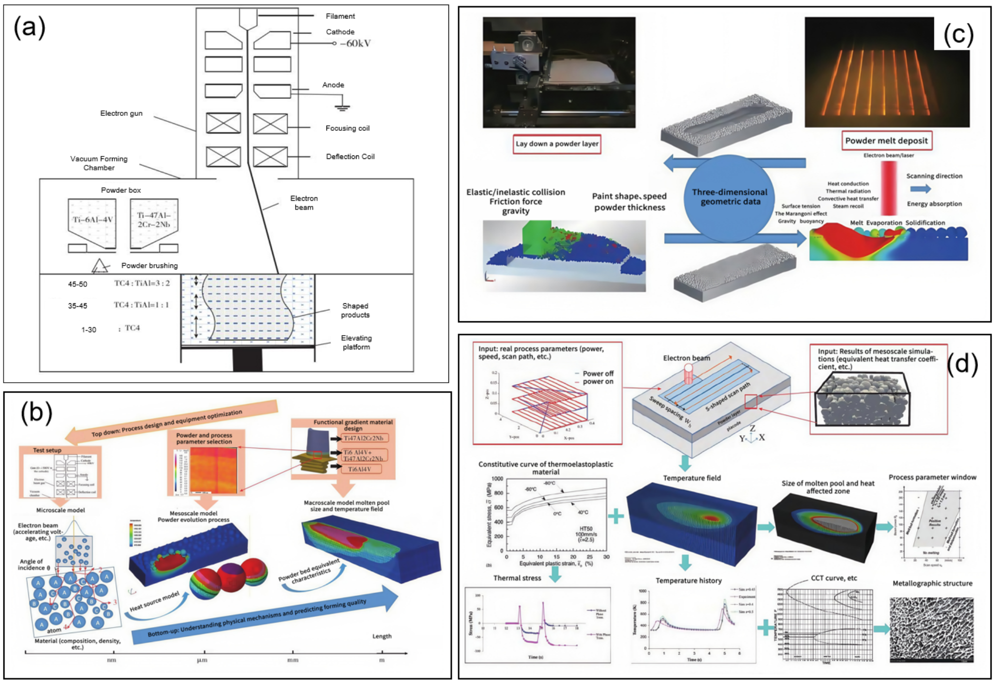

Figure 6: a) Schematic diagram of electron beam selective melting equipment for formable gradient materials; b) Schematic diagram of multi-scale and multi physics field model for electron beam selective melting process; c) Microscopic scale selection melting whole process model; d) Macro scale Part Forming Process Model

Electron beam melting (EBM) refers to the additive manufacturing technology[47] that uses the electron beam to scan the powder material according to the model section in the vacuum environment to melt it and deposit it layer by layer to form a three-dimensional entity (Fig. 6a). In 2015, Tan et al[48].

prepared Ti6Al4V alloy by electron beam melting technology. Through scanning electron microscope observation and analysis of its microstructure characteristics, it was found that with the increase of printing height, the morphology of primary β grains experienced a significant transformation from equiaxed to columnar. This morphological change affects the mechanical properties of the material, which is manifested by the increase of yield strength, ultimate tensile strength and hardness, while the elongation of the material decreases accordingly. In 2017 (Figure 6cbd), Yan Wentao et al.[49] constructed an advanced multi-scale and multi physical field model based on EBM (electron beam melting) technology. The model achieves a comprehensive coverage from micro to macro: the interaction between electron beam and material is accurately simulated at the micro level; At the meso level, the behavior of the material in the complex process of heating, melting, flowing to solidification is displayed; At the macro level, the complete process of constructing functionally graded materials by layer by layer deposition is simulated. This multi-scale model can be used to predict the processing process and results of functionally graded materials.

Electron beam melting (EBM) technology can produce functionally graded materials (FGMs) with metal, polymer, ceramic and other components. It has the advantages of high molding efficiency, good repeatability, no support for parts, and high green body strength. However, due to the molding principle and powder preparation cost, the gradient layer is less, which is not conducive to the elimination of interface stress, and the remaining powder is difficult to recycle after preparation, which is easy to cause material waste. However, the support is not needed to be considered in the process of optimizing the porosity of materials, which helps to adjust the strength, elastic modulus and other properties of materials through the design and preparation of complex pore gradients.

3.5 Research progress of functionally graded materials prepared by arc additive manufacturing technology (waam)

The arc additive manufacturing technology (waam) uses the surfacing principle to deposit metal layer by layer on the substrate to form components with preset shapes. These components are composed of all weld metal, with compact structure, balanced composition and excellent mechanical properties (Fig. 7a) [50]. Gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and plasma arc welding (PAW) are often used in waam technology. Due to its advantages of high flexibility, high integration, efficient deposition, high material utilization, low cost and efficient production, waam technology shows great development potential [51]. In recent years, a variety of deposition methods, such as single arc+single wire, single arc+multi wire, multi arc+single wire, and multi arc+multi wire, have emerged, especially the heterogeneous welding wire waam, which provides greater flexibility and deposition efficiency for the preparation of gradient materials.

In 2014, Xiong et al.[52] introduced the auxiliary wire filling technology on the basis of the traditional GMAW system. By adjusting the proportion of wire filling, the precise control of the composition of deposited metal was achieved, and the materials with gradient characteristics were prepared. In 2016, Shen et al.[53] prepared Fe FeAl functionally graded materials by using GTAW arc technology and variable proportion of iron wire and aluminum wire feeding process. The material shows a gradient change in hardness and tensile strength in the vertical dimension, that is, from 150hv and 39.5mpa at the bottom to 650hv and 145mpa at the top. Takeyuki et al.[54] used the "double arc+dissimilar double welding wire" technology, using ni6082 and ys308l two kinds of welding wires, under the cooperative operation of two GMAW equipment, realized the alternate deposition of welding wire materials, and prepared functional gradient materials. In 2020, Huang Jiankang and others[55] focused on the arc additive manufacturing of titanium alloy gradient materials, using TIG arc as the heat source and adding an appropriate amount of nitrogen in argon protection to realize the in-situ formation of tin reinforcement phase. By dynamically adjusting the ratio of nitrogen and argon, the content and distribution of tin strengthening phase in each region of the part were controlled. In 2022, Ayan et al.[56] used gmam technology to prepare gradient metal materials by combining ER70S-6 low alloy steel and 308lsi austenitic stainless steel wire. The analysis of microstructure and mechanical properties showed that the interface was flawless. Compared with the single material manufacturing, the tensile strength was significantly increased by 46%, and the horizontal fatigue limit was 25% higher than the vertical (Fig. 7b). Miao et al.[57] prepared Cu Ni gradient thin-walled structure through bypass current plasma arc welding technology. It is found that this technology not only improves the forming accuracy, but also significantly reduces the transverse component fluctuation in the gradient layer. The mechanical properties of TA1/Ti6Al4V Inconel 625 FGM were revealed by the research of Lianzhong in 2023[58]. Compared with TA1 Inconel 625 FGM, the minimum microhardness of Ti6Al4V Inconel 625 FGM is 108.72% higher, reaching 370hvo.2, showing stronger deformation resistance. Its comprehensive compression performance is also better, which is attributed to the less NiTi2 phase in Ti6Al4V Inconel 625 FGM. Therefore, Ti6Al4V is more suitable for the preparation of titanium nickel FGM (as shown in Figure 7cd).

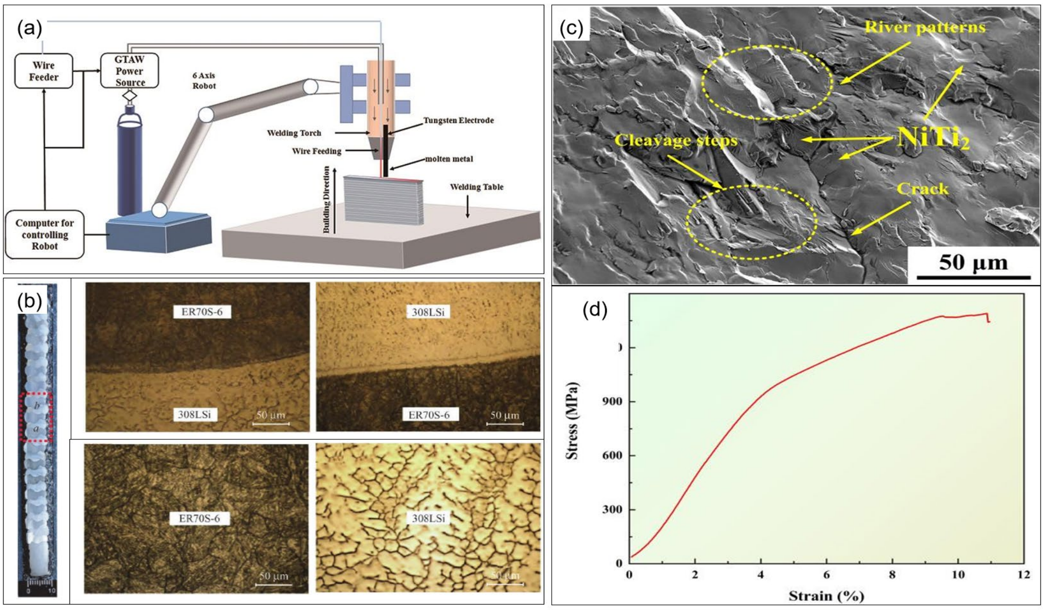

Figure 7: a) Schematic diagram of preparing functionally graded materials using arc additive manufacturing technology (WAAM); b) Microstructure of alloy steel/stainless steel gradient materials; c) SEM image of the microstructure of the fracture surface of the compressed specimen; d) Engineering stress-strain curve of vertical compression specimen of Ti6Al4V Inconel 625 FGM

4. Conclusion and Prospect

(1) Additive manufacturing technology, as a new way for the preparation of functionally graded materials, currently focuses on experimental research, mainly covering process optimization, organization regulation, gradient structure improvement, forming mechanism, trajectory design and optimization and other dimensions. Optimizing the accuracy of material design, realizing the simple and controllable preparation process, constructing the accurate structure and trajectory planning strategy, integrating the existing additive manufacturing technology and equipment, realizing the "short process of material/structure/shape integrated forming" formed by the control of material organization and forming process at one time, and forming the large-scale, energy-saving, industrialized and low-cost additive manufacturing and preparation technology are the key to the development of FGM industrialization technology.

(2) Strengthen the research on basic scientific problems in the process of additive manufacturing such as structure and phase transformation, pores and cracks, stress concentration, etc; At the same time, combined with the application of auxiliary composite field (ultrasonic, electromagnetic and force) with other methods, the microstructure gradient and forming can be accurately controlled.

(3) Strengthen the integration and application of artificial intelligence technology, numerical simulation, machine learning and computer technology, focus on meeting the needs of service in special environment, integrate the core links such as "structural design - alloy composition - Model Construction - Method Selection - path planning - process parameters - quality monitoring", design the optimal combination of process parameters, so as to shorten the development time, and prepare FGM products suitable for multidimensional complex environment and with multiple functions. Promote the application of functionally gradient materials in more fields.

References

[1] Mahamood R M, Akinlabi E T, MWahamood R M, et al. Types of functionally graded materials and their areas of application[M]. Berlin, German: Springer International Publishing, 2017: 9-21.
[2] Mondal K, Nuñez L, Downey C M, et al. Recent advances in the thermal barrier coatings for

extreme environments[J]. Materials Science for Energy Technologies, 2021, 4: 208-210.

[3] Mallick A, Setti S G, Sahu R K. Centrifugally cast functionally graded materials: fabrication and challenges for probable automotive cylinder liner application[J]. Ceramics International, 2022, 49(6): 8649-8682.

[4] Johari N, Rafati F, Zohari F, et al. Porous functionally graded scaffolds of poly(ε-caprolactone)/ZnO nanocomposite for skin tissue engineering: morphological, mechanical and biological evaluation[J]. Materials Chemistry and Physics, 2022, 280: 125786.

[5] Zhang G, Li P, Wang X, et al. Flexible battery-free wireless sensor array based on functional gradient-structured wood for pressure and temperature monitoring[J]. Advanced Functional Materials, 2023, 33(2): 2208900.

[6] Lim H, Kim H S, Qazi R, et al. Advanced soft materials, sensor integrations, and applications of wearable flexible hybrid electronics in healthcare, energy, and environment[J]. Advanced Materials, 2020, 32: 1901924.

[7] Bartlett N W, Tolley M T, Overvelde J T, et al. A 3D printed, functionally graded soft robot powered by combustion[J]. Science, 2015, 349(6244): 161-165.

[8] Yootaek Kim, Jun-Tae Choi, Jong Koen Choi,, et al.Effect of source gas composition on the synthesis of SiCC functionally gradient materials by CVD[J].Materials Letters,1996,26(4-5) 249-257.

[9] Ero011Flu, S., Birla, N.C., Demirci, M. et al. Synthesis of functionally gradient NiCr-AL/MgO-ZrO2 coatings by plasma spray technique[J]Journal of Materials Science Letters 12, 1099–1102 (1993).

[10] Neubrand A,Becker H,Tschudi T.Spatially resolved thermaldiffusivity measurements on functionally graded materials[J].Journal of Materials Science,2003,38(20):4193-4201.

[11] Yang Sen, Zhao Jinlan, Yang Xin. Research Status of Gradient Functional Coatings Prepared by Laser Cladding[J]. Laser Technology, 2007, 31(2): 220-224.

[12] Li Jian, Chen Tijun, Hao Yuan, et al. Preparation of Al_3Ti/Al in-situ Functionally Graded Composite Materials by Centrifugal Casting Method[J]. Hot Working Technology, 2007, (05): 31-34.

[13] CLAUSSEN Kai U, SCHEIBEL Thomas, SCHMIDT Hans-Werner, et al. Polymer gradient materials: Can nature teach us new tricks?[J].Macromolecular Materials and Engineering, 2012, 297(10):938-957.

[14] Suresh S, Mortensen A. Fundamentals of Functionally Graded Materials: Processing and Thermomechanical Behavior of Graded Metals and Metal-Ceramic Composites [M]. London: IOM Communications Ltd., 1998.

[15] Xu Zijie. Study on the Molding of Gradient Phase Structure in Amorphous Polymer-based Composite Systems[D]. Henan Polytechnic University, 2020.

[16] Loh Gh, Pei E, Harrison D, et al. An overview offunctionally graded additive manufacturing [J]. Additive Manufacturing, 2018, 23(23): 34-44.

[17] Xia Xiaoguang, Duan Guolin. Research Progress and Prospects of Additive Manufacturing Technology for Functionally Graded Materials[J]. Materials Review, 2022, 36(10): 134-140.

[18]Mogas-Soldevila L, Duro-Royo J, Oxman N. Water-Based Robotic Fabrication: Large-Scale Additive Manufacturing of Functionally Graded Hydrogel Composites via Multichamber Extrusion[J]. 3D Printing and Additive Manufacturing, 2014, 1(3): 141–151

[19] Weiming J ,Runhua Z ,Priyanka V , et al.Recent progress in gradient-structured metals and alloys[J]. Progress in Materials Science,2023,140

[20] Junyu C ,Binqi L ,Leilei X , et al.Toward tunable mechanical behavior and enhanced elastocaloric effect in NiTi alloy by gradient structure[J].Acta Materialia,2022,226

[21] Xue Dingxi, Yi Bingyao, Li Guojun, et al. Numerical Simulation of Thermal Stress in Functionally Graded Anode Solid Oxide Fuel Cells[J]. Journal of Inorganic Materials, 1-9[2024-07-12].

[22] Chen Yuguang, Tan Hua, Fan Wei, et al. Thermal Behavior and Microstructure of Functionally Graded TC4-TA19 Materials Fabricated by Laser Additive Manufacturing[J]. Foundry Technology, 2022, 43(07): 497-505.

[23] Song W ,Zhao D ,Guo F , et al.Additive manufacturing of degradable metallic scaffolds for material-structure-driven diabetic maxillofacial bone regeneration[J].Bioactive Materials, 2024, 36413-426.

[24] Mahamood R M. Functionally Graded Materials [M]. Switzerland: Springer International Publishing AG, 2017.

[25] Mahamood R M, Akinlabi E T. In: Conference Record of the 2012 World Congress on Engineering [C]. London, 2012: 0966.

[26] Fang Yuan, Su Yunfeng, Zhang Yongsheng, et al. Design, preparation, and performance optimization of zirconia-based functionally graded materials [J]. Journal of the Chinese Ceramic Society, 2016, 44(12): 1729-1735.

[27] Li Qiang, Zhang Fengfeng, Yu Jingyuan, et al. Study on the Mechanical Properties of Gradient Porous Mg-Ca Alloys [J]. Functional Materials, 2013, 44(14): 2032-2035.

[28] Lu L ,Chekroun M ,Abraham O .Mechanical properties estimation of functionally graded materials using surface waves recorded with a laser interferometer [J].NDT & E International: Independent Nondestructive Testing and Evaluation,2011,44(2):169-177.

[29]Garland A, Fadel G. Design and mechanical characterization of functionally graded materials fabricated by dual-nozzle fused deposition modeling [J].Journal of Computing and Information Science in Engineering, 2019, 19(2):123-135.

[30] WU H H,LIU L,CAI Y,et al.A Novel Gradient Graphene Composite with Broadband Microwave Absorption Fabricated by Fused Deposition Modelling [J].Materials Technology,2020,35.

[31] Craveiro F, Nazarian S, Bartolo H, Bartolo P J, Duarte J P. An automated system for 3D printing functionally graded concrete-based materials [J]. Additive Manufacturing, 2020, 33: 101146.

[32] Zhang Jing, Zhou Jing, Duan Guolin. Research Progress on Multi-Material Printing Based on Direct Writing Technology [J]. Materials Review, 2022, 36(08): 220-227.

[33] Liu Qiaoling, Yang Qianrong. The effect of polymers on the rheological properties of 3D printing construction mortar [J]. Journal of Building Materials, 2020, 23(05):1206-1211.

[34] Ge Jie, Bai Jie, Yang Yan, et al. Experimental Study on the Bearing Capacity of Reinforced Masonry Walls with 3D Printing[J]. Journal of Building Materials, 2020, 23(02): 414-420.

[35] Nida S ,Anukiruthika T ,Moses A J , et al.3D Printing of Grinding and Milling Fractions of Rice Husk[J].Waste and Biomass Valorization,2020,12(1):1-10.

[36] He C ,Zhang M ,Guo C .4D printing of mashed potato/purple sweet potato puree with spontaneous color change[J]. Innovative Food Science and Emerging Technologies, 2020, 59, 102250-102250.

[37] Cotabarren I M, Cruces S, Palla C A. Chapter 3 - Development of functional foods by using 3D printing technologies: application to oxidative stress and inflammation-related affections[J]. Food Research International, 2022, 35-55.

[38] Giachini S G A P ,Gupta S S ,Wang W , et al.Additive manufacturing of cellulose-based materials with continuous, multidirectional stiffness gradients[J].Science Advances,2020,6(8):eaay0929.

[39] Tang D ,Hao L ,Li Y , et al.Dual gradient direct ink writing for formation of kaolinite ceramic functionally graded materials[J].Journal of Alloys and Compounds,2020,814, 152275-152275.

[40] Wei C, Gu H, Sun Z, et al. Ultrasonic material dispensing-based selective laser melting for 3D printing of metallic components and the effect of powder compression[J]. Additive Manufacturing, 2019, 29: 100818.

[41] Zhang X, Chueh Y, Wei C, et al. Additive manufacturing of three-dimensional metal-glass functionally gradient material components by laser powder bed fusion with in situ powder mixing [J]. Additive Manufacturing, 2020, 33: 1-20.

[42] Wei K, Zeng Xiao Y, Li F Z, Interfacial microstructure and mechanical properties of 316L /CuSn10 multi-material bimetallic structure fabricated by selective laser melting[J]. Journal of Metals, 2020, 72: 1031-1038.

[43] Chen K Y, Wang C, Hong Q F, et al. Selective laser melting 316L/CuSn10 multi-materials: Processing optimization, interfacial characterization and mechanical property[J]. Journal of Materials Processing Tech, 2020, 283: 116701.

[44] Song Bo, Wang Min, Shi Yusheng. An integrated forming method for a part with a multimaterial gradient lattice structure: CN107774996B[P]. 2020-01-21.

[45] Li Xingran, Liu Zhenglin, Jiang Pengfei, et al. Interface Characteristics and Properties of Laser Additive Manufactured Ti6Al4V/NiTi Bionic Functionally Graded Materials [J]. Transactions of the China Welding Institution, 2023, 44(10): 27-33+134.

[46] He Xin, Luo Xia, Tang Jinguang, et al. Microstructural Evolution and Crack Generation Mechanism of CuSn10/AlSi10Mg Functionally Graded Materials Prepared by Selective Laser Melting[J/OL]. Chinese Laser: 1-20[2024-05-09].

[47] Necati U ,Adem Ç ,Kubilay A .Machinability of 3D printed metallic materials fabricated by selective laser melting and electron beam melting: A review[J].Journal of Manufacturing Processes, 2022,80, 414-457.

[48] Tan X ,Kok Y ,Tan J Y , et al.Graded microstructure and mechanical properties of additive manufactured Ti–6Al–4V via electron beam melting[J].Acta Materialia,2015,97: 1–16.

[49] Yan Wentao, Qian Ya, Lin Feng. Research Progress on Multi-scale and Multi-physics Field Modeling of Selective Melting Process [J]. Aeronautical Manufacturing Technology, 2017(10):50-58.

[50] Tawfik M M, Nemat-Alla M M, Dewidar M M. Enhancing the properties of aluminum alloys fabricated using wire + arc additive manufacturing technique - A review [J]. Journal of Materials Research and Technology, 2021, 13: 754-768.

[51] Lu L, Tian Y, Cai Y, et al. Microstructure and mechanical properties of a functionally graded material from TA1 to Inconel 625 fabricated by dual wire + arc additive manufacturing [J]. Materials Letters, 2021, 298: 130-141.

[52] XIONG J, ZHAN G. Adaptive control of deposited height in GMAW-based layer additive manufacturing[J]. Journal of Materials Processing Technology, 2014, 214(4): 962-968.

[53] SHEN C, PAN Z, CUIURI D, et al. Fabrication of Fe-Fe Al functionally graded material using the wire-arc additive manufacturing process[J]. Metallurgical & Materials Transactions: B, 2016, 47(1): 763-772.

[54] TAKEYUKIAbe, HIROYUKI Sasahara. Dissimilar metal deposition with a stainless steel and nickel-based alloy using wire and arc-based additive manufacturing[J]. Precision Engineering, 2016(45): 387-395.

[55] HUANG J, LIU S, YU SH, et al. Arc deposition of wear resistant layer TiN on Ti6Al4V using simultaneous feeding of nitrogen and wire[J]. Surface and Coatings Technology, 2020, 381(5): 125141

[56] AYAN Yusuf,KAHRAMAN Nizamettin.Fabrication and characterization of functionally graded material(FGM)structure containing two dissimilar steels(ER70S-6 and 308LSi)by wire arc additive manufacturing(WAAM)[J].Materials Today Communications,2022,33:104457.

[57] MIAO Y G, LI CH, ZHAO Y, et al. Material properties of gradient copper-nickel alloy fabricated by wire arc additive manufacturing based on bypass-current PAW[J]. Journal of Manufacturing Processes, 2022, 83: 637-649.

[58] Lu Liansheng. Study on Microstructure and Mechanical Properties of Titanium-Nickel Functionally Graded Materials Fabricated by Twin Wire Arc Additive Manufacturing[D]. Tianjin University of Technology, 2023.