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REVIEW

Review on Characteristic and Mechanical Behaviour of FGMs Prepared by Additive Manufacturing

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Abstract: The functionally graded materials (FGMs) are obtained by various processes. Although a few FGMs are obtained naturally, such as oyster, pearl, and bamboo, additive manufacturing (AM), known as 3D printing, is a net-shaped manufacturing process employed to manufacture complex 3D objects without tools, molds, assembly, and joining. Currently, commercial AM techniques mostly use homogeneous composition with simplified geometric descriptions, employing a single material across the entire component to achieve functional graded additive manufacturing (FGAM), in contrast to multi-material FGAM with heterogeneous structures. FGMs are widely used in various fields due to their mechanical property advantages. Because FGM plays a significant role in the industrial production, the characteristics and mechanical behaviour of FGMs prepared by AM were reviewed. In this review, the research on FGMs and AM over the past 30 years was reviewed, suggesting that future researchers should focus on the application of artificial intelligence and machine learning technologies in industry to optimize the process parameters of different gradient systems.

Key words: additive manufacturing; functionally graded material; manufacturing process; mechanical behaviour; characteristic

1 Introduction

A composite material with variations in the structure and composition throughout the capacity or volume and tailored properties is termed as functionally graded material (FGM) [1–2]. Various FGMs, like bone's spongy trabecular structure, are found naturally in seashells and plants, such as oyster, pearl, bamboo, peristernia incarnate, and cypraecassis rufa[3–4]. The manufacturing idea of metal-ceramic thermally graded phase for the application of thermal barrier and FGMs is intensively investigated. Contrary to isotropic materials, FGMs' structure and composition are accurately considered to tailor the functional properties[5]. This attracts interest from various applications, which include nuclear power, aerospace engineering, biomedical implants, energy absorption, and optoelectronic devices[6–10].

Additive manufacturing (AM), known as 3D printing, is a net-shaped manufacturing process, which is employed to manufacture complex 3D objects without tools, molds, assembling, and joining[11]. AM provides the benefits of design flexibility and can be enhanced for specific geometry requirements/applications in which the composite process/geometries using the processes of conventional manufacturing (CM) are more expensive, time-consuming, and challenging to manufacture. At present, the rapid advancement of AM techniques is not constrained anymore to the single-phase materials (SPMs). Functional graded additive manufacturing (FGAM) is to generate the multi-phase materials (MPMs) along with steady variations in structure and composition. It signifies layer after layer fabrication, which can steadily alter the composition of material and composition inside a component to attain the anticipated functionality[2]. FGAM can generate three kinds of materials, which are a SPM along with gradual variants in density (in the cellular functionality graded structures), MPM along with gradual variants in the composition of material, and amalgamation of gradual variants of both material and density composition.

By spatial variants of composition and density, flexible FGMs can be obtained by AM using multiple functions, namely graded thermal, mechanical, magnetic, and captivating energy effects, which are presently inaccessible through CM

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procedures. Mostly, FGAM workflow involves numerous stages, comprising modelling (material modelling, microstructural design, and geometrical modelling), followed by slicing, and then simulation, on-site characterization, and at last, performance analysis. Still, there are many challenges in each step of FGAM techniques. For instance, due to the greater incidence of external or internal defects and bad dimensional control, there is a difficulty in regulating the operational variables. Moreover, the quality of the fabricated fragments has a great difference between diverse types and batches of machines[12]. The delivery hustle, accuracy, and swapping material effectiveness among layers should be constantly enhanced to fabricate FGAM components with refined internal structures and composition precision delivery at the micro/nanostructural level[13].

Currently, commercial AM techniques mostly use homogeneous composition with simplified geometric description, employing a single material across the entire component to achieve FGAM, in contrast to multi-material FGAM with heterogeneous structures. Additional limiting factors, namely FGAM materials, products, and processes, are required for higher precision in onsite methods for characterization, for instance, real-time and in-situ AM monitoring employing acoustic emission, in-situ synchrotron XRD in the time of laser melting, and solidification and camera imaging in high speed[14–16]. Besides, using traditional design methods restricts the capacity to creatively use the full competencies of FGAM. Even though a reputable modelling design for variable property gradient printing is available, there is still a need to improve the process and protocols to achieve more predictable and reliable product results, particularly regarding the material distribution, constituent stage, and properties of variables all over the fabricated structures[17].

The characteristics and mechanical behaviour of FGMs prepared by AM were reviewed. The characteristics, properties, applications, and fabrication of FGM, AM-prepared for FGM, and influence of AM on microstructure, mechanical strength, and behaviour of FGM were discussed. The review recommends future researchers for creating new FGM combinations, which are useful for various application requirements like pneumatic applications, and testing new FGM combinations under various testing parameters, like tension, impact, yield, elongation, and vibration.

2 Properties and Applications of FGM

FGM has been developed primarily for the application of thermal barriers. Recently, however, FGMs have begun to be used in many applications, including high abrasion resistance areas, high penetration resistance areas, the mineral processing industry, flame retardant, and ballistic applications. There are several types of gradients in FGMs, which include microstructural gradients, material gradients, and porosity gradients. The notion of this concept was developed in the late 1970s in Japan. The new material concept involving class of CM was anticipated, decreasing the stresses generated by conventional liquid composite molding (LCM) due to thermal factors when using recyclable rocket engines. FMGs are categorized according to the gradual change of material structure or composition in the structural direction. FGMs with a graded microstructure can be realized in the overall material by changing the composition of the material in terms of microstructure.

FGM was conceptualized for the first time in Japan during the space plan proposal for the applications of thermal barriers. The necessary composite material must be able to endure a surface temperature of 2000 K and a temperature gradient of 1000 K with a cross-section of less than 10 mm. The continuous failures involving the conventional LCM were verified during the research period. It was found that this has happened due to the unsuitable adhesion of sharp interfaces of LCM and the unequal characteristics possessed by those two materials. This issue was resolved by swapping these sharp interfaces along with the slowly modifying interface, which can help remove the sites in an aspect of a high stress concentrations. As a result, this led to the improvement of materials design with some special features, such as improved wear resistance, increased tensile strength, and higher Young's modulus value.

FGMs with their unique mechanical properties provide various benefits for various substances, which are vulnerable to risky conditions, and are once equated to the traditional composite material. FGM is a significant research domain, and it has attracted much attention of scholars in the last few years, with the application area of this innovative material continuously increasing. Constantly controlling microstructure control in a material to modify the properties and functions of the material is also a goal constantly pursued by the research community. The properties of natural FGM have been the driving force for improvement of this artificial FGM. A natural FGM is wood, which is made up of cellulose in a lignin matrix. Other types of FGMs originally comprise the mollusc shells with the exoskeleton of arthropods, hierarchically structured ligaments with mineralized fibrous chitin and based on nano-composite materials with hierarchically organized tissues, spider fangs that act like hypodermic needles, and narwhal teeth with hierarchically cemented dentin junctions.

FGMs have been extensively investigated for biomedical applications, like in orthopaedic implants, dental restorations, and other medical instruments. The nature lessons have been implemented greatly to resolve several engineering issues. Functionally graded bulk materials as well as FGM coating are studied for the required properties under risky conditions to improve the service life of engineering components[18].

2.1 Properties of FGM

The most significant FGM application is in the skin of hypersonic aerospace and supersonic vehicles, which should have appropriate properties to endure the mechanical and thermal loadings. Metals have been utilized in this domain for several years due to their excellent toughness and strength. However, the metal strength decreases after exposure to extreme temperatures for a period of time. To withstand the high temperature, the metal surfaces are typically coated with heat proof materials directly. For instance, the space shuttle uses ceramic tiles as the thermal protection to prevent heat produced during return to the Earth's atmosphere.

However, as these ceramic tiles are laminated to the superstructure of the vehicle, they are susceptible to matrix cracking because of the variation in thermal enlargement coefficients between the superstructure and tiles. The properties of plates are anticipated to be graded in the thickness direction, corresponding to a simple power law distribution of the constituent volume fractions. Certain numerical instances are given to display the impacts of several factors on the static bending of FGM plates. The material properties and the constituents' volume fractions are anticipated to differ only in thickness direction. To measure the accuracy of current formulations, the deflections attained by the current sinusoidal plate theory are equated with the existing outcomes in literature acquired by the boundary element approach, finite element, and series method[19].

FGM is an inhomogeneous, advanced composite material with constant modification of properties in any predefined direction and the volume fractions of constituent materials. Constant altering of properties would effectively avert the stress concentration that is seen in fibre-reinforced or conventional laminate composites. The best thermal features of the ceramic constituent enable these FGMs to endure the high-temperature environment, when the metal constituent gives the needed mechanical strength against catastrophic fracture[20].

Aluminium Die Cast-14 (ADC-14) is reinforced with silicon nitride. Post-fabrication, microstructure test, hardness test, tensile test and compression test were done to verify the gradation of FGM. It is found that the outer region of ADC-14 has higher hardness, ultimate tensile strength, and compression strength compared with the inner region[21].

2.2 Applications of FGM

Ref. [22] showed various combinations of FGM in different fields, such as biomedical engineering, defence, nuclear energy, semiconductor, and cutting tools. Fig. 1 shows application fields of different FGMs. These are used in many different applications with strict operating conditions. For instance, resistant lining is provided for handling heavy and large abrasive particles in the mining sector, heat engine components, heat exchanger tubes rocket, heat shields, and thermo-electric generators. In nuclear reactor plant and in the electrical insulating applications, plasma-facing fusion reactors are provided. FGM also reduces the discrepancy of thermo-mechanical properties of bonded metal-ceramics, thus preventing debonding. The demands for FGM include mechanical, chemical, and thermal properties, and FGMs must also be sustainable for working under serious conditions. These possible applications include engineering and structural uses for incompatible functional combinations, like toughness and hardness.

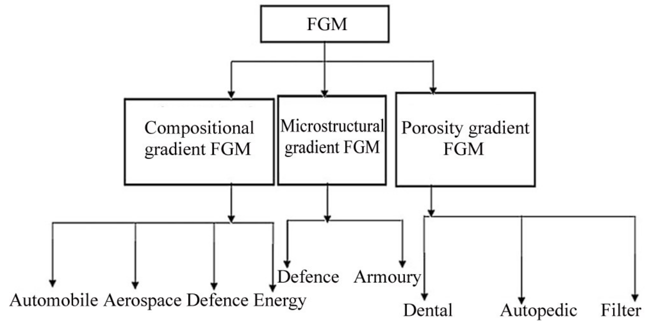

Fig.1 Application areas of different FGMs[23]

(1) Aerospace industry

The structures and equipment used in the aerospace are made of FGM, which include spacecraft truss structures, components of rocket engine, heat exchange panels, and others like camera housing, solar panels, reflectors, nose caps, turbine blade coatings, space shuttles, and missiles at the leading edges. FGMs are also used in the structural walls, which link the sound insulation and thermal properties[24].

(2) Automobile industry

FGMs are used in diesel engine pistons, engine cylinder liners, the springs of leaves, spark plugs, drive shafts, flywheels, combustion chambers, window glass, shock absorbers, certain parts of car body, and racing car brakes. Additionally, FGM can enhance the body coatings in cars, including the sorted coatings containing the particles, like mica/dioxide[25].

(3) Biomedical industry

As most of FGMs are available naturally, they are mostly used in the field of biomedicine, such as implants. FGMs with porosity gradient are used when they intend to replace the body parts. For instance, FGMs with porosity gradient are used in the implants for replacement of permanent skeleton and reduction the stress shielding[26]. The dental implants possessing gradient porous titanium likewise help to enhance the properties involving the implantation of osseointegrations[27–28]. The porous graded hydroxyapatite mimics the bimodal structure in the bones of humans (cancellous and cortical) that helps in surging the growth of new tissue, and also enhances the mechanical property of FGMs[29].

(4) Defence industry

Various types of FGMs are required in the defence sector. This is because it is required to enhance the equipment used in this particular sector. Applications of FGMs in the field of energy contain the inner walls of nuclear reactors, solar panels, thermo-electric converters utilized for the conversion of energies, tubes, pressure vessels, solar cells, and graded electrodes for producing the fuels of solid oxides. And FGMs possessing the piezo-electric characteristics can be used for the ultrasonic transducers, turbine blade coatings, dielectrics, fuel cell, and the coatings involving the thermal barriers[30].

(5) Electrical and electronic application

FGMs are used in the field of electronic and electrical sectors in many ways, which include stress relaxation in the electrodes, the interfaces of diode field-spacers, semiconductors, insulators, and production of sensors. The elements, which are used in thermal-shielding processes in the field of micro-electronics, are likewise prepared from the nanotubes of carbon FGM[31].

The natural model of a crane pneumatic distributor with the drive from the electric step motor is created and tested. Tests confirmed operability of model. The pilot unit on the basis of the pneumatic FGM-9C robot with application of the offered control system is developed, and the pilot studies of its dynamic characteristics are conducted. The positioning error of the robot action at operating load of 0.1 kg is about 0.14 mm (or 0.11%) with a fiducial probability of 0.993[32].

By direct laser metal deposition technique and using stainless-steel 316L and Inconel 718 powders as raw materials, Ghanavati et al[33] prepared continuous-component and gradient-component FGMs with a gradient from 100% stainless-steel 316L to 100% IN718. By directed energy deposition technique and using TC4 powder as the raw material, Zhang et al[34] obtained solid-solution-enhancement FGMs by changing the composition of the shielding gas. The powder carrier gas was changed from Ar to N_2 to produce titanium nitride (TiN) with high hardness when depositing the enhanced region of titanium alloy. Titanium alloy (TC4) FGMs were fabricated by wire arc additive manufacturing (WAAM) with different contents of TiN strengthening phase in different parts of the structure, which was controlled by the percentage of N_2 in the Ar shielding gas. Continuous-component FGMs with a gradient from Fe to Fe-Al with aluminium content from 0% to more than 50% were fabricated. It was found that the large columnar Fe-rich grains were present at the bottom, the equiaxed Fe-rich grains were present in the upper section, and lump-shaped Al-rich grains were present at the very top section. Moreover, the grains in the sample showed an epitaxial growth trend[34].

3 Fabrication of FGM

Fabrication methods of FGM can be classified as liquid-based method, gas-based method, and solid-based method. The gas-based methods are differentiated as thermal spray process (TSP), chemical vapour deposition (CVD), and surface reaction process (SRP). The solid-based methods are categorized as powder metallurgy (PM) and spark plasma sintering (SPS). The liquid-based methods contains centrifugal casting process (CCP), electrophoretic deposition, chemical solution deposition (CSD), and slip casting process (SCP) [35]. FGMs are synthesised by three-layered system AA7075-B4C by plasma activated sintering[36], and the three point bending shows high bending strength without cracks. Al_2O_3 five-layered FGM with FeCrAl alloys has high-temperature properties in their applications[37]. NiCr-partially stabilized zirconia (NiCr-PSZ) FGM has been equipped with four-layered grading[7], and PSZ increases the bending strength of NiCr by 20%, which is twice as much as that of pure Ni. As the hardness increases, PSZ composition is also improved. The radical cracking problems are seen in the Al_2O_3-rich region due to high residual stresses. The addition of ZrO_2 has intermediate characteristics of thermo-mechanical properties, which prevents the cracking and strengthens the component[38].

CVD is applied to form FGM coating of silicon carbide (SiC) in the graphite[39]. There is a continuous conversion of SiC in graphite. A mixed gas source (CH_4-$SiCl_4$-H_2) with controlled composition is used at a deposition temperature of 1400–1500 °C and the pressure of 1.3–6.5 kPa.

3.1 Solid-based methods

(1) PM

PM method is one of the viable, old, and the most appropriate manufacturing processes for constructing engineering components, and it is now also used to prepare FMGs[40]. To fabricate FGMs by PM technique, many phases are included in the powder preparation, involving forming functions (ramming and stacking of the previously mixed powders), processing powder (mixing and weighing of the powder with the previously designed spatial distribution as operational requirement), and ultimately pressure-aided or sintering hot associations relying on the service requirements of FGMs[41].

The stages of FGM production using PM method are shown in Fig. 2. Generally, various processes are utilized for the powder preparation, comprising the electrolytic deposition, chemical reaction, solid-state reduction, atomization, centrifugal grinding, and disintegrating. For processing the powder, the key concern is to focus on the accuracy in amounts weighing and the mixed distribution of powders. In other words, these aspects will impact the structural properties and must be managed in a very precise way. The formation process includes compacting powder into a geometric shape, which is finished at room temperature[42]. Processing factors, such as time, temperature, and pressure, have a very significant effect on the properties of FGMs fabricated by PM technique. Because of lower cost, broad control of microstructure and composition, easy operation, less energy required for combustion, manageable properties, and less processing time, various studies on PM technique to fabricate FGMs structures and composites have been done[43–46].

(2) SPS

Fig.3 shows schematic diagram of SPS equipment, Chen et al[47] studied that the Mo and aluminium nitride (AlN) can be utilized for the fabrication of Mo/AlN FGM by SPS technique. Results showed that the Mo/AlN FGM is effectively prepared by SPS without cracks and delamination

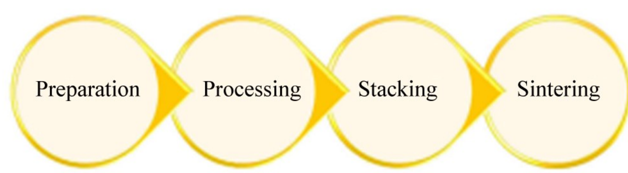

Fig.2 Stages of FGM production using PM method

in the graded layers. The mechanical properties of Mo/AlN FGM are accurately linked to the value of composition exponent, and the disparity of mechanical properties in Mo/AlN FGM can be attributed to metal/ceramic interface, porosity, and distribution of two components. Additionally, two FGM cemented carbides (Al_2O_3-TiC with WC-Co and Al_2O_3-ZrO_2 with WC-CO) have been fabricated by Bertolete et al[48] in six layers with high wear resistance and high toughness. The most significant outcome confirmed that FGMs can substantially enhance the flexural strength and expand the application domain of ceramics.

3.2 Gas-based methods

(1) CVD

Various CVD techniques are used to provide a thin film material. Basically, the vapour deposition is classified into two categories, which are chemical vapour composition and physical vapour composition. CVD technique is utilized in fabricating the coatings as well as thin films for FGM. FGM is fabricated with chemical composition gradient, deposition temperature, gas ratios, gas pressure, gas type, and flow rate, which can be changed according to the requirement of circumstance[49]. The enhanced CVD methods combine processes such as plasmas, photons, ions, lasers, hot filaments, and combustion reaction, thereby increasing the deposition rates and decreasing the deposition temperature[50]. The advantages and disadvantages of CVD are illustrated in Fig. 4[51–52]. There are many advantages in CVD method to fabricate FGM[53–54].

(2) TSP

Generally, TSP is an old method, which originated in the patents of Max Ulrich Schoop, between 1882 and 1889. Schoop applied a patent for the electric arc spray in 1908, which allowed spraying more materials. The enhancement of the technique did not occur after World War II. In this era, the powdered spray and plasma spray have been

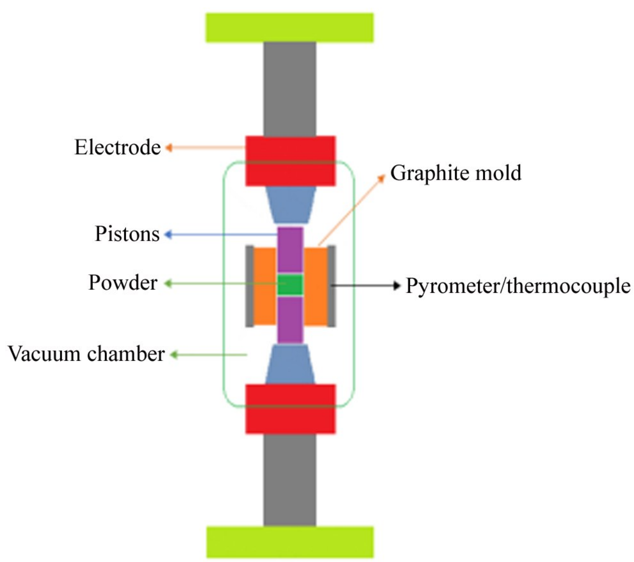

Fig.3 Schematic diagram of SPS equipment

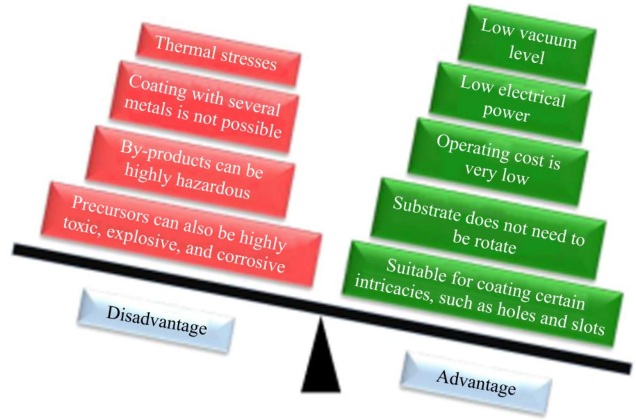

Fig.4 Advantages and disadvantages of CVD[51–52]

acquainted. After this period, various enhancements are made[55], whereas the conventional operating principles are unchanged[56–60]. TSP is the coating process for non-metallic and metallic coatings. TSP methods are classified into flame spray, plasma arc spray, and electric arc spray, which can heat the coating material to semi-molten or molten state. The resulting heat particles are propelled and quickened to fix the surface by gases or atomization jets. A bond is formed between obtained particles, which increases the thickness and forms the lamellar surface[61]. Fig. 5 shows the schematic diagram of TSP method.

(3) SRP

SRP, like carburizing and nitriding, is used frequently in surface treatments of steels and other metals[62–64]. The process of diffusing nitrogen into the steel surface at the temperature between 495 and 565 °C is called nitriding. Atomic nitrogen generated on the steel surface subsequently diffuses internally. The process of hardening the steel surface by nitriding is the commercial process in the earlier stage. This growth is based on nitriding. The toughened surfaces are achieved without any modification or changes in the material properties. There are several processes to form nitrides in various alloys, and there have been several experimental reports on this process[65]. The schematic diagram of low-

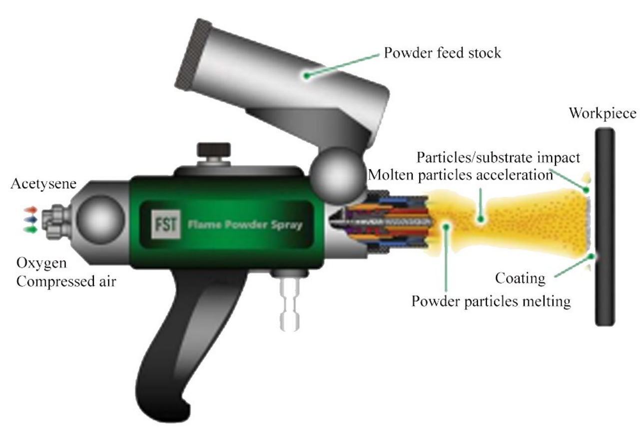

Fig.5 Schematic diagram of TSP method[60]

temperature plasma nitriding process is shown in Fig.6.

3.3 Liquid-based methods

(1) CCP

A casting process mainly used to adjust the cylindrical parts production is termed as CCP. In spinning, the molten metal is discharged until the metal solidifies and the spinning process continues[66]. FGM is formed by spinning the mould using gravity. Alternatively, during the centrifugal casting of metal-based FGMs, in order to obtain a uniform mixture, the reinforcement phase is mixed with molten metal. The reinforcement segregation of particles and liquid is the result of centrifugal or gravitational forces. There is a design gradient in the chemical composition by monitoring the process of solidification[67]. Generally, FGM fabrication based on the process of centrifugal casting is differentiated into 2 types: centrifugal solid particles and in-situ centrifugal technique[68]. During the centrifugal solid particles method, the dispersed phase remains unchanging in liquid matrix. In the in-situ centrifugal method, the centrifugal force is functioned during the solidification process in both dispersed phase and matrix. Moreover, these two types of CCP processes are based on the distinction between the master-alloy temperature and processing temperature. When the processing temperature is greater than the master-alloy temperature, it is termed as in-situ centrifugal method, and the centrifugal forces are used for solidification process. When the master-alloy temperature is higher than the processing temperature, the molten metal remains solid in the next phase, and this technique is called centrifugal reliable particle method. Fig. 7 shows the schematic diagram of CCP[69].

(2) SCP

SCP is cost-effective and colloidal for the fabrication of engineering ceramics and composites. Further, FGMs in aqueous suspension use draining water and porous mould from the green body slurry, which is ready for the sintering process[70]. This process fabricates the product with high density and fine performance. The vital factors concerned in

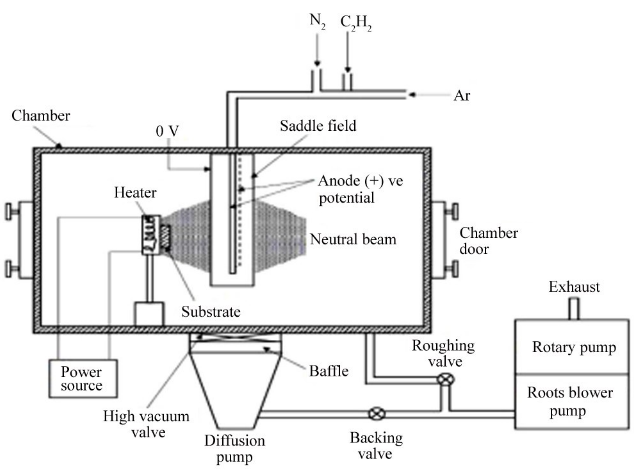

Fig.6 Schematic diagram of low-temperature plasma nitriding process[65]

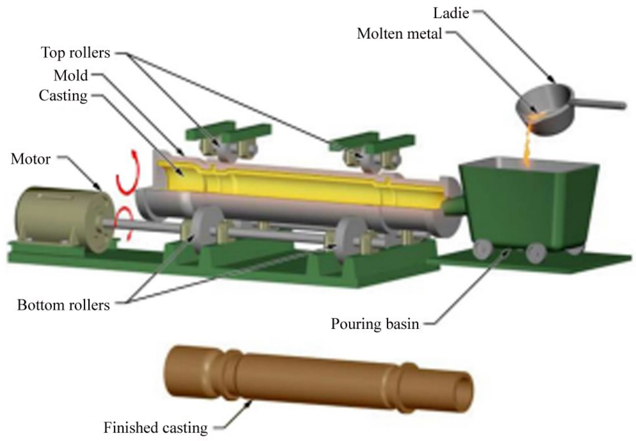

Fig.7 Schematic diagram of CCP[66]

this process are particle distribution, particle size, morphology and shape of the particle, inner particle force, and volumetric solid content. The pH values and stabilization using dispersant should be optimized and controlled[71].

(3) CSD

CSD process has been developed as an advanced system to create functional oxide thin films due to its numerous advantages. However, in CSD method of sol-gel type, the improvement of glass dates' optical coatings was made during the 1950s, and the principal chemical solution was used to deposite electronic oxide thin films, which were complex and prepared during the 1980s[72].

3.4 CPS

CSP is a leading-edge method for synthesizing a wide variety of advanced materials, including powders and near-net-shape products of ceramics, intermetallic, composites, oxides/non-oxides, and FGMs[73]. Through the scientific studies conducted by Boro and Merzhanov, the initial published work on CSP was related to Booth in 1953. Volume combustion synthesis (VCS) and self-propagating high temperature synthesis (SHS) are two possible manifestations of CSP. Then, to initiate the exothermic reaction, the specimens are heated externally by either uniform VCS or local SHS. There are three types of CSP methods depending on the chemical nature, which include gas-less CSP, gas-solid CSP, and reduction CSP.

3.5 WAAM

WAAM has attracted significant attention in industry and academia due to its ability to capture the benefits of AM for production of large components with medium geometric complexity. Uniquely, WAAM combines the wire and electric arc as a fusion source to build components in a layer-by-layer approach, both of which can offer significant cost savings compared to powder and alternative fusion sources, such as laser and electron beam, respectively. Meanwhile, a high deposition rate is provided, which is the key for producing such components and is significantly material-saving, compared to CM processes. However, high quality production in a wide range of materials is restricted by the elevated levels of heat input, which poses a number of challenges for materials by WAAM. Compared with directed energy deposition (DED), a major benefit of WAAM process relates to the low capital investment, as the components of a WAAM machine may be derived from open-source equipment, sourced from an array of suppliers in the mature welding industry. The effectiveness of DED in manufacturing these parts can be attributed to unconstrained build volumes and substantially higher deposition rates than alternative approaches, such as powder bed fusion[74]. The selective laser melting-wire arc additive manufacturing (SLM-WAAM) hybrid fabrication technique can further reduce the time and costs. The SLM-WAAM samples with high density and good mechanical properties can be fabricated[75].

3.6 AM

AM is an effective fabrication process for FGM with optimal stress and high formability. Different qualities of AM provide advantages for controlling the temporal and spatial microstructures, like geometrically complex components that are difficult to fabricate using machines. For instance, the geometrically complex components can be manufactured using concomitant environmental benefits[76–78]. Ref. [79] indicated that the geometrically complex is fused by the deposition modelling. Table 1 illustrates the constituent materials, advantages, disadvantages, and surface roughness of samples prepared by different AM techniques.

4 Mechanical Behaviour and Characterization of FGMs

The mechanical properties, such as resistance properties under high-temperature in thermal insulation coatings, engines, and turbines, high hardness[81], magnetic properties, dielectric and optical properties in batteries, fuel cells, and laser telecommunication systems, sonic properties possessed in the fields like acoustics systems[82], are numerous obtained by incorporating the multiple types of materials. Furthermore, dental and medical fields require implants that possess high-performance with necessary characteristics, which are required for the applications in biomedical field. The industries are possibly benefitted from the methods involving multi-material printing with numerous material combinations, like ceramics, polymers, and metals[13]. The mechanical properties of FGM can be calculated utilizing the rule of mixture[83]:

$$E(z)=g(z)E_{Zn}+[1-g(z)]E_{Al} \quad (1)$$

where $E(z)$ denotes the target properties of FMG in the z-direction, such as modulus of elasticity and conductivity; $g(z)$ is the volume fraction of Zn; $1-g(z)$ is the volume fraction of Al; E_{Zn} and E_{Al} represent the corresponding property values for Zn and Al, respectively. Hardness testing is normally conducted on alloy steels, carbon steels, cast iron, machinery plastics, and nonferrous metals. Furthermore, the process of loading as well as unloading is automatic, with usage in wide manner, high accuracy, connectivity of computer, and printing of the test results.

5 Influence of AM on Microstructure and Mechanical Strength of FGM

Achieving the design specifications for gradient structures in terms of chemical composition, geometric aspects, microstructure, characteristics, performance, and manufacturing processes of FGMs is crucial. Additionally, the choice of manufacturing technique is crucial in terms of both environmental (pollution and consumption) and economic (time and cost) considerations. Using AM process, components are added level by level on top of one another to produce the ultimate form of an item. Therefore, it is also known as a layered manufacturing technique. The fundamental idea of layered manufacturing is that everything can be divided into multiple layers, and then reconstructed by joining the layers together, irrespective of the complexity of the geometry. The unique characteristics associated with AM technique have significant benefits beyond traditional methods. Complex items can be manufactured using AM in a single step, nearly exactly to the design requirements and without the constraints of traditional manufacturing processes. Additionally, through removing or lowering the requirement of assembling many components, this approach makes it potential to reduce the total amount of components

Table 1 Characteristics of different AM techniques[24,80]

Technique	Constituent material	Advantage	Disadvantage	Surface roughness
Laser based process	Metals and hybrid	High quality parts, excellent for repair applications, and fast build process	Balance between surface quality and speed and restricted raw materials	Less than 10 μm
Stereolithography process	Polymer, ceramics, and composites	Large parts, excellent accuracy, and excellent surface finish and details	Poor mechanical properties of sample, high cost, and slow building process	10–100 μm
Material jetting process	Polymers, ceramics, composites, metals, and hybrid	Various raw materials, low waste, and low cost	Support material is required, more waste, and post process needed	Around 0.1 mm
Fused deposition modelling (FDM) process	Polymers and composites	Widespread use, low cost, and ability to build ready-to-use product	Vertical anisotropy, slow building process, and rough surface	Around 0.1 mm

considerably. With the aid of AM method, it is possible to build components on demand, which eliminates the requirement for storage parts and shipping. These factors have led to the widespread use of AM method in the automobile, aerospace, energy, and medical sectors for the designing and producing the parts with high performance. While in FGMs, the processes based on AM include stereolithography process, solidification, and melting. Fused deposition modeling and material jetting are also utilized extensively. However, the techniques involving solidification and melting have been utilized frequently in AM for FGM microstructures[84]. Ref. [85] shows that a variety of modern and established simulation methods, such as the use of Lagrangian method for the modelling of the process behaviour (distortion and residual stress), and implicit and explicit solution methods are used to calculate the thermo-mechanical fully coupled and uncoupled models.

In the last few years, the developing AM technique is used in manufacturing process to make complex designs, which is used to create rapid prototypes manufacturing in the 1980s[86–87]. AM provides a distinct probability to fabricate materials of greatly complex geometrics, which is inadequate in traditional processing. Compared with the conventional manufacturing techniques, AM does the deposition process layer by layer with a previously determined sequence, offering a near-net-shaped components with high precision in quick fabrication[88].

Specific stainless steels and ferrous alloys are implemented as frequent feedstock materials that are utilized for the components fabrication via AM in industries[89–92]. The martensitic stainless steel (MSS) features assure their performance in most potential applications, such as machine components and surgical instruments[93]. MSS is sturdy but also delicate because martensite has some well-designed slip systems in the body-centered tetragonal crystal structure[94–95]. Austenitic stainless steel (ASS) is a significant metallic component with great corrosion resistance and mechanical strength. This is mostly used in many industrial sectors, which comprise marine and nuclear plants[96]. The incorporation of MSS and ASS provides a material with high strength and toughness[97]. Combination of these materials is challenging, because their main difference is based on their physical and chemical properties[98]. Slow modification process with more than one dimension from other parts of material and structure is described as FGM. This alteration has an impact on the chemical and physical properties[99]. FGM is enhanced based on these characteristics to obtain a balance and to benefit the material[24]. Ref. [100] shows the bending behaviour of compositionally graded martensitic steel by decarburization. This investigation has provided best outcome with high strength and bendability.

In other associated research by Roumina et al[101], higher sturdy functionally graded martensitic steels with enhanced fracture properties are also attained by decarburization. Mishina et al[102] examined the mechanical properties of FGMs containing ZrO_2/AISI316L that were fabricated by SPS. The wear features and fracture toughness of FGMs were strongly influenced by the thickness of layers. Watanebe et al[103] examined the possibility of fabricating a nickel-steel/aluminide clad pipe with functionally graded structure by a sensitive CCP technique.

Investigation regarding stainless steel has displayed a central point of mechanical properties. Dissimilar from traditional approach, the unique thermal field of AM procedure will be main aspect to enhance mechanical properties of materials that are fabricated. Saeidi et al[104] substantially enhanced mechanical properties of SS316L, which is caused by the fine and hierarchical microstructure of SS316L steel deposited by SLM. Dryepondt et al[105] studied the anisotropic behaviour of SS316L prepared by laser powder-bed fusion (LP-BF) technique by examining the several building directions, and demonstrated that heat treatment can decrease the anisotropic behaviour. Jamshidinia et al[106] stated the impact of processing factors on the properties of 420 SS deposited by LP-BF. In a related research by Zhang et al[107], C300 maraging steel and SS316L are combined by heat treatment and DED technique, and the resultant mechanical properties are the same as those of SS316L. However, the impact of gradient structure on the microstructure evolution and mechanical properties is rarely reported .

FGM part was fabricated by depositing a Cu-based alloy on top of a high-strength low-alloy steel by twin-wire and arc additive manufacturing. Cu and steel parts have received a lot of attention in many industries, because they can combine high thermal/electrical conductivity and good wear resistance with excellent mechanical properties. However, mixing Cu with steel is difficult due to mismatches in crystal structure and the coefficient of thermal expansion at the melting temperature. Moreover, when the melt is undercooled, the existence of miscibility gap during solidification causes serious phase separation and segregation during solidification, which greatly affects the mechanical properties[108].

The corrosion resistance and hardness of SS316L can be improved by the advancement of the microstructure from austenite to martensite without variation in chemical properties and cryogenic treatment. The technique of plasma nitrating and nitrocarburizing was conducted on austenitic stainless steel SS316L, and the results showed that it can induce an expanded austenite layer. This technique involves supersaturating the surface with nitrogen, which results in increased wear resistance and hardness[109]. Inconel 718 has excellent properties at high temperatures and pressures, and it has strong corrosion resistance against high-temperature chemical fluids. It also has strong resistance to chloride and water-based corrosion cracking. Nb enables age-hardening, which allows annealing and welding without spontaneous hardening during heating and cooling. Nb acts with Mo to strengthen the matrix of alloy and provides high strength without heat treatment. Inconel 718 is widely applied to parts in high-temperature and high-pressure environments, such as heat exchangers, gas turbines, and valves. However, Inconel

718 is costly and can cause weldability deteriorated by cracks due to Nb-rich or Mo-rich Inconel[110]. The commercially pure Ti was chosen as metallic phase of FGM dental implants because of its good mechanical properties (elastic modulus, toughness, fatigue, and strength), excellent corrosion resistance compared with other metallic biomaterials, good biocompatibility, high strength per unit mass, benign and safe biologic response, low density, and resistance against electrochemical decomposition and destruction[111]. Ti and its alloys have sufficient mechanical properties, but they are bioinert and cannot promote tissue bonding to the implants. To improve bioactivity of dental implants and to increase osseointegration, hydroxyapatite was chosen as a bioceramic phase for FGM samples[111].

FGMs are usually used as thermal barrier materials, and thermal shock environment is a regular working condition during the preparation and service process of FGMs. Under thermal shock environment, both compressive stress and tensile stress exist, which may lead to multiple inner cracks (or surface cracks). This kind of environment usually results in great temperature gradient and thermal stress in a FGM plate, which may cause further fracture in a short time. When thermal shock is applied, the temperature fluctuates significantly, and the temperature jump would lead to thermal shock failure. In recent years, more and more attention has been paid to thermal shock resistance of materials[112]. AM leads to new structural design constraints and manufacturing defects, such as accuracy, structural connectivity, additional support structure, surface roughness, and material properties. Design for AM requires to deeply integrate product design and manufacturing via considering AM process constraints and real material properties during AM, and takes full advantage of AM to maximize product performance. In addition, thermal histories (cooling rate) usually severely affect microstructural features, such as grain morphology and defects, which in turn affect performance of FGM, such as strength and hardness. The thermal history is not only related to process parameters (laser power, scanning speed, and scanning path), but also closely related to geometric model and deposition height[113].

6 Conclusions

The work reviewed the existing literature based on the characteristics and mechanical behaviour of FGMs prepared by AM, and discussed the properties, applications, and fabrication of FGM, AM-preparing for FGMs, mechanical behaviour and characteristics of FGM, influence of AM on microstructure, mechanical strength, and behaviour of FGM. FGMs are obtained by various processes, and a few FGMs are obtained naturally, such as oyster, pearl, and bamboo. Because the materials play a significant role in the industrial production, the characteristics and mechanical behaviour of FGMs prepared by AM were reviewed. FGMs are used in various fields. Literature regarding FGM and AM over the past 30 years was reviewed, suggesting that future researchers should focus on the application of artificial intelligence and machine learning technologies in industry to optimize the process parameters of different gradient systems.

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增材制造制备FGMs的特性及力学性能研究进展

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摘　要：功能梯度材料（FGM）可通过多种工艺制备。虽然自然界中少数物质（如牡蛎、珍珠和竹子等）具有天然梯度结构，但增材制造（AM），即3D打印，作为一种近净成形技术，无需工具、模具，无需装配连接即可直接制造复杂三维物体。当前商业化的增材制造技术主要采用均质成分与简化几何描述，通过单一材料实现功能梯度增材制造（FGAM），这与具有异质结构的多材料FGAM形成鲜明对比。FGM凭借其力学性能优势，已在多领域获得广泛应用。鉴于FGM在工业生产中的重要作用，综述了AM制备FGM的材料特性与力学行为。通过梳理过去30年FGM与AM相关研究，建议未来重点关注人工智能与机器学习技术在工业领域的应用，以优化不同梯度体系的工艺参数。

关键词：增材制造；功能梯度材料；加工工艺；力学性能；特性

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