Research and Application of Functionally Gradient Materials

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Abstract. Functionally gradient materials are continuous in their physical and chemical properties, such as composition, texture, density and elastic modulus. This material is an advanced material with different functions. The current states and preparation methods of functionally gradient materials are reviewed. Applications of functionally graded materials in biological, chemical, aerospace and other fields are summarized, the development and research hot-points of functionally gradient materials are also prospected.

1. Introduction

In the 1980s, Functionally Graded Materials (FGM) was first proposed by Japanese scholars. It was originally designed to solve the huge temperature difference caused by the overheating of the outer surface of the spacecraft while keeping the internal temperature unchanged [1]. Functionally graded materials combine the best of different materials to achieve their good performance. Once introduced, this concept has aroused worldwide exploration and expanded it into many fields such as metal-ceramic, metal-polymer, and ceramic-polymer and so on. In general, FGMs exhibit regular gradient changes both in the macro and the micro-scale (including uniform variation and layering variation). Therefore, FGM has many physical and chemical properties [2]. Gradient structure can effectively enhance the strength, toughness, wear resistance and other properties of a particular region of the material, the material life and application performance of a qualitative leap, and even become a composite material development direction [3]. Due to the incomparable advantages of functional graded materials in general composites, there is a great prospect in various fields with special requirements on material properties [4-6]. The purpose of this paper is to introduce the current methods of preparing functional graded materials and their applications in various fields.

2. Functionally Graded Material Preparation Method

The functionally graded material is prepared through the diffusion and bonding of different materials between atoms, so as to achieve the purpose of permanent connection and good performance. At present, there are many reports about the preparation methods of functionally graded materials, but from the fundamental principle, we can summarize them as physical combination method, chemical combination method and physical and chemical synthesis method. The physical combination method, as shown in Table 1, refers to the layering of materials by controlling the variation of the movement direction and velocity of liquid particles with different sizes and shapes under the action of gravity, centrifugal force, electric field force and magnetic field force. The chemical bonding method, as shown in Table 2, refers to the use of sintering, deposition and other methods to make the material changes in the molecular level, in the new phase and the resulting old gradient structure, so as to achieve the desired performance.
Physical and chemical combination of law, as shown in Table 3, refers to the combination of physical and chemical synthesis, so that the material in the reaction process while taking advantage of its physical and chemical properties, to achieve the connection of materials, so that the gradient derived from each phase derived from the combined method.

Table 1. Physical methods [7-9]

| Method                        | Specific content                                                                                                                                                                                                 |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wet powder coating method     | The raw material powder is added into a dispersant to make a suspension, and then the suspension is sprayed onto the substrate. By controlling the spraying rate, a gradient composition of the composition can be obtained. The method of spraying a greater impact on impurities, coating adhesion is not easy to control. |
| Directional solidification method [7] | In the process of solidification, coercive measures are used to make the material appear in a specific direction during solidification and finally obtain a grain structure with a specific orientation, so as to achieve a gradient structure. The method is complicated, and the two parameters of the temperature gradient and the solidification rate in the solidification process are not easily controlled. |
| Centrifugal casting method [8] | Centrifugal force field using different density particles in the centrifugal force to move in different directions in order to achieve structural stratification. The method can prepare large-scale and high-density gradient materials, but does not work well for preparing high-melting-point ceramic system functionally graded materials. |
| Settlement casting method [9]  | Add a certain size of the powder particles in the melt, under the action of gravity, through the settlement parameters and subsequent cold processing to form a gradient structure of the material. The method is complicated process, long working hours. |
| Filling casting method         | First, a melt is injected into the cavity, and then the second melt is injected into the first non-condensed melt to achieve gradient connection between the two melt under the effect of thermal convection. |

Table 2. Chemical methods [10-13]

| Method                          | Specific content                                                                                                                                                                                                 |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrodeposition method [10]   | Under the action of electrolysis or chemical reaction, different active particles undergo chemical reduction reaction at the same time and deposit on the surface of the substrate to form a coating. Process equipment is simple, easy to operate, easy to control the accuracy, low cost, but only for the preparation of thin foil FGM body. |
| Laser cladding method [11]      | The mixed powder is sprayed onto the substrate to control the laser heating power and other parameters to melt the substrate surface to produce a molten pool, and then the powder is added to react to form a gradient structure after cooling. FGM can be prepared film and body, wide adaptation; but the preparation process is complex, expensive equipment. |
| Reactive infiltration method [12]| The preform reacts with the infiltrated material through a chemical reaction to couple the solute distribution at the interface, thereby forming a gradient structure. The method has the advantages of short preparation period and close size forming. |
| Self-propagating high temperature synthesis [13] | The reaction of the material itself is continued by the heat release of the material itself, and it has a good prospect for the preparation of large size and complex materials. This method has the advantages of high efficiency, less energy consumption, rapid reaction and high purity of the product. |
Table 3. Combination of physical and chemical methods [14-16]

| Method                        | Specific content                                                                                                                                                                                                 |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Powder metallurgy method [14] | The raw material powder is arranged in order according to a predetermined order, then pressed and shaped through a molding process, and finally a functionally graded material is obtained through a densification process such as sintering. High reliability, suitable for the preparation of simple shape FGM parts, but the supply and demand is complex and the cost is high. |
| Vapor deposition method [15]  | Divided into physical vapor deposition and chemical vapor deposition, the principle is the use of active gaseous substances deposited on the substrate surface film, forming a gradient structure. The method has the advantages of rapid deposition speed, flexible process, and high gradient material binding. However, due to the volume limitation of the deposition chamber, only small-sized materials can be prepared. |
| Plasma spraying method [16]   | The raw material powder is added into the plasma jet, and the high temperature of the plasma is used to melt or partially melt the raw material powder during jetting, so that a gradient film structure is sprayed onto the substrate. The method is suitable for the gradient coating of complex geometrical devices, but the bonding strength between the gradient coating and the matrix is not high, and the coating has the defects of uneven microstructure, loose porosity and rough surface. |
| Grouting method               | The raw material powder is poured into a liquid to form a suspension, and then the suspension is injected into the cavity, to be cooled and dried, and then hot-pressed to form a gradient structure. The process is suitable for mass production of gradient materials. |

3. Functionally Graded Materials Applications
Materials play a crucial role in industrial production. With the improvement of social productivity, the requirements for materials are also correspondingly improved. As an advanced branch in the field of materials, functional graded materials undertake the task of providing advanced performance materials. Functionally graded materials have been used in many fields such as aerospace, nuclear energy, biology, electromagnetism, optics, energy and other fields through the ingenious combination of inorganic and organic materials such as metals, ceramics and plastics.

3.1. Aerospace Field
Functionally graded materials with high temperature resistance, thermal shock resistance, thermal fatigue resistance and corrosion resistance can be applied to heat-resistant surface of space shuttle and aircraft engine parts [17]. Spacecraft engine combustion chamber wall at work, the side need to withstand high temperature and thermal erosion above 2000K, the material has excellent heat and heat insulation properties, while the other side will have low temperature liquid hydrogen cooling, the material proposed Low temperature and high thermal conductivity requirements. Functionally graded materials with high strength and toughness, able to withstand such a large temperature difference under the conditions of mechanical load and temperature gradient caused by thermal stress, to maintain a long working life, with other materials do not have the excellent performance. At the same time, the aircraft engine is a high-precision components, requires high hardness, wear resistance, corrosion resistance and low thermal expansion coefficient, density. Therefore, the functionally graded material has the physical and chemical properties that traditional materials cannot achieve, and can be used as an easy-worn and easy-to-consume part of an aircraft engine blade.

3.2. Nuclear Energy Field
The high strength, heat resistance and corrosion resistance of FGM provide a reliable guarantee for the development of next generation nuclear industry. Nuclear power generation, nuclear power and the storage of nuclear weapons are extremely dangerous. Once the accident is triggered, it will have serious
consequences. Therefore, it is imperative to ensure its safety. In the application of nuclear fusion reactor in the nuclear fusion reactor, a good thermal stress relaxation effect is shown, which makes the nuclear fusion reaction safer. As a high-strength, heat-resistant and shielding material, functionally graded materials show great superiority in the construction materials of nuclear furnaces and inner wall materials of nuclear furnaces, which greatly protects the safety of the nuclear industry [18].

3.3. Biological Field
The gradient material is common in nature, such as the shell of layered structure, the hard and tough animal skeleton, and the layered human skin. The medical development of FGM makes medical assistance to patients more timely and effective. The functionally graded material has the characteristics of high specific strength, high specific modulus, abrasion resistance and biocompatibility. Based on this, the artificial joint developed makes the artificial prosthesis and the patient's own skeleton have strong binding force and reliable Durable, showing good biocompatibility [19], but also has good self-healing and repair of regenerative properties. With its superior properties, FGM has a good application prospect in the biomedical fields, such as artificial bones, teeth, and heart.

3.4. Electromagnetic Field
Due to the graded distribution of functionally graded materials, special structures have special properties. In the electromagnetic field, the gradient structure has the piezoelectric gradient function and the electromagnetic gradient function, and can be used to make electromagnetic shielding materials, ceramic filters, ultrasonic oscillators, etc. [20]. And the application of functionally graded materials on disks, permanent magnets, electromagnets and oscillators can reduce the mass and size of the corresponding devices and improve their performance [21].

3.5. Optical field
The hardness of ordinary glass is high, but its brittleness is large. Because of the uncertainty of the external environment, the service life of the glass is greatly reduced. At the same time, the transmittance of common glass cannot be changed with the change of environment, which will bring certain impact on production and living and work. Therefore, improving the mechanical and optical properties of glass has become an important direction in the field of development [22]. By adding rare earth elements and materials with different refractive indices to the functionally graded material, the optical properties of the glass can be changed according to the environment. The relevant scholars have successfully prepared materials such as glass lasers, optical fiber lenses, anti-reflection films, and discolored glass.

3.6. Energy Sector
Functionally graded materials also have special properties based on heat resistance, corrosion resistance and thermal shock resistance. In particular, the development of various special function graded materials has made FGM play an important role in the energy field. For example, in the aspect of power generation system, the application of gradient thermoelectric energy conversion material makes the emitter not cracked in the high temperature working environment of 1860 °C and greatly reduces the thermal stress of the system. Meanwhile, the application of the heat release substrate at the low temperature electrode of the system also shows high thermal conductivity and radiation exothermic rate [23].

4. Functionally Graded Material Performance Evaluation
Different from the traditional conventional materials, FGM has its own unique performance, so it needs to establish a set of special performance evaluation system. However, scholars from all over the world have not established a set of accurate and systematic performance evaluation methods, which greatly restricted the further development of FGM. The concept of FGM was first proposed in the field of aerospace for the research and development of ultra-high temperature structural materials. Therefore, scholars all over the world have conducted research on their mechanical properties, thermal insulation properties, thermal fatigue properties, thermal shock resistance and thermal stress relaxation properties
a series of studies. But nowadays, the performance evaluation of functional graded materials is still only at the stage of basic laboratory work. How to establish a systematic evaluation system is a key point in the development of FGM in the future.

5. Functional Gradient Material Research Direction
At present, the research on FGM is still at an advanced stage. Although a large number of high-performance gradient composites have been developed and applied in recent years, some key problems remain to be solved [24, 25]. In the future, the development of FGM will be in the following directions: (1) To further explore the microstructure, phase transformation and phase composition of gradient materials, and to thoroughly understand the microscopic mechanism; (2) to improve the preparation process so that large size and complex Process, complex size and other parts of the production process becomes simple and efficient, and to achieve the level of industrial mass production; (3) more functional graded materials to establish a unified FGM performance evaluation system; (4) without changing the product (5) Extend the concept and principle of FGM to other fields, and provide a good reference for scientific research in various fields.

6. Conclusion
Due to its novel concept and excellent performance, FGM has become a research hotspot in the field of materials at present, and its research and application fields are gradually expanding. Compared with the traditional materials, the functionally graded materials are more complicated in the production process, and the combination of the gradient layers becomes a key issue in the field of FGM preparation. Moreover, under the combined action of mechanical load and thermal load, the stress and stress variation of functionally graded materials are more complicated, and research in this area will become a key issue in FGM applications. At the same time, combining the performance of functionally graded materials with biomimetic materials and smart materials for the development of a new generation of materials will inevitably bring about major changes and great developments in the material industry.

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