Fabrication of Functionally Graded Materials through Severe Plastic Deformation of Powders: Process, Significance, and Future Development

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Abstract. Functionally graded materials (FGMs) are a remarkable invention in materials science and engineering, that offers unique properties useful in various applications. Having the ability to gradually change properties, like composition, microstructure, or mechanical properties of materials, gives FGMs unparalleled adaptability, making them suited for a wide range of high-strength applications. One of the novel methods of creating FGMs is to use severe plastic deformation (SPD) techniques on powdered materials. The SPD of powders involves a few critical steps; The process begins with selecting materials with varied compositions and phases then mixing the powders, cold compaction, SPD methods, and, if necessary, heat treatment. The process is completed with characterization and testing, to evaluate the microstructure and characteristics of the final FGM formed.

FGMs will continue transforming materials engineering and pushing the boundaries of their applications in many engineering fields and industries since they exhibit attractive capabilities like improved efficiency, durability, and performance. Therefore, this article explores the process of fabricating FGMs by SPD and emphasizes its significance and future trends in FGM production.

1 Introduction

Functionally graded materials (FGMs) have seen a rise in research efforts over recent years, due to the remarkable qualities and wide range of applications. The capacity of FGMs to demonstrate a controlled variation in properties such as composition, microstructure, and mechanical characteristics has drawn much attention of research [1–4]. The FGMs' flexibility has been a focal point in recent research, where they have demonstrated remarkable potential in applications ranging from aerospace to medicine to automotive and energy sectors [5–10]. For example, recent studies have explored the development of FGMs with thermal properties for aircraft components, which have led to the design of composites with a range of thermal properties to improve the performance and life of parts that experience extreme temperature changes [11]. Studies have further reported the potential effectiveness of FGMs in reducing fuel consumption and increasing aircraft's overall efficiency.

Research has also been carried out into creating automotive components with divergent mechanical properties to increase crash resistance and simultaneously reduce body weight [6]. These developments can potentially reshape the automotive industry by creating safer

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and more environmentally friendly vehicles. Furthermore, FGMs have proved to be a game changer in the energy sector. High-temperature components such as turbine blades have been the subject of intensive research for enhanced heat resistance properties [7].

In the process of creating FGMs, severe plastic deformation may be used. The purpose of SPD is to improve the microstructure and properties of the materials. SPD has demonstrated outstanding potential for enhancing efficiency and extending the service life of some components [12–14]. Moreover, a hive of research activity has emerged around using SPD on powders to fabricate FGMs. Recent advancements have improved the SPD method to obtain better accuracy and control over material properties, resulting in high-performing FGMs. These developments underscore the growing interest in optimizing the SPD approach to unlock the full potential of FGMs. However, recently, in order to attain more accurate and control over material properties, studies have focused on improving SPD procedures. This has eventually led to the fabrication of FGMs with improved performance characteristics [13].

The high-pressure torsion (HPT) has become more popular as an SPD method for processing powders. Estrin and Vinogradov [15] investigated how the microstructure and characteristics of FGMs were affected by varying the deformation rates and parameters during SPD processing. The study reported that producing better FGM material was possible by optimizing the process parameters. Similarly, there has been research about the influence of post-SPD annealing on the performance of FGMs. Researchers have been able to enhance material properties and refine the microstructure of FGMs through the careful application of heat treatment [16, 17]. This has created opportunities for customizing FGMs for particular uses. The impact of heat treatment on the phase transitions and mechanical characteristics of FGMs made using SPD has been investigated in recent research [18]. The study reported that heat treatment affects phase transitions and mechanical properties of FGMs.

In essence, the increasing amount of research on FGMs shows that they have the potential to be transformative materials that can help solve some challenges in most industries. FGMs are expected to significantly impact materials science and engineering going forward, providing innovative solutions to challenging issues and advancing the fields. Some of the studies conducted on SPD of FGMs are included in Table 1.

Table 1. Some of the studies conducted on FGMs (methodology, characterizations, key findings and gaps)

Title of publication/author/year	**Methodology**	**Characterizations**	**Key Findings and Gaps**
A novel two-step method for producing Al/Cu functionally graded metal matrix composite by Tayyebi and Alizadeh **[19]**	The methodology involved the fabrication of 6 composites (Al/Al, Al/20Cu, Al/40Cu, Al/60Cu, Al/80Cu, and Cu/Cu) using a combination of cumulative roll bonding (ARB) and cold roll bonding (CRB) with multiple cycles to achieve the desired thickness.	To evaluate the mechanical characteristics and microstructure of the materials, fractography analysis, microhardness analysis, and microstructural studies are used.	- The hardness of the layers increased as the volume % of Cu changed from the Al side to the Cu side. SEM pictures show that Cu concentration in the composites changed continuously from the Al side to the Cu side. As the volume fractions of Cu increased, the composites' strength increased progressively. - It does not investigate how variables like the ARB's temperature and time affect it.
Centrifugally cast functionally graded materials: Fabrication and challenges for probable automotive cylinder liner application by Mallick *et al.* [20]	The study focuses on cylinder liners made of high-hardness aluminium alloys and reinforced with ceramic particles, emphasizing the fabrication process of functionally graded composite materials (FGMs) for potential use as liners in response to environmental regulations	The study investigates liner material enhancement by discussing the effect of ceramic reinforcement on mechanical and tribological properties, comparing these FGM liners to typical aluminium liners	- The results show that incorporating ceramic particles into aluminium liners can significantly improve their strength, hardness, stiffness, thermal stability, and wear resistance; however, the study emphasizes the need for a comprehensive framework for material selection, parameter selection, and processing procedures to develop optimized FGM liners, addressing current research gaps.
Compositionally graded Tidal + TiC made by direct laser fabrication using powder and wire by Wang *et al.* [21]	Ti6Al4V reinforced with TiC was manufactured as a compositionally graded material using direct laser fabrication, which fed TiC powder and Ti6Al4V wire into the laser focus point at the same time.	X-ray diffraction and scanning electron microscopy were used to evaluate the microstructure, and changes in composition throughout the sample length were investigated in relation to feed rate modifications.	- TiC was found to be melted over most of the sample length, forming primary TiC, eutectic TiC, and secondary TiC. The study discovered that the inclusion of reinforced TiC particles improved the tribological properties of Ti6Al4V, with the most favourable frictional behaviour occurring at approximately 24 vol.% TiC. - The study might benefit from a more thorough exploration of the material's mechanical and thermal properties to better understand its possible applications and limitations.
Compressive Properties of Ti6Al4V Functionally Graded Lattice Structures via topology optimization design and selective laser	Topology optimization was utilized to create cellular structures with RD values ranging from 0.10 to 0.30. Uniform Lattice Structures (ULSs) and Functionally Graded Lattice	ULSs were used to study the mechanical characteristics, failure processes, energy absorption abilities, and property prediction of lattice structures. The	- The study found that well-designed lattice structures with variations in lattice structure could attain mechanical capabilities comparable to genuine bone. G1 specimens had marginally more excellent mechanical characteristics

melting fabrication by Xu *et al.* [22]	Structures (FGLSs) were created utilizing Ti6Al4V alloy powder and selective laser melting (SLM) technology	mechanical qualities of the developed lattice structures were equivalent to natural bone, with mechanical values varying for different structures.	than ULSs, whereas G2 specimens had significantly poorer mechanical values than ULSs. - Further investigation of biological properties, such as cellular response and integration of these structures with host tissues, could enhance this research.
Deformation and energy absorption of additively manufactured functionally graded thickness thin-walled circular tubes under lateral crushing by Baroutaji *et al.* [23]	The study evaluated the crash-worthiness behaviour of functionally graded thickness (FGT) circular tubes with in-plane thickness gradients under lateral loads. Three distinct designs of FGT tubes with various locations of maximum and minimum thicknesses were created using selective laser melting additive manufacturing. Powders Ti6Al4V and AlSi10Mg were used. To explore these tubes' crushing and energy absorption characteristics, quasi-static crush experiments were performed.	The energy absorption characteristics of the FGT tubes were investigated and compared to a uniform thickness design. The crash-worthiness reactions of the FGT constructions were evaluated using various geometrical parameters and thickness gradient modifications.	- The study found that the FGT titanium tube had the best crash-worthiness metrics, with the most outstanding thickness portions along the horizontal and vertical directions and minimum thickness sections at a 45° angle to the loading direction. This tube absorbed 79% more energy per unit mass than its uniform thickness equivalent. - Research into such materials' biological compatibility and integration with car safety systems could help bridge the gap between research and practical application.
Fabrication of functionally graded few-layered graphene-reinforced Al-4.5Cu alloy by powder metallurgy by Borand and Uzunsoy [24]	Powder metallurgy was used to create a functionally graded graphene-reinforced Al-4.5Cu alloy with variable weight percentages of few-layered graphene (FLG) and sintering at 570 °C and 590 °C for 3 hours, following a six-layer FGM design.	According to optical and scanning electron images, FLG graded according to content worked as a barrier between grains and was homogeneously spread in the Al-4.5Cu alloy matrix.	- After sintering at 570 °C and 590 °C, the hardness of the FGM design increased by 37.11% and 24.71%, respectively, in the last layer compared to the first layer. - During the gap analysis, an inquiry will be conducted to determine the pros, cons, and obstacles of using SPD.
Improvement of tensile properties of laser-directed energy deposited IN718/316L functionally graded material via different heat treatments by Lu and Li [17]	The study aims to improve the HT process for laser-directed energy deposited (LDED) IN718/316L functionally graded material (FGM) by analyzing the microstructural evolution and mechanical properties following various heat treatments (HTs).	After heat treatment, the study observed the dissolution of the Laves phase, re-precipitation of the δ, γ', and γ'' phases at specific regions of the specimen, transition from ferrite to austenite, and changes in grain boundaries. The mechanical properties, including	- The ultimate tensile strength (UTS) and elongation of the specimen subjected to HT at 1080 °C (HT2 specimen) were higher than those of the as-built specimen (AB specimen) and the specimen soluted at 980 °C (HT1 specimen). Wear resistance in the building direction rose as IN718 powder content increased. -While the study successfully enhanced the HT technique for the IN718/316L FGM, additional research might be

		ultimate tensile strength (UTS) and elongation, were evaluated.	conducted to investigate these materials' long-term stability and performance under demanding conditions.
Influence of severe plastic deformation of Cu powder and space holder content on microstructure, thermal and mechanical properties of copper foams fabricated by lost carbonate sintering method by Shirjang and Akbarpour [25]	Semi-open cell copper foams were created by mechanically pre-activating Cu powders over a range of milling times and then adding 50-70 vol% K_2CO_3 as a filler material via lost carbonate sintering (LCS). The researchers investigated the effects of mechanical milling and K_2CO_3 volume percentage on the microstructure, porosity, strength, energy absorption, and cooling rate of foam.	The study thoroughly examined the foam's microstructure, porosity, strength, energy absorption capacity, and cooling rate. It was mainly concerned with how varying milling times and K_2CO_3 volume fractions affected these attributes and these properties.	- Foams made from long-duration milled powder had small holes and a homogeneous size distribution, yielding up to 170 MPa stresses. Notably, the foam with 70% porosity, formed by milling Cu particles for 2.5 hours, had the fastest cooling rate. The study found that employing flake Cu powder from shorter milling times improved the foam's mechanical and thermal properties. On the other hand, longer mechanical milling reduced the cooling rate of the resultant foam.
Tribological behaviour of Ti/HA and Ti/SiO2 functionally graded materials fabricated at different strain rates by Majzoobi *et al.* [26]	FGM samples of Titanium/Hydroxyapatite (Ti-HA) and Titanium/Silicon oxide (Ti-SiO_2) for dental implant applications were created using three die compaction processes. A newly built mixer was used to effectively scatter and mix the constituent powder particles, followed by consolidation using hot dynamic and quasi-static compaction procedures at different strain rates.	The study thoroughly examined the FGM samples' microstructure, hardness, wear resistance, penetration depth, and friction coefficient. Optical microscopy was utilized to evaluate particle dispersion using a linear grading function.	- Vickers hardness values of FGM samples were inversely related to reinforcing phase (HA or SiO_2) concentration and directly related to strain rate. All FGMs lowered wear penetration depth and enhanced wear resistance at more excellent strain rates, but Split Hopkinson Bar samples had the highest wear resistance. The Split Hopkinson Bar produced the lowest-friction Ti-HA samples. Microscopically, adhesion, delamination, and abrasion were the predominant wear processes in all FGM samples. The SHB-generated Ti-HA sample had superior tribological properties, similar to human teeth.

2 SPD of powders for the fabrication of FGMs

The production of FGMs by the Severe Plastic Deformation (SPD) of powder entails a sophisticated and revolutionary procedure that enables the development of materials exhibiting graded properties. FGMs are composite materials characterized by a progressive composition and/or microstructure variation along their dimension. The SPD method is employed to improve the grain structure of a given material, hence leading to the augmentation of its mechanical and functional characteristics. This section provides a comprehensive explanation of the manufacturing process employed for FGMs utilizing the SPD technique with powder materials and is illustrated in Figure 1.

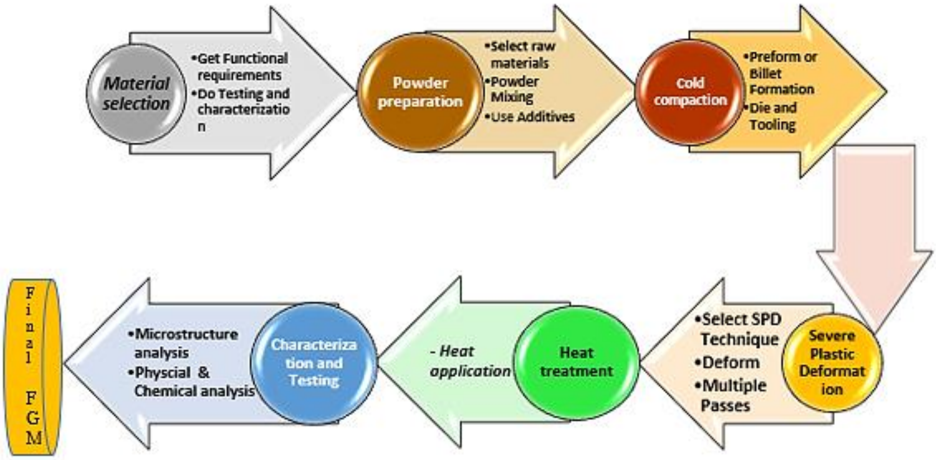

Figure 1: Production of FGMs by the Severe Plastic Deformation Procedure [27]

2.1 Material selection

When fabricating functionally Graded Materials (FGMs), one of the most critical steps in this process is material selection [28]. The selection of the quality material and the desired properties required to meet the functional conditions. Researchers in the operational setting evaluate factors such as temperature, mechanical stress, and chemical exposure. The selection of powders may include metal, ceramic, or composite materials. The powders should be compatible so that can homogeneously mix and deform without generating defects [29]. Furthermore, extensive testing and characterization is to be done to ensure that the materials meet the performance criteria [30]. After choosing the appropriate materials, they are precisely characterized in order to produce FGMs that possess specific characteristics suitable for a wide range of manufacturing industries [31].

2.2 Powder preparation

This stage is essential for producing Functionally Graded Materials, especially when using severe plastic deformation techniques. The chosen raw materials are usually crushed into a fine powder before being used to create the powders for FGM manufacture. [15]. This first stage ensures that the powders are ready for further processing. Once the powders have been obtained, the next step is thorough mixing to generate a uniform powder blend as shown in

Figure 2. This mixing guarantees that the various compositions are spread uniformly throughout the slurry. The achievement of uniformity is critical because it directly impacts the FGM's final characteristics and composition gradients [2].

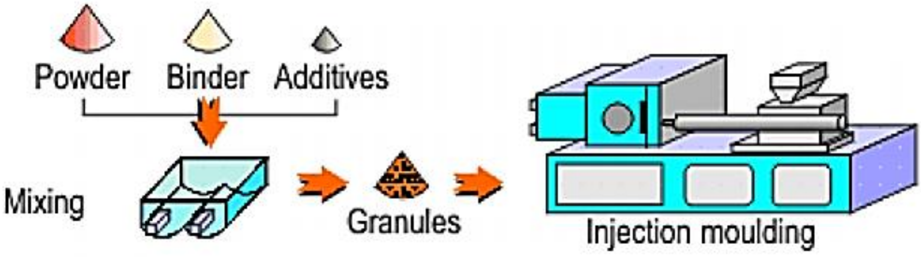

Figure 2: Powder preparation [30]

2.3 Cold compaction

Cold Compaction is an essential step in the fabrication of FGMs where the powders are mixed, and then compacted to form a preform or billet is formed. It is an important step to shape FGM into a more suitable form for further analysis. After blending the powders, they are cold pressed into a preform or billet. The preform shape and dimensions are engineered to match their respective desired use [32]. The use of a die and the proper tooling is required to accomplish consistent and regulated compaction. The tooling is necessary to uniformly distribute the necessary pressure to the powder mixture, while the die creates the proper shape for the preform. In doing so, the powders are guaranteed to be crushed into the exact density and shape required for the subsequent processing steps [33].

2.4 Severe Plastic Deformation

The severe plastic deformation (SPD) process, which involves subjecting a material to severe plastic deformation, plays a decisive role in FGM fabrication, enabling microstructural modifications. The first step to a successful SPD process is to pick a suitable technique depending on the application's needs. Common SPD processing techniques include High-Pressure Torsion (HPT), Equal Channel Angular Pressing (ECAP), and Accumulative Roll Bonding (ARB) [34] and are shown in Figure 3. For successful FGM production, the selection of a suitable machining method will depend on specific parameters like the material to be used and the desired properties of the final product [35].

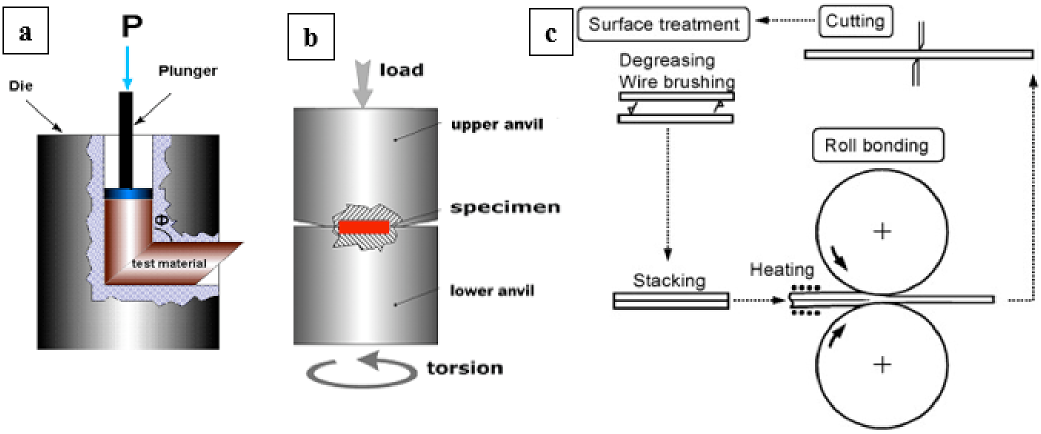

Figure 3: SPD processes, (a) Equal Channel Angular Pressing [36], (b) High-Pressure Torsion [37], (c) Accumulative Roll Bonding [38]

After the SPD process selection, the cold-pressed preform or billet is deformed by intense plastic deformation. This can be achieved by exerting considerable pressure on the material, resulting in grain refinement, higher dislocation density, and possible phase changes. These shifts in the material's microstructural properties are critical for realizing the required property gradients in the FGM. The necessity for multiple passes through the selected severe plastic deformation (SPD) process may be contingent upon the particular specifications for microstructure and characteristics. Utilizing many passes enhances refining and more control over the material's properties. As mentioned above, the phase holds significant importance in minimizing the gradient and performance of the FGM, as highlighted by Valiev and Langdon [34].

2.5 Heat treatment

Heat treatment may be used after the SPD process, depending on the unique needs of the FGM. Heat treatment can be used to relieve residual tensions that may have been collected during SPD. It also aids in the promotion of phase stability inside the material. The carefully regulated application of heat allows for the microstructure and properties of the FGM to be adjusted to correspond with the desired qualities. Heat treatment can be essential for optimal material performance in its intended application [15].

2.6 Characterization and testing

Characterization and testing are critical steps in manufacturing FGMs since they allow for evaluating their microstructure and properties [9]. The FGM is thoroughly characterized by utilizing several techniques to examine its microstructure and characteristics. Microscopy (e.g., scanning electron microscopy, transmission electron microscopy), X-ray diffraction analysis, and other analytical procedures are frequently used in these techniques. Microscopy allows for a detailed analysis of the material's internal structure, while X-ray diffraction aids in identifying and distributing crystallographic phases [39–41]. Comprehensive characterization sheds light on the material's composition and distribution across the gradient.

Testing is essential for assuring that the FGM fits the specific requirements of its intended application. Mechanical testing evaluates qualities such as tensile strength, hardness, and fracture toughness, providing information on the material's structural integrity. Thermal testing, which includes thermal conductivity and thermal expansion measures, aids in determining the FGM's temperature response. Chemical property testing assures that the material will not degrade or corrode when exposed to particular conditions. These tests, taken together, determine whether the FGM meets the desired performance standards for an intended use [15].

To produce excellent properties and qualities in the FGM, the process requires careful control of parameters like temperature, material properties (composition and thickness of each layer), pressure, and deformation rate [15, 42–45]. For instance, temperature is critical in the production of FGM. It influences the material's mechanical characteristics, phase transitions, and microstructure. Temperature control allows for the alteration of material properties [46]. Heat treatment refines grain structure, improves mechanical properties, and provides a smooth transition of characteristics in FGM [15]. Pressure is necessary for grain refining and consolidation in processes such as Severe Plastic Deformation. High pressure causes plastic deformation, breaking big grains into smaller ones. As a result, mechanical qualities like strength and hardness improve [14].

Moreover, grain size and mechanical properties are affected by deformation rate, which is the rate at which a material is exposed to plastic deformation. Finer grains are often produced when the deformation rate is increased. An adequate deformation rate must be chosen to achieve the desired microstructure and characteristics of the FGM [43]. Combining these characteristics enables the customizing of FGMs with differences in composition, microstructure, and properties. Researchers and engineers continue to investigate and refine procedures for producing FGMs to address the expanding demands of diverse industries. The whole process needs to be closely monitored concerning parameters like temperature, pressure, and strain rate to attain the ideal gradient and properties in the FGM. Scientists and engineers are continually developing and refining methods to produce FGMs that meet the ever-increasing expectations of various sectors.

3 The Significance and applications of FGMs through SPD

Functionally Graded Materials made from SPD procedures have shown great significance and applicability in various functions. They include:

3.1 Cutting Tools, Shafts, and Rollers

FGMs have been used in mechanical engineering to increase the performance and longevity of cutting tools, shafts, and rollers. For example, gradient compositions of FGM-coated cutting tools can improve wear resistance at the cutting edge while retaining tool toughness. This lowers machining costs and increases tool life [10].

3.2 Optics

FGMs have interesting prospects, particularly for creating gradient refractive index lenses. By effectively reducing light dispersion and correcting optical aberrations, these lenses can enhance the performance of optical instruments such as telescopes and camera lenses [44]. Sharper images are produced by the gradient design's precise control over light bending.

3.3 Aerospace applications

In the design of airplanes, lightweight FGM parts with specific thermal characteristics have been employed. For instance, FGMs increase heat resistance in turbine blades, allowing aircraft engines to run smoothly at high temperatures. In doing so, the aviation industry's environmental concerns are addressed while reducing fuel consumption and improving overall aircraft performance [11].

3.4 Automobile

According to Ford *et al.* [47], FGMs are important to the automotive industry when it comes to making parts like exhaust systems, engine cylinder liners, engine pistons, car body and engine parts, window glass, and car brakes. The FGMs increase crash resistance in car structures, which can improve safety. Furthermore, FGMs in exhaust systems improve thermal properties, which helps to lower emissions and improve fuel economy [27].

3.5 Energy

Turbine blades made from FGMs have improved heat resistance, which increases power generation's energy efficiency. These blades' ability to resist high temperatures makes power plants run more efficiently, lowering energy production costs [44].

3.6 Biomedical

FGMs are utilized in the biomedical industry to make biocompatible implants similar to natural tissues' properties. FGM dental implants, for instance, can offer a smooth transition from implant to natural bone, lowering the possibility of issues and increasing patient satisfaction [5, 28].

3.7 Electronics

FGMs have also found applications in the electrical and electronic industries. These applications include the relaxation of field stress in the electrode and field spacer interface, as well as in diodes, semiconductors, insulators, optoelectronics, and sensor production [48]. By combining materials with different thermal and electrical conductivity properties in a single device, FGMs have the potential to transform electronics completely. Due to this innovation, more efficient electronic components could include heat sinks with customized thermal conductivity or transistors with improved electrical properties.

4 Sustainability assessment of FGM fabrication

The factors such as energy consumption, waste materials, and chemical emissions can be used to assess the sustainability of FGM fabrication processes as discussed in this section.

4.1 Consumption of energy

Energy consumption is an essential factor in producing FGMs, and it varies greatly depending on the fabrication method used. Some FGM fabrication methods are intrinsically more energy-intensive than others, affecting overall sustainability. For example, a study by Maih *et al.* [49] discovered that the energy consumption associated with laser cladding was nearly ten times more than that of standard manufacturing techniques. The energy requirements for FGM production are an essential part of environmental sustainability. High energy consumption not only raises production costs but also has consequences for carbon emissions and depletion of resources. Sustainable FGM fabrication aims to reduce energy consumption by using more efficient manufacturing methods, improving process parameters, and exploring renewable energy sources where possible. Reducing energy consumption in FGM fabrication promotes both the environment and economic sustainability. Lowering energy usage can result in lower operational expenses, which are critical for economic viability. Furthermore, energy-efficient operations can help to reduce greenhouse gas emissions, suggesting a link between environmental and economic dimensions.

4.2 Material waste

Material waste plays a significant role in producing FGMs, with obvious environmental and economic sustainability implications. FGM fabrication methods can generate substantial waste, necessitating appropriate waste management strategies to reduce pollution and maximize resource use. For instance, research studies by Richardson *et al.* [50] and Hamamcı *et al.* [51] discovered that material waste was significant during FGM manufacturing using the in-situ powder metallurgy process. This emphasizes the importance of addressing material waste in FGM manufacturing processes.

The production of significant quantities of waste during FGM manufacturing raises environmental issues. Waste disposal can cause environmental damage and resource depletion. Inadequate waste management can lead to the discharge of dangerous compounds into the environment, causing ecological damage. FGM fabrication should involve waste reduction measures, such as recycling and reusing materials, to improve environmental sustainability. Furthermore, reducing waste reduces environmental consequences and can contribute to cost savings, establishing a connection between sustainability's environmental and economic components. When a significant number of raw materials is abandoned as waste, it raises material costs and impacts the manufacturing process's overall economic sustainability. Recycling and reusing waste materials can help in the recovery of valuable resources, the reduction of raw material costs, and the improvement of economic sustainability.

4.3 Emissions of chemicals

Chemical emissions from FGM manufacturing are essential to environmental sustainability. Using toxic chemicals in some FGM fabrication methods endangers human health and the environment, emphasizing the significance of careful handling and risk mitigation. The emission of toxic chemicals during the manufacture of FGM biomedical implants caused significant environmental issues, according to a study conducted by Canpolat *et al.* [52]. Chemical emissions can have far-reaching consequences, affecting the immediate production area, ecosystems, and communities nearby. The release of dangerous substances can pollute the environment by contaminating the air, water, and soil. To address this element of environmental sustainability, proper chemical management, and disposal procedures must be implemented to reduce the danger of environmental contamination. The primary objective is to replace harmful compounds with safer substitutes whenever possible. This strategy decreases chemical emissions' hazards and contributes to FGM manufacturing's general sustainability.

5 Future SPD developments that will result in improved FGMs

This section discusses the Functionally Graded Materials (FGMs) developments, trends, and possibilities that are set to shape the future of materials engineering and manufacturing. It elaborates on the importance and possibilities of improvement in the FGMs using SPD processes and other complementary techniques. The following are important avenues for further study and advancement in the field of FGM:

5.1 Multi-Gradient FGMs

FGMs with multiple compositional and property gradients is an innovative method. These materials have many layers with different properties, allowing for highly customized properties for specific applications. This advancement involves the creation of new SPD approaches capable of precisely controlling various gradients [12, 15]. Multi-gradient FGMs, for example, can be developed in aerospace applications to optimize heat resistance and mechanical strength within components, such as turbine blades, increasing aircraft efficiency [11].

5.2 Nano-structured FGMs

Using SPD techniques to produce nano-structured FGMs offers enormous promise. These FGMs have extraordinary qualities due to nanoscale materials and architectures, including superior strength and thermal stability [15]. Significant benefits are expected for the aerospace, energy, and electronics industries. Nano-structured FGMs, for example, can change aerospace by enabling the production of lightweight yet strong components, resulting in lower fuel consumption and improved aircraft performance.

5.3 Advanced Characterization Techniques

Advanced characterization techniques are essential for developing a comprehensive understanding and optimizing FGMs. In-situ microscopy and spectroscopy techniques can provide real-time insight into material behaviour during SPD and allow for better control over the manufacturing process and material properties [34]. Such techniques are paramount in accurately controlling gradient formation, resulting in FGMs with desired and trustworthy properties.

5.4 Computational Modelling

A critical element in predicting the behaviour of FGMs in SPD is using computational modelling and simulation. This method helps to optimize the production conditions and predict the final properties of materials, minimizing the time and costs spent on exhaustive trial and error experiments [53]. Such modelling can be very promising for fast prototyping and materials design in different industries.

5.5 Integrated Processing

Investigating techniques combining several manufacturing processes, such as SPD and additive manufacturing, can result in composite FGM structures. The above methods allow the creation of components with complex gradients [15, 48]. This implies significant consequences for industries with detailed, high-performance components are needed.

5.6 Environmentally Friendly SPD

Eco-friendly SPD methods that reduce energy consumption and waste generation should be researched as sustainability emerges as a critical goal. Sustainable manufacturing methods can minimize the ecological footprint of the FGM production process to correspond with global efforts to minimize environmental impact.

5.7 Customization and Small-Batch Production

Cost-effective methods for mass production of the customizable FGMs and smaller units/batches are required to bring these into multiple industrial applications and end-use cases. Progress in producing materials and processing equipment can make FGMs more applicable for various applications. It is also necessary to establish industry standards and certification methods for FGM materials to ensure their dependability and safety [54]. Standardization encourages consistent quality control and performance standards, promoting the broad use of FGMs in essential applications.

5.8 Biomedical and Healthcare Applications

Focusing on developing FGMs for biomedical and healthcare applications such as implants and prosthetics might be a promising path toward their expansion and utilization. The benefits of creating FGMs for specific tissues that match the tissue's mechanical and biocompatibility needs, leads to better patient products [5, 28]. This is the future of improving the quality of life through material innovation.

Therefore, what lies ahead for the FGMs is an explosion of novelty and newness, where developers and researchers embark on further investigation into these various avenues. Multi-gradient FGMs, nano-structured materials, advanced characterization techniques, computational modelling, integrated processing, sustainable practices, customization, biomedical applications, and standardization are some areas where material design in engineering will see remarkable changes that will have a massive impact.

6 Conclusion

Fabrication of functionally graded materials (FGMs) by using the innovative course of severe plastic deformation of powders opens up a new horizon in materials science. With their unique ability to provide precise characteristics, FGMs have shown great potential for various industries. Given the ongoing research behind this field, there is likely to be a flurry of revolutionary advances and applications for FGMs. With the ongoing development of FGMs via severe plastic deformation, there is a potential to drive a revolution in material science and engineering that delivers efficiencies, sustainability, and performance improvements for the various industries.

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