Chapter 17

Laser Engineering Net Shaping Method in the Area of Development of Functionally Graded Materials (FGMs) for Aero Engine Applications - A Review

Patricia Popoola, Gabriel Farotade, Olawale Fatoba and Olawale Popoola

Additional information is available at the end of the chapter

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Abstract

Modern aero engine components are subjected to extreme conditions were high wear rate, excessive fatigue cycles, and severe thermal attack are inevitable. These aggressive conditions reduce the service life of components. Its generic effect is magnified in the light of understanding the fact that aero engine parts are highly sensitive to functional and dimensional precision; therefore, repair and replacement are great factors that promote downtime during operation. Hard thermal barrier coatings have been used in recent times due to their optimized properties for maximum load bearing proficiency with high temperature capability to meet performance and durability required. Nevertheless, less emphasis is being given to the coating-substrate interaction. Functionally graded structures have better synergy and flexibility in composition than coatings, giving rise to controlled microstructure and improved properties in withstanding acute state of affairs. Such materials can be fabricated using Laser Engineered Net Shaping (LENS™), a laser-based additive manufacturing technique. LENS™ offers a great deal in rapid prototyping, repair, and fabrication of three-dimensional dense structures with superior properties in comparison with traditionally fabricated structures. The manufacture of aero engine components with functionally graded materials, using LENS™, can absolutely mitigate the nuisance of buy-to-fly ratio, lost time in repair and maintenance, and maximize controlled dimension and multi-geometric properties, enhanced wear resistance, and high temperature strength. This review presents an extensive contribution in terms of insightful understanding of processing parameters and their interactions on fabrication of functionally graded stainless steel, which definitely influence the final product quality.

Keywords: Functionally graded materials, LENS™, processing parameters

1. Introduction

1.1. The aerospace industry

The urge for advanced materials and faster processes for manufacture of products and delivery of services is critical in the aerospace industry due to the increasing rate of air travel and stringent environmental regulations. Researchers and manufacturers, under constant hand-to-hand interactions, are strained to meet demands and maintain supply chains. However, research-driven technologies have, relatively, created a platform for non-stop affordable flights with destinations as far as the North Pole, belting over to the other flank of the world. These advances suppress the underlying challenges in the past, a major percentage of aero engines parts are made of super alloys and hard alloys coated with thermal barrier coatings (TBCs) to improve their elevated temperature strengths. The use of super-alloys is a valuable consideration, withstanding high temperatures, mitigating the concern for premature part failure and limited air travel-engine use duration but to a reduction in application as a result of low service strength at ultra-high temperatures for a very long time. In turn, repair and replacement of intricate regions of the aero engine, such as compressors, turbine blades, pistons, and cylinders, may have adverse effects in terms of loss time during service. Another issue is the need to reduce the usage of expensive rare elements in the manufacture of high strength-high temperature components in the engine, as this will pull a net positive effect on the customer's effective evaluation and interest [1]. Based on its high precision and sensitivity to minute anomalies, engines account for approximately 30% of the life cycle cost of modern airlines [2]. As a result of this, materials engineers are constantly on the frontline of developing highly multi-functional materials with less production time, which will maintain their operating properties over a wide range of extreme temperatures for extended flight hours.

2. Functionally Graded Materials (FGMs)

2.1. History

The concept and processing of FGMs seem to be a new generational novelty but only the processing techniques, invented by humans, can be considered as innovative. FGMs have been existing as a result of nature. Human bones, skin, and bark of trees are examples of naturally occurring FGMs. The first humanly created FGM was industrialized in Japan in the early 1980s with the idea of fabricating a space craft during a space plane project. Eventually, enormous studies have been performed on advancing the viability of these materials [3].

2.2. Definition

FGMs are composites possessing continuous and coherent variation in composition, micro-structure [4], and even mechanical properties [5] from a region to another along the build axis, in an effect to attain improved performance and reliability. Traditional composites are associated with frequent thermal stresses, stress singularities, and residual stresses due to

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solidification history while the FGMs offer new generational components that can endure these critical thermal and mechanical stresses that are typical with aircraft engines and aerospace assembly during operation [6]. The rationale for the resistance to these stresses is the gradient effect of properties in FGMs and also the ability to integrate materials with contradicting properties such as high wear resistant ceramic and a tough metal in a single structure [7]. In addition, the feasibility and ease of tailoring material properties to match the desired requirements is a tip of the numerous benefits of these advanced composites. Patterns made with FGMs are presented in Figure 1.

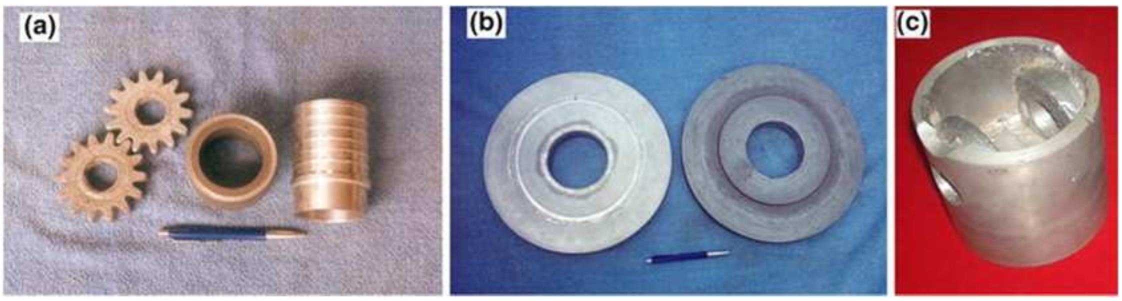

Figure 1. Functionally Graded Components; (a) Cylinder liners and gears; (b) Brake rotor discs; and (c) Piston fabricated by centrifugal casting method [8].

There are two major ways by which FGMs are synthesized, the first is an incessant formation, whereby compositional change seems invisible with no distinct discrete gradation of layers. Secondly, a step-wise synthesis is achieved by stacking layers with near-composition as a fractional material's composition dominates while the other declines with position. In the latter, the inhomogeneity in composition can physically be detected. These methods of synthesizing FGMs consist of similar preparation modes namely: gradation and consolidation. Gradation enables the formation of layers of different percentage compositions with little or no significance in the composition change along the axis of build up, while consolidation takes care of the elimination of sharp discontinuous interfaces present between these successive layers and conversion of these layers into continuous or single gradient structure through material transport. Optimal achievement of a successful FGM structure is highly dependent on the chemistry of bonding between successive layers, therefore materials scientists have combined different techniques to achieve suitable functionally graded structures that are functions of the component materials [9, 10] and prior knowledge of the uneven shrinkage of sintered layers, as a result of dependence of sintering pattern to the particle size, porosity, and composition of the elemental powders [11]. However, numerous theoretical efforts on fabricating and analyzing the adherence of FGMs to required expectations have been reported four decades ago, but industrial applications have been restricted due to little knowledge of processing techniques of these materials until recent times [12].

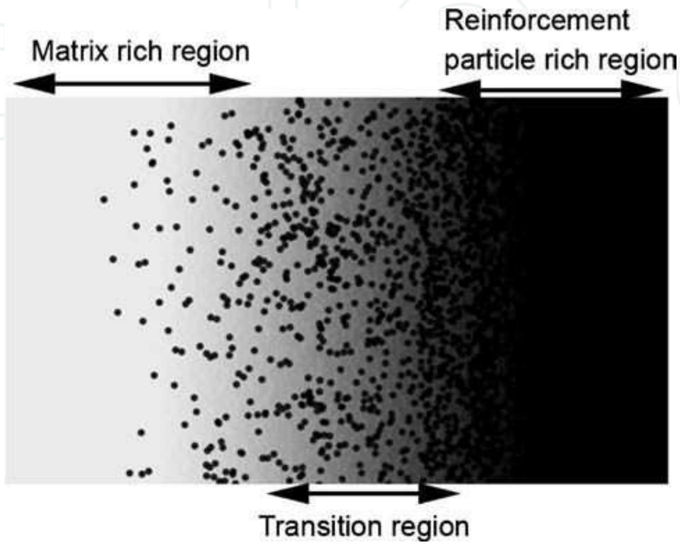

Figure 2. Representation of a typical functionally graded material [8].

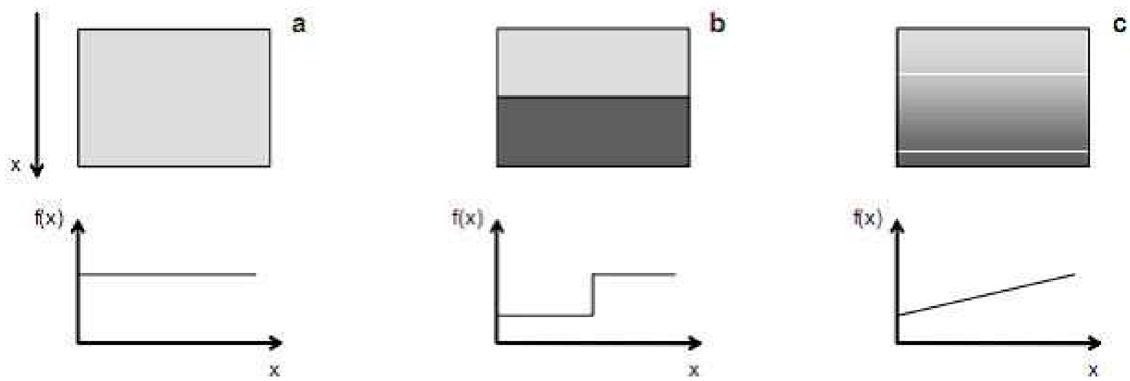

Figure 3. Diagrammatic representation of (a) homogeneous material; (b) layer-wise and; (c) FGM [13].

3. Operational properties of FGMs

In an FGM, the presence of different phases account for the various properties possessed. These phases make the material behave as a heterogeneous material unlike alloys and composites that have unique properties. An effect of this is the difficulty of enumerating material parameters [14]. In recent times, several studies have been performed to produce models that account for the effective material properties. Application of the Mori-tanaka method to establish directives for mixing of ceramic-metal composites [15], synthesis of experimental and analytical methods to determine elastic behavior of graded materials using micro-indentation approach [16], the investigation of properties of graded materials by inverse analysis, and instrumented indentation using kalman filter technique [14]. Also, the thermal residual stresses at the layer interface that also influence the mechanical properties of these materials have been studied [17]. Different approaches are adopted to investigate and determine the effective material parameters in order to understand the elastic-plastic behavior of FGMs when subjected to thermo-mechanical loading.

4. Processing techniques of FGMs

With increasing development of automated materials processing techniques, suitable techniques have been constructed in order to achieve various graded structures irrespective of component geometry and size. The use of these techniques is based on the position of the desired gradation. There are two types of gradation in a component. The thin gradation is mostly situated at the top part of the component while the bulk gradation is effective in the wholeness of the component. Thin gradation can be achieved by plasma spraying, self-developing high temperature synthesis, and vapor depositions (Chemical or Physical). Centrifugal method, powder metallurgy, hot and cold pressing, sintering method, infiltration method, and solid free form techniques are typical bulk gradation techniques [3]. The current and typical processing techniques adopted in fabricating FGMs are discussed below.

5. Thin FGM processing techniques

5.1. Vapor deposition

The vapor deposition technique is of importance due to its concept of iso static or vacuum hot pressing of desired alloys to form a composite component. With this technique it is possible to achieve a controlled deposition and deposition thickness, also, layer spacing precision for laminated grading. Sputtering [18], thermal deposition, and chemical vapor deposition are forms of direct vapor deposition that have been reported to be of good consideration for microlaminates [19]. Jet Vapor Deposition (JVD™) is a later form that deposits concentrated levels of different materials at reduced vacuum situations using an unreactive gas jet. The unreactive gas jet is combined with a resistive evaporation supply that concentrates the deposits [20]. Vapor deposition can be adopted to deposit functionally graded coatings with exceptional fine microstructure on surfaces of aero engine components. Mitsubishi Miracle inserts were functionally graded with chemical vapor deposition of a three-layer structure on a carbide substrate. This tremendously reduced the challenge of plastic deformation and damage [21].

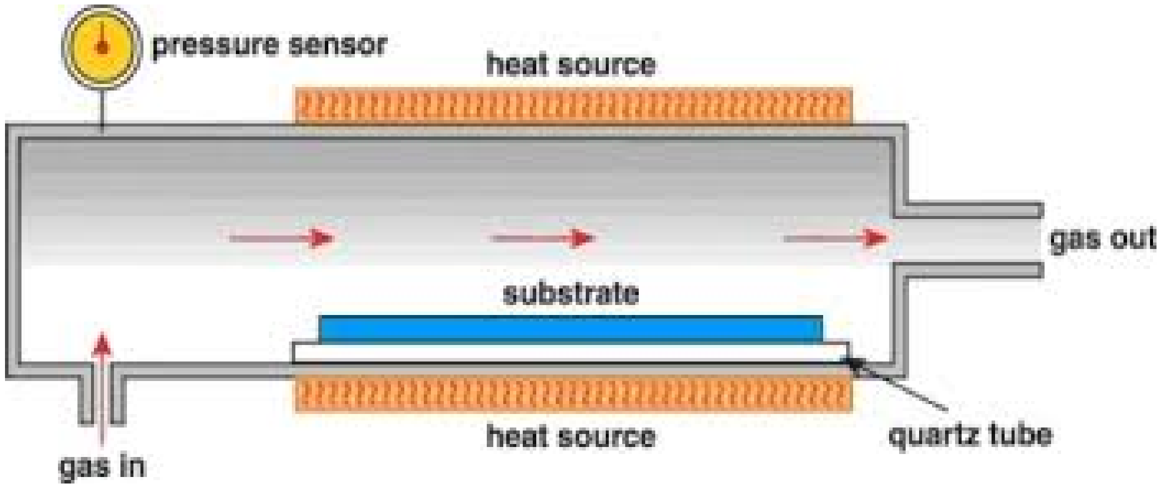

Figure 4. A schematic view of the chemical vapor deposition process [22].

5.2. Plasma spraying

Thermal spraying processes are typically called different names such as plasma spraying, metal spraying, high velocity oxygen fuel (HVOF) spraying, arc spraying, etc. Considering a porous ceramic coating that is applied to a low corrosion resistant component, a typical composite for the hot regions in aero engines, high velocity powder particles possessing elevated melting point is melted and accelerated by the heat generated by the plasma cloud towards the substrate. Required coating thickness is achieved by successive actions of the plasma cloud. Hard, low friction, and improved fatigue resistant coatings can be achieved for applications, such as airplane landing gear piston surfaces, applying this technique [23].

Conventional thermal-sprayed TBCs have been reportedly stated to spall when subjected to mechanical loading at ultra-high temperatures due to their low bonding strengths and residual stresses. Functionally graded TBCs are suitable materials to resist such challenges. In the work performed by Khor and Gu, functionally graded coating of yttrium-stabilized ZrO_2/NiCo-CrAlY was used as a TBC. The coating was applied using thermal spray technique. Highly deposited coating with enhanced coating density and chemical homogeneity was achieved compared to the results from duplex coatings, in addition it was observed that the oxidation of the FGM coating was impeded. Zirconia-based coatings are commonly used in thermal spraying due to the formation of non-transformable tetragonal phase that does not undergo martensitic transformation during cooling by quenching [24]. A schematic illustration of thermal spraying is shown in Figure 5.

5.3. Ion Beam-assisted Deposition (IBAD)

Ion Beam Assisted Deposition (IBAD) can be referred to as deposition of thin film by the blending of evaporation with simultaneous bombardment in high vacuum environments. The simultaneous bombardment involved in this technique makes it different from other deposition techniques. Effective modification can be achieved by the bombardment of developing

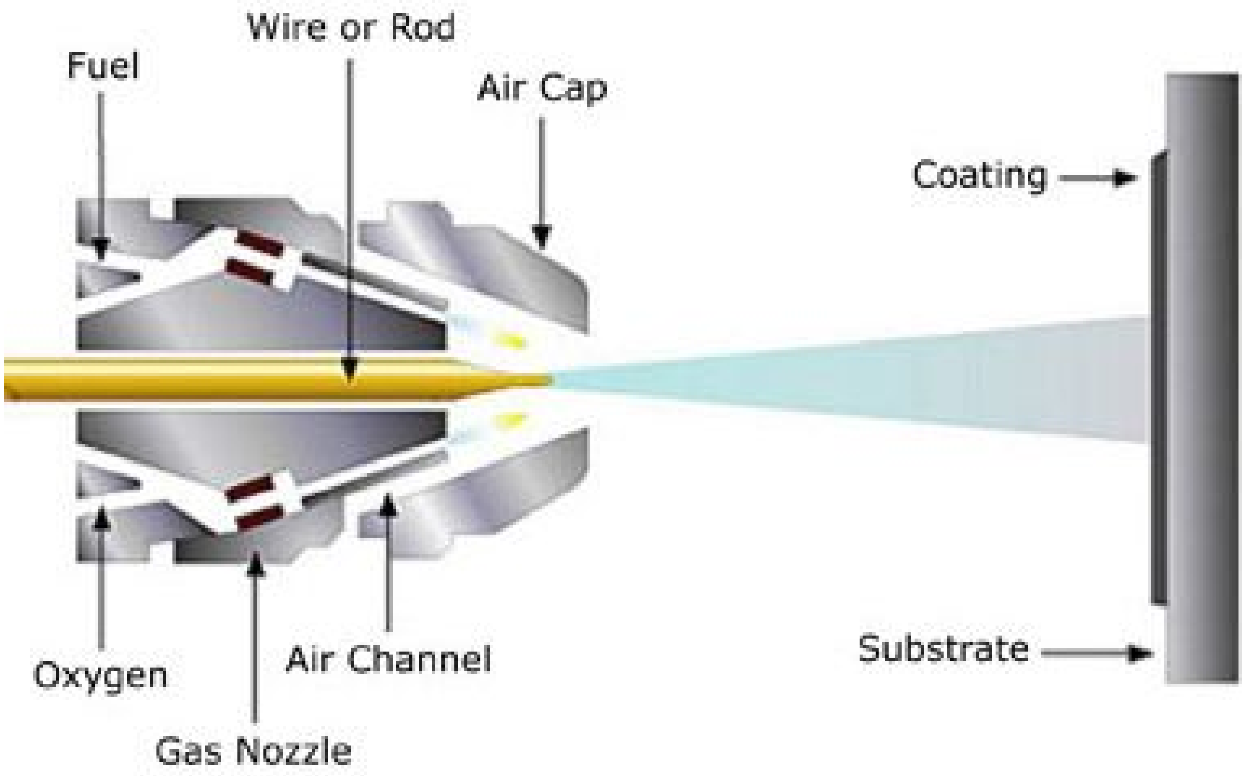

Figure 5. Concept of thermal spraying [25].

films with high velocity particles in various morphologies that is crucial to the activity of thin coatings. These can be achieved by: change in orientation, densification of developing films at low temperatures, and alteration of grain size and mechanical properties. This technique can be used to deposit coatings of high bond strength, varying the concentration of particles for each successive layer through simultaneous bombardment. Functionally graded coatings fabricated by IBAD are suitable for applications at low temperatures, having a high control of developed film/coating, while the chemical mixture of the substrate with the film provides better adhesion compared to vapor deposited counterparts [26]. Ion beam assisted deposition can be limited by substrate geometry and low mechanical strength of deposition.

5.4. Electrodeposition

Functionally graded deposits of metal-ceramic composites and bi-metals have been achieved by electrodeposition in recent times. This is attained by co-deposition of ceramic particles and metallic particles from electrolytes containing the metal ion, varying either the particle ratio or the current density with respect with time. Pulsed ElectroDeposition (PED) is a novel technique of depositing nanocrystalline materials on numerous metallic substrates.

With electrodeposition, single-layered coatings have proven to project lower expectations compared to their graded counterparts in terms of corrosion, mechanical, and wear properties. Deposition with just a single electrolytic bath has also been performed with less additive involved to achieve controlled, excellent graded coatings.

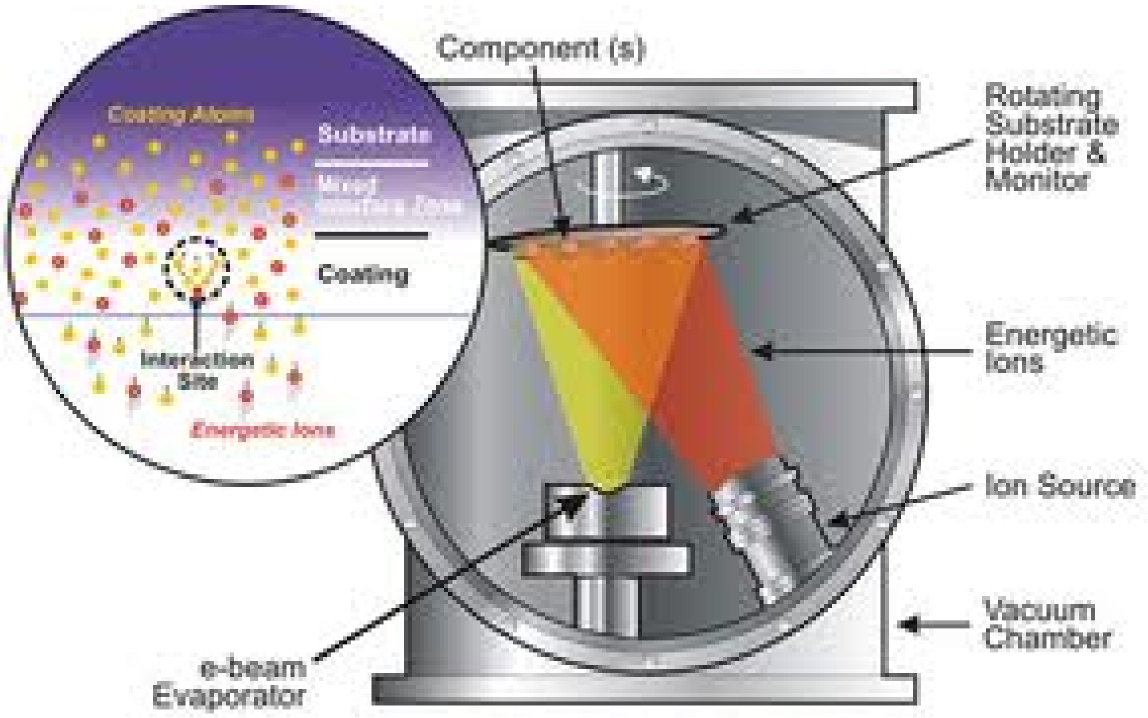

Figure 6. Ion Beam Assisted Deposition (IBAD) Process [27].

Coatings are graded perpendicular to the surface providing properties parallel to surfaces where composition is uniform, hence functionality cannot be tailored in any direction with these techniques [28].

6. Bulk FGM processing techniques

6.1. Powder metallurgy

Powder metallurgy is one fabrication technique that is obviously adopted for FGMs that makes use of solid materials (powders). Powder preparation, material processing, and forming and sintering processes are stages that appear as principal characteristics of this technique. The powder preparation entails methods such as grinding, deposition or chemical reactions, and producing a massive rate of powder. Also, the rate of production can be controlled to the desired size. Considering the processing stage of the powder, attention is placed on the sampling and distribution of the powders while those of forming (piling and pressing stage) and sintering (consolidation of powders) stages are influenced by the working environment, which must be achieved at room temperature and high pressure, consecutively. Powder metallurgy possesses the feature of premixing powders and piling layers with graded compositions that fuses the layers together with either hot pressing or cold pressing [8]. During the sintering stage, preservation must be incorporated in order to achieve good product quality because some metals that are highly reactive can be oxidized during hot pressing. However, the limitation in fabricating FGMs with powder metallurgy is the complexity in densification

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mode because densification is based on the dominant fraction of powder (positional matrix) which, thus, results in distortion and variation of shrinkage of the layers [29].

6.2. Centrifugal casting

FGMs fabricated by centrifugal force can undergo either centrifugal, centrifugal slurry, centrifugal pressurization, or centrifugal casting method [30]. Gradation occurs when a homogeneous molten metal, dispersed with ceramic particles, is stirred and left to settle based on differences in density. Studies have shown suitable centrifugal methods for different materials; for instance, centrifugal solid-particle method is suitable for Al/SiC and Al/Al_3Ti FGMs and centrifugal in situ method used for the processing of Al/Al_3Ni FGMs [31]. Unlike stepwise gradation, which occurs in powder metallurgy technique, FGMs processed with this technique possess continuous gradation [32]. Centrifugal casting of FGMs is dependent on the molten matrix content, rotation speed, and the rate of settling conditions of the particle to achieve a controlled and desired production in mass [33]. However, this technique is limited in producing FGM components with regular geometrical shapes.

Other common techniques that are not elaborated are infiltration [4], spray casting [8], and ultrasonic separation [34].

7. Laser-based fabrication of FGMs

FGMs by laser-based techniques in the aerospace industry is rapidly sky-rocketing because they offer unique solutions to industrial problems. Aero engines experience limited off-flight time in order to maximize their service life and this requires cyclic rapid heating and cooling of the engine parts. As a result of this effect, materials may fail due to fatigue and thermo-mechanical stresses. As stated earlier, FGMs are applicable to mitigate these situations but most techniques used in fabricating these materials fail to produce consistent and desired properties at ultrahigh temperatures and extreme stresses that are typical with aero engine components. Therefore, laser-based techniques are outstandingly appropriate to fabricate these materials with better flexibility of controlled fabrication to produce complex components having superior hardness/toughness compatibility and minute differential shrinkage. Rapid manufacturing is another advantage of fabricating bulk FGM components with laser-based techniques, whereby functionally graded engine parts are produced within hours. Composition and properties can be highly monitored within the structure during fabrication by either pre-mixing or combining various elemental powders using multiple feeding systems, depositing the powders in a melt pool created by a laser. The different forms of laser-based techniques used for FGMs are: laser surface melting, laser cladding, laser surface alloying, direct laser deposition, LENS™, and so on. Powder feed systems have better adhesion and metallurgical properties than powder bed systems, and also the manufacture of FGMs with powder bed laser based systems is limited to layer-wise gradation and not localized functionality. This is due to the fact that positional distribution of elemental powders cannot be accounted for in every layer. Examples of powder feed systems are direct laser metal deposition, laser surface melting, laser surface alloying, laser cladding, and LENS™ techniques.

Laser surface melting, alloying, and laser cladding are mostly referred to as laser-based surface modification techniques. These techniques are used to apply heat- and wear-resistant coatings on surfaces of alloys and metal matrix composites. Based on the direct localized laser energy density, limited zones are affected by heat so grains are refined due to rapid cooling as heat is conducted away from the modified surface regions. In the case of laser surface melting and alloying, mixing between the deposited coatings and the substrate occurs at regions close to the surface. This allows proper metallurgical cohesion between the coating and substrate while the bulk material is unaffected. Laser cladding possesses a very low dilution of coating in the substrate surface. Although these techniques provide improved graded properties to components, the presence of sharp discontinuities between the substrate composition and the coating may not withstand extreme thermal stress conditions components are exposed to in aero engine compartments. Furthermore, smart structures that possess functionality in any direction as desired for respective applications cannot be achieved with laser surface modification techniques as gradation of properties is limited to directions perpendicular to layer surface. For instance, complex components and intricate regions of components cannot be altered satisfactorily with laser surface modification techniques. On the other hand, the LENS™ technique can be used to scale through these challenges because of its flexibility to pre-design the desired component with a CAD software and convert it to an STL (Standard Triangulation Language) file that slices the bulk design to thousands of layers. The composition of each layer can be fabricated by using multiple powder feeding systems and controlling their speed of deposition. The realization of the final product can be achieved within weeks irrespective of the size of the engine component.

Here, in this chapter, we will look into the fabrication of FGMs using the LENS™ technique.

8. LENS™ technique

Highly dense three-dimensional FGMs are produced using a CAD model that is then fed into the laser system through an STL file (slicing of the designed model into layers). The sliced image is interpreted by the laser system. The laser system can be connected to a CO_2 laser or an Nd:YAG (Neodymium Yttrium-Aluminium Garnet) laser source. Powder feeding systems are connected to a delivery head of the laser system, whereby an inert gas serves as the carrier gas of the material powders from the feeding system to the work area. The delivery head is made up of a lens that concentrates the laser beam to a focal point to create a molten pool. As the deposition of the powder is done co-axially with the laser beam into the molten pool, the powder melts and fuses, thus, creating a layer along the direction of deposition. This process can be seen in the illustration given in Figure 7.

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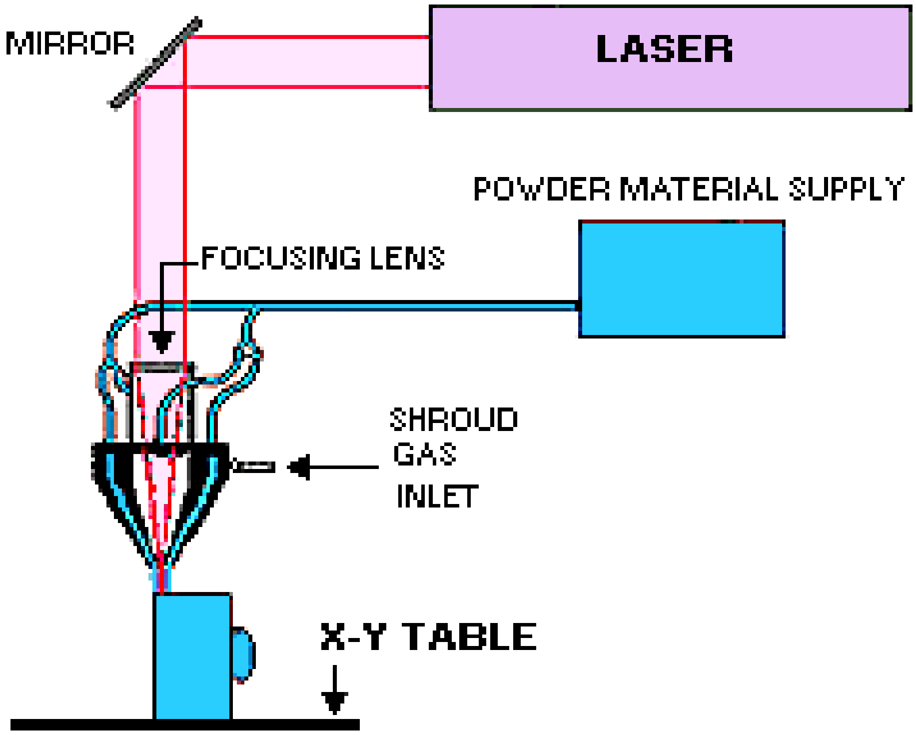

Figure 7. Set up of a LENS™ process [35].

9. Benefits of LENS™ over other techniques

The manufacture of FGMs using LENS™ have been realized efficaciously [36]. The process is carried out in an inert environment having an oxygen concentration that is less than 10 ppm, as this protects the melt from oxidation. The fabricated part may undergo heat treatment, hot iso-static pressing, or light machining to fit the required specification. Fine microstructures develop while consolidating metal powders due to rapid cooling of preceding layers. This results in improved tensile strength and toughness of metallic components than conventionally fabricated ones.

LENS™ is not restricted to proprietary material formulations, which encourages the formation of numerous novel alloys and composites, as is typically the case with most other processes. The powder size generally used ranges from 20 to 100 μm. Either pre-alloyed powders or suitably blended elemental powders can be used. Elemental powders can be delivered in precise amounts to the melt zone using separate feeders to generate various alloys and composite materials in situ. With the adoption of this technique, countless number of FGMs can be fabricated into complex shapes as the rate of elemental powder deposition can be controlled for each feeder during the fabrication for each layer and the final product can be achieved within hours. The following is a summary of the advantages of LENS™ over other laser-based additive manufacturing techniques:

- Fully dense fabricated parts with no compositional degradation
- Possibility of repair and overhaul, rapid manufacturing, and limited run manufacturing
- Reduced manufacturing time and cost in realization of functional metal parts [37]
- Additional cost savings is realized through increased material utilization as compared with bulk removal processes
- Components can be fabricated with reduced or eliminated micro-segregation, refined microstructure [38], and graded compositions
- Closed loop control of process for accurate part fabrication
- Potential to significantly reduce manufacturing costs, reduce the time from design to market, and simultaneously improve component performance
- Ability to tailor deposition parameters to feature size for speed, accuracy, and property control (i.e., the possibility to create parts where the composition and properties can be tailored to best meet the needs of the application)
- Composite and functionally-graded material deposition
- Mechanical properties similar or better than traditional processing methods
- Environmental compatibility based on controlled containment of expensive and hazardous materials during processing using inert conditions [39]

Figure 8. Fabrication of impeller pump using LENS™ [40].

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10. Processing parameters of LENS™

The desired properties and outstanding performances of aero engine components made of FGMs using LENS™ can only be achieved if the various parameters and their influences on the final outcome are properly understood. For this reason, the primary processing parameters that are dominant are briefly discussed below.

10.1. Feed rate

The powder feed rate is the speed at which the carrier gas (inert gas that is mostly argon) conveys the elemental powders through the tubing to the delivery head, depositing the powders into the melt pool created by the focused beam on the substrate. Associated problems of powder delivery in LENS™ are the constraint in sustaining retention capability, poor deposition rate, and high surface roughness in the finished part [41]. The layer thickness is influenced by the corresponding feed rate. If the feed flow rate is high, its outcome is a highly thick layer formation. The deposited layer thickness is a function of dimension, geometry, and chemistry between layers, i.e., the thicker the deposited layer, the poorer the adhesion between layers [37]. Feed rate is key in the development of FGMs. Light components are needed for aerospace engines, therefore, amount of deposited layers should be minimum as possible to achieve the desired functionality. Higher feed rate will cause more deposition of powders, with this, the material/component thickness and density are increased, having a net increase in the weight of the engine. In addition, increasing the feed rate attracts higher beam energy to fuse the powder deposited, resulting in an increased thermal stress and distortion in the fabricated part.

10.2. Laser power

As the intensity of the laser beam increases, with time the energy injected into the melt pool also increases. This time rate of energy from the laser beam is called the laser power. Mahamood and Akinlabi [42] studied the effect of laser power on the surface finish of the Ti6Al4V substrate with deposited Ti6Al4V powder using laser metal deposition. The scanning speed, powder flow rate, and the gas flow rate were kept constant. According to their analysis, surface roughness decreased linearly with increasing laser power, thereby improving the surface finish. A study by Alimardani et al. [43] on the effect of scanning speed and melt pool dimension increase on surface finish quality showed that the melt pool geometry control and temperature had a positive influence on surface finish.

Considering the laser surface modification techniques mentioned earlier, laser surface melting and laser surface alloying require high energy input in order to achieve a thorough dilution of the coating in the surface region of the substrate. High laser power encourages large heat affected zones that may eventually alter the properties of the bulk substrate. For materials with low thermal conductivities, such as titanium, formation of large grain structures is inevitable, consequently, diminishing high temperature strength during service. This problem can be corrected with secondary heat treatment but the technique becomes less economical.

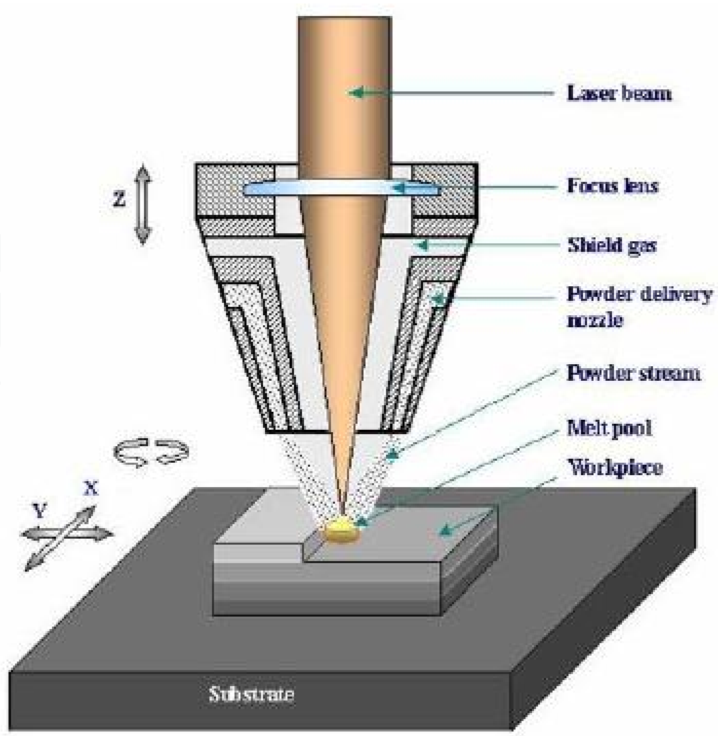

Figure 9. Schematic illustration of the LENS^{TM} process [44]

10.3. Scan speed

The speed at which the laser beam carries out its deposition along a track path, as the component is being built, is known as the scanning speed. An increase in the scanning speed can result to a reduction in the expected time for completion of the proposed component. Nonetheless, this can be deleterious to the final product in such a way that the difference in layer height between the edges and the midmost regions may occur as the delivery head decelerates, at constant powder flow rate, depositing more materials at the edges, as in the case of a reverse deposition for each layer.

11. FGMs and LENS^{TM}

Co-axial deposition capability of LENS^{TM} enables the feasibility of fabricating smart and functional components, allowing maximum precision in composition and improved properties compared to conventional methods. This technique takes care of the issue of oxidation during material processing by working in an enclosed compartment. The compartment is stripped of oxygen to a level lower than 10 ppm, while further prevention is realized by the use of an inert carrier gas from the powder feed system, through the delivery head to the work area, and also a shielding gas. This makes the process much effective in recycling the unmelted powders.

New innovation can be introduced into the aerospace technology with a reduced trepidation over ultrahigh temperature effects on engine parts when fabricated with LENS™. The use of metallic bond coat to prevent migration of delicate elements either from substrate to coatings or otherwise can be eliminated because such migration leaves the region bare and exposes the coating/substrate to oxidation/corrosion as the case may be, thus, functionally graded coatings blended with substrate will achieve higher reliability.

Author details

Patricia Popoola[1], Gabriel Farotade[1], Olawale Fatoba[1] and Olawale Popoola[2]

*Address all correspondence to: popoolaapi@tut.ac.za

1 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa

2 Centre for Energy and Electrical Power, Department of Electrical Engineering, Tshwane University of Technology, Pretoria, South Africa

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