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SOME AEROSPACE APPLICATIONS OF FUNCTIONALLY GRADED MATERIALS

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Abstract

Functionally graded materials (FGMs) are currently the subject of great and ever-growing interest from industry and science, and are widely used due to their advantages. These advantages are due to their unique properties and, therefore, their many real and potential applications in various fields of industry, science and everyday life. In this literature review paper, we will briefly focus on some of the properties of FGMs and on some of the existing and expanding future applications of FGM in aerospace and related industries. A critical discussion is presented. Possible future expansion of work in this area is being considered.

Introduction

The present review paper is motivated by a huge interest in the rapidly developing field of materials science, namely, functionally graded (or functionally gradient) materials (FGMs). This interest is due to the ability to produce materials with tailored properties which are suitable candidates for numerous high tech applications such as aerospace, bioengineering and nuclear industries. Over the past two decades, the number of publications in the field of FGMs research is growing exponentially. The information provided has been compiled from the existing literature on FGMs and it may be considered as a brief introduction review to the subject mentioned above. Functionally Graded Material (FGM) is an advanced material that exhibits a gradual change in material properties in at least one spatial direction. FGMs can be designed for specific properties, functions and applications.

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Overall properties of FMG are unique and different from any of the individual material that forms it. FGMs are now recognized, by many people, as important composite materials throughout the world. But they are not only a special class of composite materials, although some of them today can be considered as the next step in the development of composite materials. There is a wide range of FGMs and a variety of their applications, and their number in the future is expected to increase. In this paper, an overview of some of the most promising properties and aerospace applications of FGMs is presented.

Definition, origin, classification, methods of production of FGMs

FGMs are an advanced and artificial class of engineered materials characterized by gradual variation in properties depending on the spatial position in the material. Functional change occurs in at least one of their properties. The FGMs area is still under development and the precise definition, classification and properties of this relatively new advanced class of materials are still not generally accepted and are constantly being supplemented. FGMs occur in nature as: bones, teeth, human skin, wood, bamboo etc. The property gradient in the material is caused by a position-dependent chemical composition, microstructure, porosity, density, grain size, refractive index, lattice constant, atomic order, etc. The gradient change in FGMs can be of various types, but it is always continuous and smooth, and it is never abrupt in all directions of the gradient. In FGMs the composition and/or microstructure vary in space, following a predetermined law, in one or in more than one specific space direction.

FGMs are microscopically inhomogeneous materials, such as: composites, single-phase materials, two-phase materials, multiphase materials or nanostructures. Functional properties of FGMs change uniformly at least in one dimension of the particle, film, joint, coating, nanostructure or a bulk sample.

Due to the continuous gradient in their microstructure, FGMs do not possess well distinguished specific interfaces or boundaries between their different regions, as in the case of conventional composite or inhomogeneous materials. Because of this, such materials posses good chances of reducing mechanical and thermal stress concentration in many structural elements, which can be developed for specific applications.

For the first time, in 1970, the general idea for theoretical applications of graded structure composite and polymeric materials was suggested as a concept by Bever et al. [1]. However, these works had only limited impact, probably due to a lack of suitable production methods and technologies for FGMs at that time.

The necessity to bring into practice new materials appears crucial with space vehicles: on the surface side and the skin plates should have very good heat-resistance; on the inside however, – high mechanical qualities (e.g. toughness) were needed. The problem was successfully solved in Japan in the mid of 1980s by manufacturing specific composite: metallic matrix and ceramic particles with graded distribution of these particles. So, the scientific term “functionally graded material” was first introduced in Japan in 1984 for development and implication of thermal barrier materials, being developed for the reusable rocket engine [2–4].

The structural unit of a FGM is referred to as an *element* or a *material ingredient* [2]. FGMs can be composed of various *elements*. *Element* is a conceptual unit for constructing a FGM that includes various aspects of its chemical composition, physical state, and geometrical configuration. The term *element*, probably expresses the overall FGM concept best. *Elements* can resemble biological units such as cells and tissues. As example: bamboo, tooth, and bone all have graded structures consisting of biological *elements*. Examples of typical *elements*, of which FGMs can be composed, are listed below:

- chemical – inorganic, organic, ceramic, metal, polymer, alloys, semiconducting materials, nonmetallic materials;
- physical – electronic state, ionic state, crystalline state, dipole moment, magnetic moment, band gap, potential well, barrier, quantum well;
- geometrical – granule, rod, needle, fiber, platelet, sheet, pore, texture, orientation;
- biological – complex macromolecule, organelle, cell, tissue.

Depending on the geometry and cross-sectional area of the produced material, FGMs can be divided into two main groups; thin and bulk FGMs [5,6]. Thin FGMs are usually in the form of relatively thin sections or thin surface coatings and have thin cross sections. Bulk FGMs are those with thickness greater than 1 mm and whose functional properties vary with respect to the gradient profile of the material.

A separate group of very thin FGMs are low-dimensional nanostructured FGMs (or functionally graded low dimensional nanostructures) [7–9]. Examples are semiconductor graded gap quantum wells (QWs) [10] and semiconductor graded gap superlattices, which electronic structure may tailor for specific applications. Most often this happens in their structure by graded compositional and doping changes in the growth direction. These properties enable one to use these nanostructured FGMs for high-performance room temperature optoelectronic devices. Moreover, to improve the performance of these optical devices, band structure modifications have also been investigated. The modification of the well potential shape (functionally graded QW region) can create different optical properties and thus optimize nanostructure-based devices compared to conventional rectangular QWs. In Fig. 1 is presented a schematic band diagram of: (a) conventional rectangular QW (without grading); (b) linear analog graded-gap QW; (c) parabolic graded-gap QW [10]. The $Al_xGa_{1-x}As$ alloy composition x in homogenious rectangular QW is constant, equals zero, i.e. the well is made of pure GaAs. The alloy composition $Al_xGa_{1-x}As$ in the linear well region varies linearly from x = 0.3 to x = 0.0 (from the left to the right side of the QW; see Fig. 1b). The aluminium concentration x for $Al_xGa_{1-x}As$ alloy in parabolic quantum well varies parabolically (Fig. 1c). In these three QWs cases we have pure AlAs at the barriers and the arrow above shows the growth and grading directions.

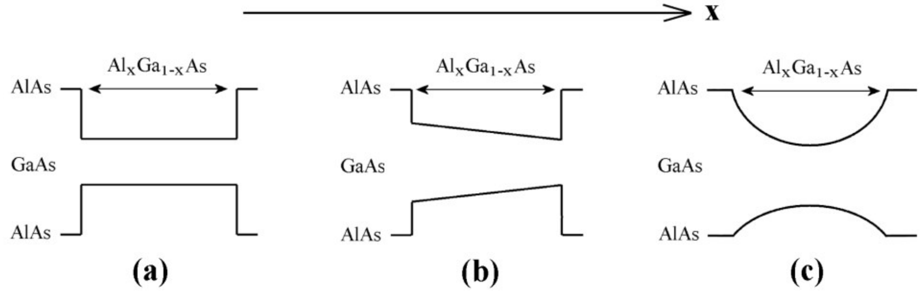

Fig. 1. Schematic QW band diagram: (a) rectangular QW - without grading, i.e. constant composition x; (b) linear graded-gap QW; (c) parabolic QW

Depending on the number of directions in which the properties have changed, we can distinguish one-dimensional, two-dimensional or three-dimensional FGMs.

Different types of functionally graded composites, depending upon the nature of gradient, are the following: fraction gradient; shape gradient; orientation gradient, size gradient type and dispersed phase gradient. [6, 11].

Some schemes of FGM structures are shown in Fig. 2. In Fig. 2a for comparison are shown two nongraded homogenous materials with abrupt interface. In one of the simplest FGMs, two different material elements change gradually from one to the other side as illustrated in Fig. 2b. In Fig. 2c two different material elements continuously change gradually from the center to the end (outer side). The elements can also change in a stepwise gradation illustrated in Fig. 2d. Fig. 2e shows the functionally graded joint/transition between two materials. Fig. 2f shows the continuously functionally graded outer surface or coating. The x arrow in Fig. 2 shows the grading direction.

Physical properties of FGMs can be described by material function f(x). This function shows the change/gradient of a particular property (for example such as composition) along one space direction – x, always following a predetermined law. In homogenous materials this function is constant (see Fig. 1a). In FGM (see Fig. 1b,c and Fig. 2-b,c,d,e,f). The only requirement for material function f(x) is that it be continuous or quasi-continuous, and smooth.

In Fig. 3 are presented material functions f(x) in the x direction of the corresponding material structures, shown in Fig. 2.

In the case of continuous graded structure, the change in composition and microstructure occurs continuously depending on the position. On the other hand, in the case of stepwise grading (Fig. 2d and Fig. 3d), composition and microstructure feature changes in stepwise manner, giving rise to a multilayered structure with interface existing between discrete layers. In some materials, if the width of the step is small enough (two or several atomic layers in a given direction, as with semiconductor hetrostructures and graded gap quantum wells, and superlattices), there are no obvious interfaces between layers which is achieved by current epitaxial methods of crystal growth.

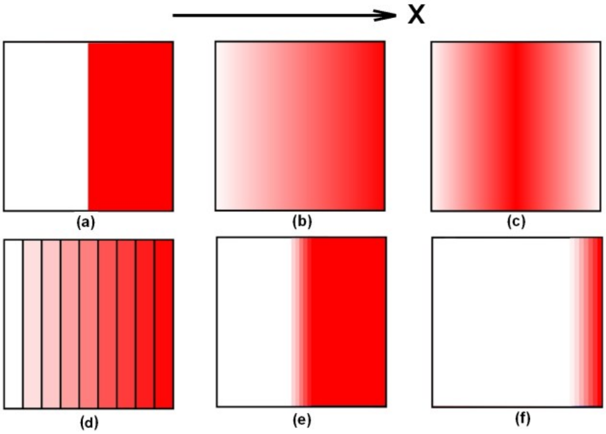

Fig. 2.: Type of FGM structure: (a) – structure without grading; graded structures - (b), (c), (e), (f) – continuous - linear; (d) - stepwise graded structure. Arrow x - is the grading direction.

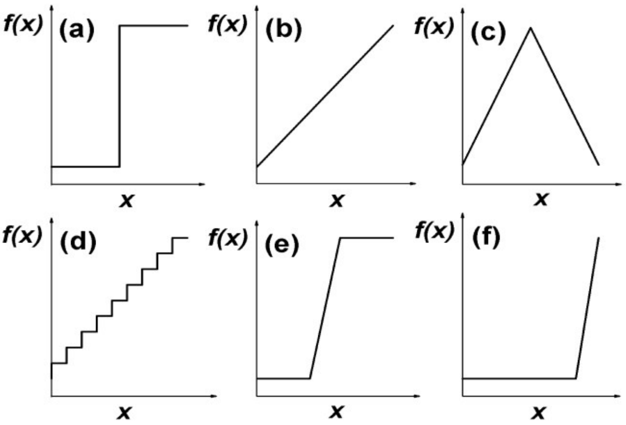

Fig. 3.: Material function f(x) in x direction (a) - structure without grading; (b), (c), (e), (f) – continuous- linear graded; (d) - stepwise graded structure.

A gradual distribution of pores, from the interior to the surface, is also a FGM. Even if the gradation of the *elements* is limited to a specific location in the material such as the interface, a joint (Fig. 2e), or a surface as shown in Fig. 2f, the material can be considered to be an FGM because it incorporates the FGM concept.

The fabrication process is one of the most important fields in FGM research. There are many different methods for producing FGMs [2, 5, 12–14]. Most of the processes for FGM production are based on a variation of conventional processing methods which are already well established. These methods are physical and chemical in form. There is a lot of literature available on the subject of their production. The choice of FGM manufacturing technology is mainly influenced by: the desired application, the FGM group of material to be produced, the material combination, geometry of the desired component, available manufacturing equipment for FGMs.

Major thin FGMs production techniques are various deposition processes such as physical or chemical vapor deposition, atomic layer deposition, spray deposition, electrodeposition, laser deposition, plasma spraying, self-propagating high temperature synthesis, ion beam assisted deposition, electrophoretic deposition, surface deposition method and coating processes. The choice of deposition is dependent on the performace required of the material.

Processing of bulk FGMs are usually energy intensive and slow, and cannot be produced using deposition techniques, such as vapor deposition [4, 15]. The process of manufacturing bulk FGM is generally grouped into two: the gradation process and the consolidation process. The gradation process comprises the constitutive, homogenizing and the segregation processes. The bulk FGMs consolidation process follows the gradation process. This process involves the sintering and solidification of the powder material. Processing conditions for the material are chosen such that their gradient structure is not altered while unequal shrinkage is also mitigated. Bulk manufacturing processes include powder metallurgy, metal casting, solid freeform fabrication techniques [5, 7], sequential casting, infiltration process, frictional stir casting, centrifugal casting method, melting processes.

A special group of very thin FGMs – functionally graded low dimensional nanostructures (such as compositionally graded gap QWs and superlattices) [7] are produced mainly by two epitaxial methods: molecular beam epitaxy and metalorganic vapor phase epitaxy. These modern crystal growth techniques make it possible to control the purity, size and directions at the atomic level.

Application areas of FGMs

The concept of FGMs, applicable to almost all material fields, is described as a systematic process of bringing incompatible functions such as thermal, wear and corrosion resistance, toughness and machinability into a single part [2, 15].

This has expanded the application of FGMs in many sectors. There is a big amount of real and potential applications of FGMs. The main, but not the only area of usage of FGMs, are materials and devices operating in extreme conditions (high temperature gradients, mechanical loads, etc.). In aerospace and nuclear energy applications, reliability rather than cost is the key issue. But in applications such as cutting tools, high temperature rollers, and engine components, which require wear, heat, mechanical shock, and corrosion resistance; the key issues are the cost/performance ratio and reliability.

Some examples of various applications of FGMs in different sectors are given below:

- aerospace (rocket nozzle, heat exchange panels, solar panels, turbine wheels, space plane nose, combustion chamber protective layer, body components, rocket engine components, reflectors, camera housing, caps and leading edge of missiles and space shuttle. etc);
- automobile (combustion chambers, diesel engine pistons, racing car brakes, crown of piston, cylinder liners, exhaust valves and valve seating);
- medicine (medical implants, teeth and bone replacement, artificial skin, drug delivery system);
- construction (roads – e.g. pavement life can be increased by 59% as a result of the grading of the asphalt concrete and base layers together);
- commodities (car body, sport goods, window glass, etc.);
- energy (energy conversion devices, nuclear energy, thermionic and thermoelectric converters, fuel cells, solar batteries, fuel pellet, etc.);
- electronics (graded band semiconductor, substrate, sensors);
- optoelectronic (antireflective layers, fibres, GRIN lenses);
- nanotechnology (nanostructured devices and systems etc);
- chemical plants (heat exchanger, heat pipe, slurry pump, reaction vessel);
- optics (optical fibre, lens);
- nuclear (first wall of fusion reaction, fuel pellets);
- energy conversion (solar cell, fuel cell, thermoelectric generator, thermionic convertor);
- engineering (cutting tools, machine parts, engine components, turbine blade, roller, shaft, etc.) etc.

Some aerospace applications of FGM structures

A special class of FGMs is metal porous materials, which appears as gas reinforced metal matrix composites with graded control of pore shape and orientation [3]. Like all porous metals, the ordered porosity metals have a wide range of applications including filters, catalysis, silencers, flame arresters, heat exchangers, fuel cells, electrolytic cells, and fluid substance separators, ionic rocket engine parts, self-lubricating bearings, thermal screens and vibration dampers. The most attractive applications are as components of rocket combustion chambers and oil high pressure filters. Gasar stainless steel is a promising material for medical applications, especially for artificial bones or joints with good corrosion resistance.

Thin shells, as very common structural elements, occupy a leadership position in civil, mechanical, architectural, aeronautical and marine engineering, since they give rise to optimum conditions for dynamic behavior, strength and stability. In other words, these structures support applied external forces efficiently by virtue of their geometrical shape. An important aspect in the successful applications of these structures is fact that shells cover large pans. As for many other shape kinds, conical, cylindrical shells and shells of complex geometry are very common structural elements. In [16] a layered epitrochoidal shell element has been used for the modeling and analysis of functionally graded composite shell structures. Obtained results have shown the strengthening role of functionally graded materials for shell structure. Static analysis of the functionally graded epitrochoidal shell under self-weight and thermal loading have been done and validated with the published results.

The problems of modeling and vibrations of FGM thin walled rotating blades that could be used in helicopters and turbomachinery applications and the associated subject of spinning circular cylindrical beams were considered [2]. In these studies, the blade was modeled as a pretwisted thin-walled shear-deformable beam of a nonuniform cross section with material properties varying in the thickness direction according to a power law. The thermal field was assumed steady state, and the rotation velocity was constant. The effects of material grading and blade taper ratios on the natural frequencies were elucidated. Besides free vibrations, the divergence and flutter instability of the blades, accounting for gyroscopic forces, were analyzed where both the natural frequencies and the spinning speed corresponding to the blade instability were significantly increased by appropriate variations in grading.

Thermal Barrier Coatings (TBCs) are typically used in applications where it becomes necessary to protect metallic or composite components in military and commercial aeroengines, aircraft engines, for gas turbine engines for automobiles, helicopters, marine vehicles, and electric power generators, combustion chambers from excessive temperature. The problems that have to be addressed to design TBC include processing technology, heat transfer during and immediately after the processing, microstructure formation, residual thermal stresses, micromechanics of TBC, and thermomechanical response during the lifetime [2, 4]. FGM TBCs are attractive due to the potential for a reduction in thermal stresses, avoiding delamination and spallation tendencies, prevention of oxidation. As for FGM TBC, the heat transfer problem was simplified due to the fact that it is typically one dimensional, occurring in the thickness direction. For example, if a FGM coating consists of a number of layers with constant volume fractions of individual components, the total thermal resistance can be evaluated as the sum of individual layer resistances. According to the authors [2, 4] if the coating will be sprayed as a multilayered system with a compositional gradient varying from pure metal adjacent to the substrate to a ceramic exposed layer, then obvious interfaces between the layers of the coating could be eliminated. Thermal fatigue may occur in TBCs subject to periodic temperature variations during their lifetime. As was shown, using a FGM coating may result in a five-time increase in the resistance to thermal fatigue compared to a conventional counterpart. Additionally, the oxidation resistance was improved as a result of the grading, as reported in [2].

Turbine blades are one of the most highly stressed rotating parts in gas turbines. In order to increase the efficiency and performance of turboengines, gas inlet temperatures in the high pressure turbines must be increased, and component cooling must be decreased. Here, ceramic TBCs with a low thermal conductivity applied on turbine components play a key role. Ceramic TBCs are connected to components by thin metallic bond coats, which also protect the components from hot corrosion and oxidation. Conventional bond coats are single layers of MCrAIY (where M = Ni or NiCo) or Pt-AI based materials. The interface between the bond coat and the ceramic top coat is the most critical region with respect to the lifetime of the both TBCs and bond coat (the MCrAIY layers). Increasing their lifetimes was achieved by grading the composition (with optimal concentration distribution) across the coating thickness ([12, 17] in [2]). Graded TBC systems are potentially advantageous compared with TBC systems that have ungraded layers. The use of FGMs to join high temperature materials is being actively investigated.

Space vehicles flying at hypersonic speeds experience extremely high temperatures from aerodynamic heating due to friction between the vehicle surface and the atmosphere. They are of two types: vehicles, that are launched vertically into space by a rocket propulsion system (like the U.S. space shuttle and the capsules used for the Apollo missions); and fully reusable spacecrafts, that are based on a horizontal takeoff either from a ground-based runway or from a horizontally flying carrier (as the U.S. National Aerospace Plane) [2, 17].

In the first type, after sufficient acceleration the rocket system completely separates from the space vehicle. During reentry at velocities greater than 11 km/s, rapid heating of the leading edge, where the heat protection shield is located, occurs at altitudes between 120 and 50 km, and maximum temperatures (the radiant equilibrium temperature) above 2 500 °C develop. Because the relatively flat heat protection shield is exposed to the extreme heat of reentry for just a few minutes and is used only one time, it can be fabricated from ablative materials. The reentry velocity of the U.S. space shuttle at an altitude of 120 km is below 8 km/s, and the maximum temperature experienced is about 1 500 °C for a few minutes. Structural components that experience the maximum exposure to heat such as the nose cone, the leading edges, the rudder, and the flapperons need to be made of non-metallic carbon/carbon composites (C/C) with adequate oxidation protection coatings.

Horizontally launched space planes that are accelerated by air-breathing engines (e.g., jet engines) fly in the atmosphere at hypersonic speeds for a longer time than vehicles launched vertically by rockets. Therefore, the space plane experiences its maximum exposure to heat during its launch into space. Initially, one of the main objectives of investigating FGMs deposited by chemical vapor deposition (CVD) was to develop thermal barrier coatings for a space plane. In a comparison test, models of the components of a nose cone (hemispherical C/C composites 50 mm in diameter) were coated with an ungraded 100 μm thick protective layer of SiC. Similar C/C composite models were coated first with a graded SiC/C FGM by penetrative CVD followed by deposition of the 100 μm thick SiC protective layer. All the coated nose cone models were subjected for 1 minute at 1 900 °C to a supersonic gas flow containing an amount of oxygen approximately equal to a standard atmosphere. The nose cones with the SiC/C FGM intermediate layer showed no discernible change in structure even after 10 cycles. In contrast, those without the intermediate SiC/C layer between the C/C substrate and the ungraded SiC coating deteriorated after the first cycle [2]. Sheets of SiC/C FGMs produced by CVD provide excellent thermal stability and thermal insulation at 1 227 °C, as well as excellent thermal fatigue properties and resistance to thermal shock [2].

Most rocket and scramjet engines use TBC materials that have been previously developed for turbine engine applications. The heat flux in the path of the hot gases is much greater in rocket engines than in turbine engines. Here the TBCs are exposed to a hostile environment, that is higher temperatures and more severe thermal transients, but for shorter mission cycles. Hence, the TBCs are mainly deposited as thin structures (< 0.2 mm thick) to reduce the probability of coating failure.

For example, protective CVD-SiC/C FGMs produced for rocket combustors have undergone critical tests. The maximum outer wall temperature of these model combustors was 1376 °C to 1 527 °C, while the inner wall temperature reached 1 677 °C to 2 027 °C. No damage to the combustors was observed after two test cycles [2].

In large combustion chambers, TBCs are not commonly used, as the heat cannot be dissipated quickly enough to avoid local hot spots and coating damage [2, 6]. Here longlife polymeric graded TBCs are potentially applicable in preventing coating failures.

In large liquid propellant rocket engines, TBCs are mainly used in the high pressure hydrogen and oxidizer turbopumps ([6] in [3]). TBCs have been used as liners for the spark igniters and pre burners, for turbo housing liners, for turbine blade shanks (located between the blade platform and root), and for vane shrouds. Experimental coatings have been used on the turbine blade platforms and vane airfoils. In addition, graded TBCs have potential applications in the upper part of the main combustion chamber as coatings on the interpropellant plate, spark igniter, and injector baffle tips.

Graded TBCs have been considered also for other rocket engines such as small regeneratively cooled thrust chambers in orbital maneuvering systems. These zirconia/nickel ($Zr0_2Ni$) FGM chambers are prepared by a combination of galvanoforming and plasma spraying. The graded layer is first deposited (up to 25% $Zr0_2$ on a Ni metal chamber) by galvanoforming and subsequently coated to 100% $Zr0_2$ by plasma spraying. No delamination of $Zr0_2$ was observed after 550 s of combustion. In order to assure the reliability of the $Zr0_2$/Ni FGM, it was necessary to engineer the microstructure to form strong layers as well as to further optimize the graded structures, and also to control the reaction with a propellant. As noted above, graded TBCs are potentially applicable for engine and airframe structures in reusable hypersonic vehicles ([7–9] in [2]).

Stealthiness is now a required specification for modern weapons. Parts made of specific materials can be used in stealth missiles to absorb the emitted electromagnetic energy to minimize waves reflected in the direction of the enemy radar receiver. In some applications, e.g. high velocity missiles, the materials can be subjected to high thermomechanical stress. For these applications, the most promising new materials are ceramic matrix composites reinforced with ceramic woven fabrics. The use of long, continuous ceramic fibers embedded in a refractory ceramic matrix creates a composite material with much greater toughness than monolithic ceramics, which have an intrinsic inability to tolerate mechanical damage without brittle rupture.

The conducting properties of these ceramic composites depend on the fibers, the matrix, the interfaces, and other parameters such as the topology of the arrangement of the various phases. Nicalon® SiC fibers, which have semiconducting properties, and Nextel® mullite ($3Al_20_3\_2Si0_2\_0.1\ B_20_3$) fibers, which are completely dielectric, are used in the preparation of oxide matrix ceramic composites. Nasicon matrix composites reinforced with long semiconducting and/or dielectric fibers can have mechanical and electrical properties, ranging from dc to microwave frequencies [4]. The Nasicon solid solution, structural formula $Na_{1+x}Zr_2Si_xP_{3-x}0_{12}$ ($0 \le x \le 3$), which has a graded electrical conductivity that varies by four orders of magnitude as a function of x, is a useful system for investigating the preparation and properties of graded ceramic matrix composites with tailored microwave properties.

FGMs are used also in aerospace equipment, such as solar panels and solar cells. Gallium arsenide (GaAs) is the current market leader for solar cells deployed for extra-terrestrial applications, but it is prohibitively expensive for terrestrial applications. To reduce the cost of the GaAs solar cell, in [18] was carried out an optoelectronic optimization for an $Al_xGa_{1-x}As$ (AlGaAs) solar cell containing an n-AlGaAs absorber layer with a graded bandgap. The bandgap of the absorber layer was varied either sinusoidally or linearly. Sinusoidal grading of the bandgap was predicted to enhance the solar cell maximum effiency to 34:5%. An effciency of 33:1% was predicted with linearly graded bandgap. Thus, grading the bandgap of the absorber layer can help realize ultrathin and high-efficient AlGaAs solar cells that will be cheaper and already suitable for both extra-terrestrial and terrestrial applications.

Extensive understandings of FGMs mechanical properties permit one to design and manufacture graded composite structures with deserved functionality. So accurately modelling of FGMs mechanical properties is greatly needed. Modelling their mechanical properties is central for engineers and scientists to accurately predict their mechanical behaviors under different and/or extreme conditions and obtaining new spectacular functionalities for various aerospace applications [6–7, 19].

Future work

Due to the broad and rapidly developing field of FGMs, all their properties and aerospace applications cannot be encompassed in this paper. Nevertheless, here are some of the observations of the authors based on the published research and their own analysis of the subject.

We, in our Space Materials Science department at SRTI-BAS, are working on obtaining new FGMs based on semiconductor graded gap QWs in the $Al_xGa_{1-x}As$ system [10].

At SRTI-BAS, we are also working on new FGMs, based on reinforced Al metal matrix composites and special Al alloy materials, with high hardness, high density and high thermal stability, for space applications. SiC particles and nanodiamond particles were used as reinforcing additives.

Such materials will be of considerable interest for their application in space technology and in particular for aerospace instrumentation [10, 20]. The work is in progress in this direction. Moreover, in these fields we have some research experience in obtaining and investigating:

- Quantum confined Stark effect in compositionally graded gap $Al_xGa_{1-x}As$ QWs [10];
- an Al alloy – B95 with certain additions of tungsten and nanodiamonds (This Al alloy was a part of the international outer space experiment “Obstanovka”, carried out in the Russian sector of the International Space Station, and was exposed to outer space for 2 and a half years.) [20].

We will use theoretical methods of bandgap engineering (tight binding and ab initio methods) and the powder metallurgy methods.

Conclusion

Today FGMs are the new top trend in all aerospace materials research and development.

This paper provides a brief overview of FGMs with a focus on their aerospace applications.

FGMs represent a rapidly developing area of science and engineering with numerous practical applications. Due to functional variation of FGM-materials, their physical/chemical properties (e.g. stability, hardness, conductivity, reactivity, optical sensitivity, melting point, etc.) can be manipulated to improve the overall properties of conventional materials. Although so far the practical applications of FGMs have not yet been fully implemented and used. The research needs in this area are uniquely numerous and diverse, but FGMs promise significant potential benefits that fully justify the necessary effort.

There are still more to be done in terms of research to improve the performance of manufacturing processes of FGMs in order to make them more cost effective.

FGMs are perspective materials for modern optoelectronic devices, which are irreplaceable and vital part of aerospace equipment and structures.

The emergence of FGMs has revolutionized the aerospace and aerocraft industry. FGMs used initially as thermal barrier materials for aerospace structural applications and fusion reactors are now developed for general use as structural components in high temperature environments.

The list of applications is endless, and it will increase with improving of the processing technology, cost of production, and properties of FGMs. The development of FGMs needs an integration of multidisciplinary domains to work together in designing, manufacturing, and exploring more areas of applications.

Last but not least, both experimental and theoretical studies of the FGMs are very important and need to be developed in order to look for unknown and possible properties of FGMs for new potential applications. Future applications require materials with exceptional mechanical, electronic, and thermal properties that can withstand various environmental conditions and are readily available at reasonable prices.

References

1. Bever, M. B. and P. E. Duwez, On gradient composites, ARPA Materials Summer Conference, 1979, 117–40.
2. Miyamoto, Y., W. A. Kaysser, B. H. Rabin, A. Kawasaki and R. G. Ford (Eds.), Functionally graded materials: design, processing and applications, Vol. 5, Springer Science & Business Media, 2013, 339.
3. Sobczak, J. and L. B. Drenchev, Metal Based Functionally Graded Materials, Bentham Science Publishers, 2010, 79.

4. Mahamood, R. M.and E. T. Akinlabi, Functionally Graded Materials. Topics in Mining, Metallurgy and Materials Engineering, Springer, Cham, 2017, 103.
5. Owoputi, A.O., F. L. Inambao and W. S. Ebhota, A Review of Functionally Graded Materials: Fabrication Processes and Applications, International Journal of Applied Engineering Research, 2018, 13, 16141–51.
6. Bouzekova-Penkova, A. and A. Miteva, Aluminium-Based Functionally Graded Materials, Proceedings of the fourth national conference with international participation "Material science, hydro- and aerodynamics and national security'2014", 23-24 October 2014, Sofia, IMETHC-BAS, 2014, 152–56.
7. Bharti, I., N. Gupta and K. M. Gupta, Novel Applications of Functionally Graded Nano, Optoelectronic and Thermoelectric Materials, Int. J. of Materials, Mechanics and Manufacturing, 2013, 1, 221–24.
8. Ou, Q., X. Bao, Y. Zhang et. al., Band structure engineering in metal halide perovskite nanostructures for optoelectronic applications, Nano Materials Science, 2019, 1, 268–87.
9. Daikh, A .A., A. Drai, I. Bensaid, M. S. A. Houari and A. Tounsi, On vibration of functionally graded sandwich nanoplates in the thermal environment, Journal of Sandwich Structures & Materials, 2020, 1099636220909790.
10. Miteva, A. M., Digital versus analog graded-gap quantum well in the presence of applied constant electric field, Machines. Technologies. Materials, 2017, 11, 236–39.
11. El-Wazery, M.S. and A. R. El-Desouky, A review on functionally graded ceramic-metal materials, Journal of Materials and Environmental Science, 2015, 6, 1369–76.
12. Naebe, M. and K. Shirvanimoghaddam, Functionally graded materials: A review of fabrication and properties, Applied Materials Today, 2016, 5, 223–45.
13. Tripathy, A., S. K. Sarangi and A. Chaubey, A review of solid state processes in manufacture of functionally graded materials, Int J Eng Technol, 2018, 7, 1–5.
14. Mahamood, R. M., E. T. Akinlabi, M. Shukla and S. Pityana, Functionally Graded Material, An Overview, Proceedings of the World Congress on Engineering, III, London, U.K., 2012.
15. Miteva A., An overview of the functionally graded materials, Machines. Technologies. Materials, 2014; 8, 13–16.
16. Mathieu, G. O. and I. T. Farhan, Using FGM for cyclic shell structures, Structural Mechanics of Engineering Constructions and Buildings, 2016, 4, 14–20.
17. Mardirossian, G. Fundamentals of remote aerospace technology, (Book in Bulgarian) NBU, Sofia, 2015, ISBN: 978-954-535-882-1, 240.
18. Ahmad, F., A. Lakhtakia and P. B. Monk, Optoelectronic optimization of graded-bandgap thin-film AlGaAs solar cells, Applied Optics, 2020, 59, 1018–27.
19. Xu, X.J. and J. M. Meng, A model for functionally graded materials, Composites Part B: Engineering, 2018, 145, 70–80.
20. Bouzekova-Penkova, A., K. Grigorov, M. Datcheva and C. A. Cunha, Influence of the outer space on nanohardness properties of Al-based alloy, Comptes rendus de l'Acad´emie bulgare des Sciences, 2016, 69, 1351–54.

НЯКОИ АЕРОКОСМИЧЕСКИ ПРИЛОЖЕНИЯ НА ФУНКЦИОНАЛНО ГРАДИЕНТНИТЕ МАТЕРИАЛИ

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Резюме

Функционално градиентните материали (ФГМ) понастоящем са обект на голям и непрекъснато нарастващ интерес от индустрията и науката и са широко използвани поради своите предимства. Тези предимства се дължат на техните уникални свойства и следователно многото им действителни и потенциални приложения в различни области на индустрията, науката и ежедневието. В този литературен обзор ще се спрем накратко върху някои от свойствата на ФГМ и върху някои от съществуващите и разширяващи се бъдещи приложения на ФГМ в аерокосмическата и свързаните с нея индустрии. Представена е критична дискусия. Разглеждат се възможните бъдещи разширения на работата в тази област.