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A review on Functionally Graded Ceramic-Metal Materials

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Abstract
FGMs can be used to avoid problems associated with the presence of an interface in a material: stress singularities due to elastic or thermal property mismatch, poor adhesion, or unwanted reflections at the interface. TheCeramic/Metal FGMs can be designed to reduce thermal stresses and take advantage of the heat and corrosion resistances of ceramic and the mechanical strength, high toughnessgood machinability and bonding capability of metalswithout severe internal thermal stresses,Also exhibit higher fracture resistance parameters resulting in higher toughness due to crack bridging in a graded volume fraction. Most of the processes for FGM production are based on a variation of conventional processing methods which are already well established. Methods that are capable of accommodating a gradation step include powder metallurgy, centrifugal casting, and thermal sprayingas well as various coating techniques. This review concluded the powder metallurgy (PM) as the most suitable technique certainly for mass production and up-scaling of the FGMs. The selection was strengthen after considering the advantages of the technique such as process cost-effectiveness, reliability of the practical implementation of the process and the high capability of the process to control the quality of the FGMs.

Keywords: Functionally graded material (FGM), Fabrication, Powder metallurgy (PM).

1. Introduction
The first concept of Functionally Graded Materials (FGMs) was proposed in 1987 by Niino and co-workers during a space plane project at the National Aerospace Laboratory of Japan. Where a combination of materials used would servethe purpose of a thermal barrier capable of withstanding a surface temperature of 2000 K and a temperature gradient of 1000 k across a 10mm section. FGM, or sometimes also ‘‘gradient material’’) is characterized by a gradual change of material properties with position. The property gradient in the material is caused by a position-dependent chemical composition, micro-structure, or atomic order. The spatial extension of the gradient may differ: in a bulk FGM the property variation extends over a large part of the material, whereas in a graded coating or joint it is restricted to the surface of the material or a small interfacial region. Although FGMs attracted scientific interest only towards the end of the twentieth century, these materials are not new. In fact, spatial variations in the microstructure of materials have been exploited for millions of years by living organisms. In many structures found in plants, microstructural gradients are formed in order to produce optimum structural and functional performance with minimum material use. **[1,2].**
Forexample, the composite may contain a spatially varying volume fraction of one of the phases (Fig. 1 (a)). In this case, the gradient material can be conveniently described by the use of a transition function f (x, y, z), where f is the volume fraction of one of the phases as a function of position. In many practical cases the compositional variation will be restricted to one coordinate, z, and the different gradients can then be described by a so-called transition function of the type:

$$f(z) = \left(\frac{z}{d}\right)^{p}$$

Where f denotes the volume fraction of one of the phases, d is the thickness of the graded region, and p is the so-called gradation exponent. However, a composition gradient is not inherent to all FGMs Microstructural orientation gradients may also be obtained in composites by changing the shape (Fig.1 (b)), (Fig.1 (c)), or size (Fig. 1 (d)) of the dispersed phase **[3].**

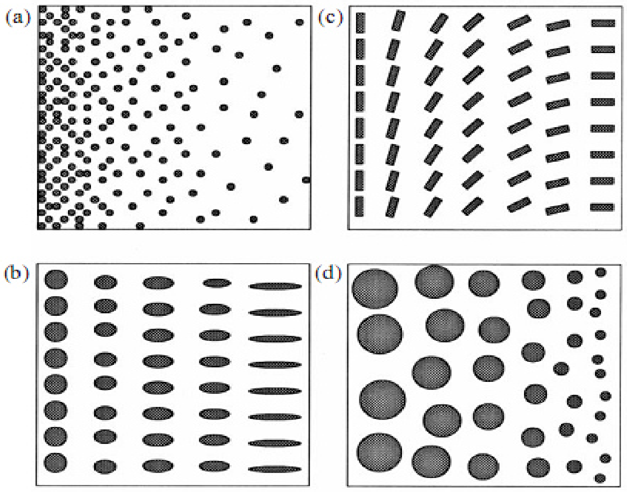

Figure. 1 Different types of functionally graded composites.
Gradient of: (a) fraction, (b) shape, (c) orientation, and (d) size of

2. FGMs Characteristics

FGM are materials in which some particular physical properties are changed with dimensions. Properties of such materials can be described by the function f(x). In homogenous materials this function is constant like in (Fig 2.a). In the case of a junction of two different material functions f(x) has a strain shape in (Fig 2.b). In FGM, this material function should be continuous or qusi-continous. It means that particular properties change consciously or qusi- consciously along one directions, like it was shown in (Fig 2.c) in many cases FGM could be presented as a composition of several connected thin layer [4].One unique characteristics of FGM is the ability to tailor a material for specific application [5].

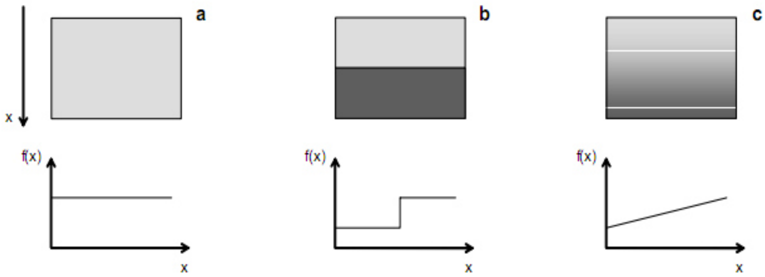

Figure.2 schematic representation of material function in different structure; homogenous material (a), junction (b), FGMs (c)

The development of FGMs emerged as a means to improve the toughness behavior of composite materials, when compared to homogeneously reinforced composites; this improvement is due to the balanced contributions of reinforced and non reinforced regions within the composite. There are three phases of FGMs (Ceramic/ Metal, Ceramic/Ceramic, Metal/Metal). As a representative example for FGMs, we just mention the metal/ceramic FGMs, which are compositionally graded from a ceramic phase to a metal phase.The ceramic/metal FGMs can be designed to reduce thermal stresses and take advantage of the heat and corrosion resistances of ceramic and the mechanical strength, high toughnessgood machinability and bonding capability of metalswithout severe internal thermal stresses.Theceramic-metal FGMs exhibit higher fracture resistance parameters resulting in higher toughness due to crack bridging in a graded volume fraction[6, 7].
Due to the high mechanical and thermal properties of the constituent materials, the Ceramic/Metal FGMs can exhibit good service performance under some severe environments, such as super high temperature and great temperature gradient. Most the researches concerned the used the Ceramic/Metal FGMs for studied the mechanical and thermal properties of the gradient structure [8-11].The microstructure and mechanical properties of ZrO_2/NiCr FGMs fabricated by powder metallurgy are investigated experimentally. It is found that hardness increases and ductility decreases with the increase of ZrO_2, which is attributed to the variation of thematrix phase from the metal to the ceramic [12].Zhou and Li[13] are introduced the inverse homogenization for FGM

microstructure design, where layered periodic base cells (PBC) are topologically optimized individually for specific graded properties. To ensure connectivity between different PBCs, heat sinks are prescribed on the PBC boundaries for maximizing their conduction.
The numerical researches also, studied the effect the mechanical properties such as the modulus of elasticity, fracture toughness, wear resistant and the hardness of the FGM. Ajdari et al[14] investigated the compressive uniaxial and biaxial behavior of functionally graded Voronoi structures by the finite element method. The finite element analysis showed that the overall d yield strength of structures increased by increasing the density gradient. However, the overall elastic modulus of functionally graded structures was more sensitive to density gradient than the overall yield strength. The study also showed that the functionally graded structures with different density gradient had similar sensitivity to random missing cell walls. The variation of elastic modulus in the ZrO_2/NiCr FGMs is investigated experimentally and theoretically. It is found that the elastic moduli decrease obviously with the increase of NiCr, which differ greatly from those predicted by the traditional Mori–Tanaka method [15].

3. Fabrication Techniques of FGM

The fabrication process is one of the most important fields in FGM research. A large part of the research work on FGMs has been dedicated to processing and a large variety of production methods have been developed for the processing of FGM. Most of the processes for FGM production are based on a variation of conventional processing methods which are already well established. Methods that are capable of accommodating a gradation step include powder metallurgy [16-18]sheet lamination, and chemical vapor deposition and coating processes. In general, the forming methods used include centrifugal casting [19-21],slip casting, tape casting [22], and thermal spraying [23-24]. Which of these production methods is most suitable depends mainly on the material combination, type of transition function required, and geometry of the desired component.

- Powder metallurgy

It is noted that powder metallurgy method is one of the most commonly employed techniques due to its wide range control on composition and microstructure and shape forming capability. Powder metallurgy offers more advantages by means of the lower costs, higher raw materials availability, simpler processing equipment, lower energy consumption and shorter processing times. In powder processing, the gradient is generally produced by mixing different powders in variable ratios and stacking the powder mixtures in separate layers. The thickness of the separate layers is typically between 0.2 mm and 1mm. Several techniques have been introduced for powder preparation such as through chemical reactions, electrolytic deposition, grinding or comminution. These techniques permit mass production rates of powder form materials and it usually offered within controllable size range of the final grain population. For the powder processing, the main consideration is focused on the precision in weighing amounts and the dispersion of the mixed powders. These elements will influence the structure properties and should be handled in very careful way. In the subsequent processes, the forming operations is performed at room temperature while sintering is conducted at atmospheric pressure as the elevated-temperature used may cause other reaction that may affected the materials. Mishina et al [25] studied the fabrication method of anther constituent, ZrO2/AISI316L FGMs for use in joint prostheses and their mechanical and biotribological properties were evaluated through fracture toughness, bending strength, and wear resistance studies. It found that FGMs with a layer thickness of less than 1.0mm showed a low wear resistance. FGMs with a layer thickness of more than 2mm therefore have mechanical and biotribological properties and are suitable for use in joint prostheses. Elwazery et al [26] The relative density, linear shrinkage and Vickers hardness of each layer of 8YSZ/Ni FGM were measured also, the microstructure and the composition of these components were studied. The results obtained show that functionally graded materials produced by spark plasma sintering exhibited a low porosity level and consequently fully dense specimens. There are no macroscopic distinct interfaces in YSZ/Ni FGM due to the gradient change in components

- Hot pressing

Yittria stabilized zirconia (YSZ) and nickel 20 chromium (NiCr) are the two materials combined using YSZ-NiCr FGM interlayer via hot pressing method [27]. At the initial stage of the processing, the powdered

YSZ and NiCr were mixed in ball milling machine for 12 h before being stacked layer by layer in graphite die coatedwith boron nitride. This study applied the concept of stepwise gradation by arranging the composition of each layer to be in certain desired percentage. The preoccupation of each layer was performed under a lower pressure before stocking the adjacent layer under higher pressure (10 MPa) to ensure the exact compositional distribution within the layers.

- Cold pressing

The powder mixture of PZT, Al2O3and the stearic acid as the PFA were initially stacked in a die at 100 MPa and restack using cold isostatic pressing (CIP) before the normal sintering process at 1473 K temperature for 1 h takes place. The binder addition is the same thing applied in another fabrication of FGM composed by Ni and Al2O3 which is in purpose to investigate the influence of the particle size used. In this study, the appropriate Ni, Al_2O_3 and Q-PAC 40 (organic binder) particle sizes were selected based on the desired microstructure at the corresponding composition. After mixed together through blending process, the powder mixtures were cold pressed under 86 MPa pressure. The process followed by pressureless sintering at 1350°C with specific sintering [28]. Figure 3 shows the flow chart of the manufacturing process of the Al_2O_3-ZrO_2FGM used in this study. Different elemental consideration under powder characteristic that is in term of the addition of the space holder material was investigated on porous Ti-Mg (titanium-magnesium) FGM.

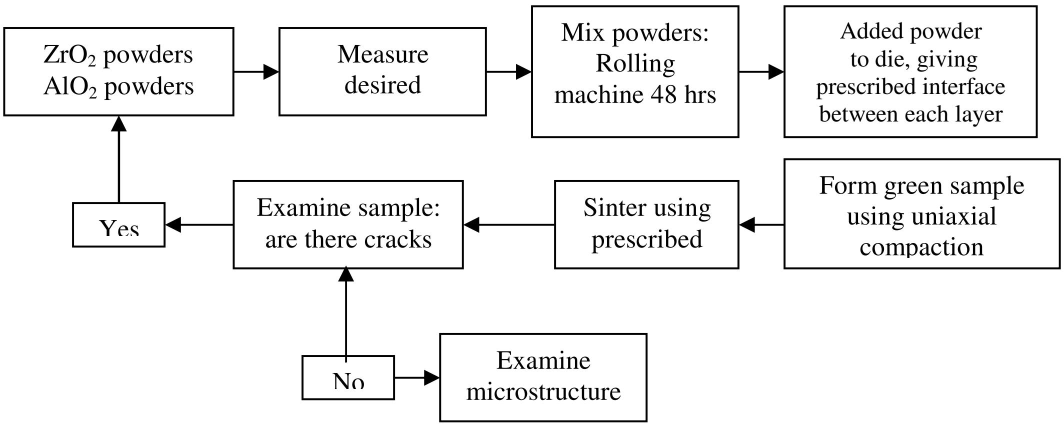

Figure 3. Flow chart detailing the manufacturing process of Al_2O_3/ZrO_2FGM [27]

- Sintering process

The sintering process is performed simultaneously with the compaction process if the FGM is prepared using hot pressing process. However in cold pressing process, the sintering process is performed only after the powders were compacted. The effectiveness of three different sintering methods including electric furnace heating, high frequency induction heating and spark plasma sintering (SPS) were investigated [29].SPS is a newly developed process which makes possible sintering high quality materials in short periods by charging the intervals between powder particles with electrical energy. SPS systems offer many advantages (ex. rapid sintering, sintering less additives, uniform sintering, low running cost, easily operation) over conventional systems using hot press sintering, hot isostatic pressing or atmospheric furnaces process applies to many advanced material, functionally graded materials, fine ceramics, amorphous materials, target materials, thermoelectric generator. The influence of ZrO_2 content and sintering temperature on microstructures and mechanical properties of the composites were investigated by Menga et al. [30]. All samples could be fully densified at a temperature lower than 1400 °C. Vickers hardness and fracture toughness of composites increased with increasing ZrO_2 content, and the samples containing 10 wt.% of ZrO_2 had the highest Vickers hardness of 18GPa (5 kg load) and fracture toughness of 5.1MPa$\sqrt{m}$.

- Centrifugal casting

Centrifugal casting is one of the most effective methods for processing the FGMs due to its wide range control on composition and microstructure.Centrifugal casting has been mainly used for obtaining cylindrical parts. The two basic types of centrifugal casting machines are: the horizontal types, which rotate about horizontal axis, and the vertical type, which rotates about a vertical axis. Horizontal centrifugal casting machines are generally used to make pipe, tube, bushing, cylinder sleeves (liners), and cylindrical or tubular castings that are simple in shape.Centrifugal casting is a process where molten metal is funneled into a rotating mold (commonly 700 to 1300 rpm). The rotation of the die creates centrifugal force which thrusts the metal towards the mold wall.Watanabe et al [18]studied the formation process of composition gradients of the motion of ceramic particles in a molten metal of a viscous liquid under a centrifugal force by numerically modeling. The graded distribution in FGMs manufactured by the centrifugal method will be significantly influenced by many processing parameters. which include the difference in density between particles and molten metal, the applied G number, the particle size, the viscosity of the molten metal, the mean volume fraction of particles, the ring thickness and the solidification time also, Tanaka et al (26)studied the particle motion moving in a mixture of molten metal and solid particles in the axially rotating casting drum. The particle motions in cold model made of acrylic are recorded by CCD camera set in the drum and based on its digital data, the particle velocity is obtained by use of PTV. It is found that particle motion in the rotating drum is captured by use of cold model centrifugal casting, and when the particle moves in the Stokes' regime; its velocity is linearly increased with the distance from the center of the drum. Centrifugal mixed-powder method (CMPM) shown in Fig. 4 is another method introduced as a solution to the limitation of centrifugal casting method in fabricating FGMs containing nano size particles **[31].**

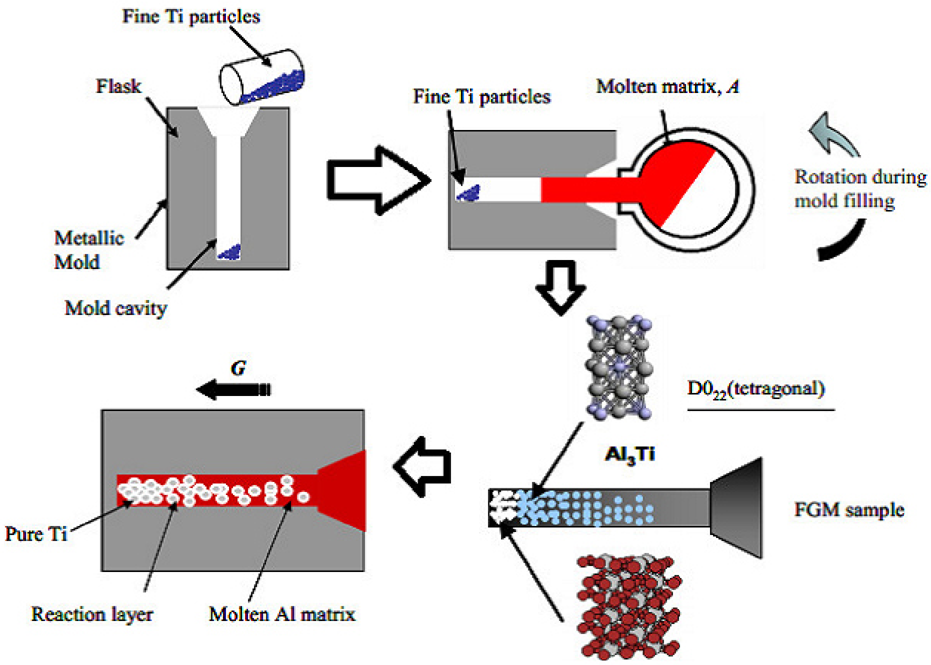

Figure 4. A schematic illustration showing CMPM [30].

- Thermal spraying

Thermal spraying has been frequently used to produce FGM coatings. Thermal spraying of FGMs offers the possibility to combine highly refractory phases with low-melting metals and allows for direct setting of the gradation profile. Xiong et al. **[32]** studied the heat insulation performance of thermal barrier-type FGM coatings under high heat flux. The FGM coatings with thicknesses varying from 0.75 to 2.1 mm were designed and deposited onto a steel substrate by plasma spraying .Pan et al. **[33]** Studied the different FG 20 wt.% MgO-ZrO_2/NiCrAl thermal barrier coatings were obtained through the plasma spraying process. The microstructures, chemical compositions and fractured surface were examined by means of electron probe microscopic analysis (EPMA), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The different functionally graded 20 wt.% MgO-ZrO_2/ NiCrAl thermal barrier coatings through the plasma spraying process are presented. The SEM observations of the fractured surface revealed that the intermediate graded layer had the compositive mechanical properties in strength and toughness, due to the microstructure improvement and relaxation of residual stress concentration.

- Laser cladding

Two or more dissimilar materials are bonded together using laser intercession in laser cladding process. During the process, the material which is in powdered form is injected into the system which is built certainly for cladding process while laser which causes melting to occur is deposited onto the substrate. Although the technique has becomes the best technique for coating various shapes and declared as the most suitable process for graded material application, the limitation still exist when that the process needs high costing for the high technology system setup and it is unsuitable for mass production due to the layer by layer process. The Nd:YAG laser power type was also being used in a fabrication via selective laser melting (SLM) of super nickel alloy and zirconia FGM, Fig.5. The resulting materials contained an average porosity of 0.34% with a gradual change between layers without any major interface defects **[34].**

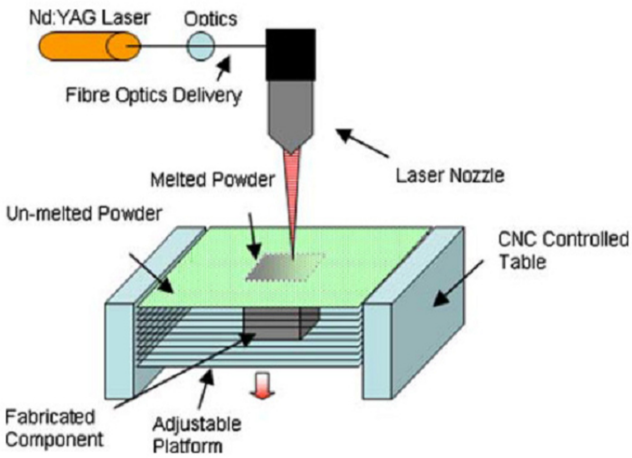

Figure 5. Experimental setup for laser assisted processing using Nd:YAG laser Power source [34]).

Application .4

FGM is widely applied for mechanical applications and used in the electrical such as electronic, diodes**,** sensor**,** heat conductors**,** and electronic devices, thermal, structural and military, shown in Fig. 6. Due to the development of the FGM concept only in the 1990s, the practical use of FGMs is still very limited. These inhomogeneous solids are used in different branches of engineering applications, e.g.

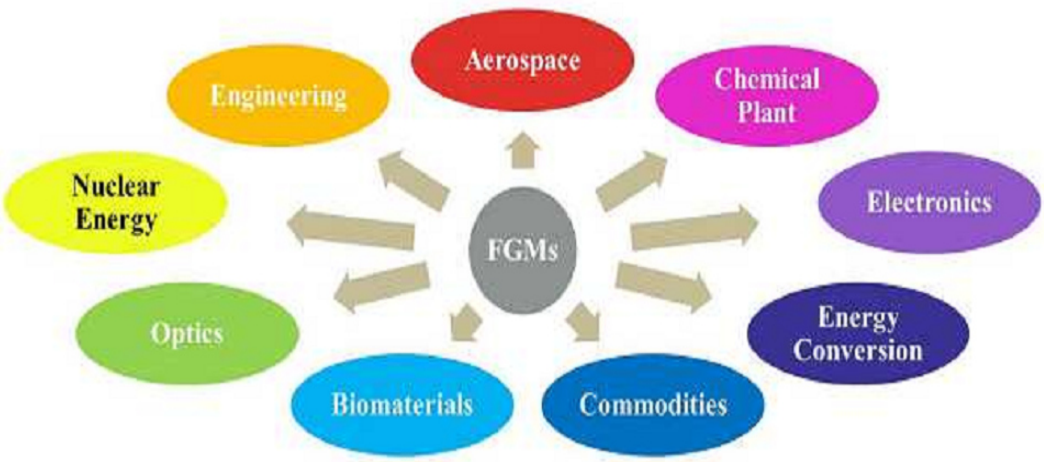

Figure.6 various fields of Application of FGM

-Nuclear Reactor. The inner wall of nuclear reactors is made of FGMs (Ceramic/ Metal) as shown in Fig. 7.

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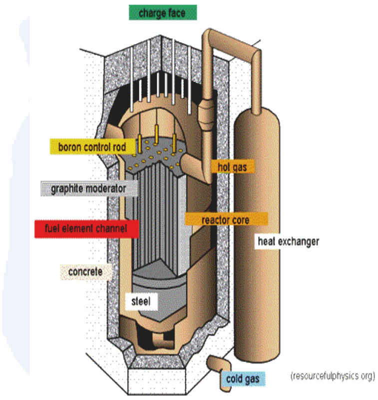

Figure.7 The nuclear reactor[2]

- Car Engine Cylinders: The car engine cylinders are made of FGMs. The inner phase is ceramic and the outer phase is metal as shown in Fig. 8.

-Turbine Blades:FGMs are applicable in the turbine blades as shown in Fig 9. Typical coatings for high-temperature applications involve an oxidation resistant coating and a thermal barrier coating (TBC). The oxidation resistant coating is also called bond coat because it provides a layer on which the ceramic TBC can adhere.

Figure 8. The car engine cylinder

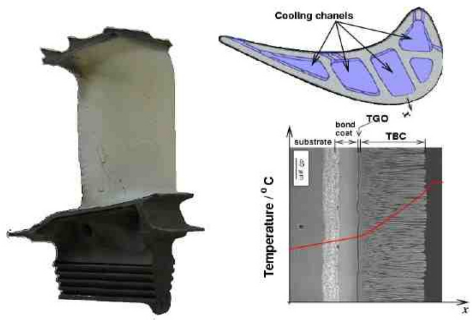

Figure 9 The turbine blades [6]

- Cutting Tools: Cutting tool is an example of FGMs as shown in Fig. 10: a) conventional type, b) FGMs design. The crack occurs near the tip-shank interface in the conventional type but in the FGMs design is occurred relaxation in stress concentration. The FGM are used in cutting tools because it is improving the thermal strength.

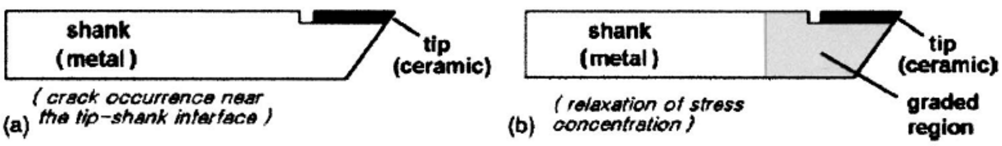

Figure.10 lathe metal cutting tool bites: (a) conventional type: (b) FGM design [6]

- Electronics and optoelectronics

Optical fibers used for wave high speed transmission. Computer circuit boards (PCB) Cellular phone.

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Conclusion and Future Work

1- Functionally graded material is an excellent advanced material that will revolutionize the manufacturing world. There are a number of hurdles for realizing this objective.Lots of studies have been conducted on behavior of functionally graded materials and the literature is very rich on this because of the wide areas of application of this novel material.

2- Functionally graded materials are very important in engineering and other applications but the cost of producing these materials makes it prohibitive in some applications.This study presents an overview on FGM, its Characteristics, various fabrication methods and its wide applications.

3-Based on these criteria, this study concluded that the powder metallurgy as the most suitable method for the manufacturing of FGMs in the future works. It is believed that the main issue in implementing the PM method which is the sintering process should be further explored in order to achieve improvement in the microstructure and mechanical properties of the resulting FGMs.

References

1- Yamanouchi M., Hirai T., Shiota I., "Proceedings of First International Symposium on Functionally Gradient Materials", *FGM Forum*, Tokyo, 1990, Japan.
2- Lannutti J., *Compos. Eng*. 4 (1994) 81.
3-Neubrand A., Rodel *J., Z. Metallk*. 88 (1997) 358.
4- Xi Q., Wang M., *Computer-Aided Des.* 40 (2008) 660.
5- Shanmugavel P., Bhaskar G., Chandrasekaran M., Mani P., Srinivasan S., *Europ. J Scient. Res*., 68 (2012) 412.
6- Suresh S., Mortensen A., *IOM Communications*, London, 1998.
7- Hirai T., Sasaki M., Niino M., *J. Soc. Mat. Sci.* 36 (1987) 1205.
8- Jingchuan Z., Zhongda Y., Zhonghong L., Jian L., *Trans. Nonferrous Met. Soc*., 6 (1996), 94.
9- Tohgo K, Lizuka M., Araki H, Shimamura Y., *Eng. Fract. Mech*. 75 (2008) 4529–4541.
10- Bocciarelli M., Bolzon G., Maier G., *Comp. Mat. Sci.* 43 (2008)16.
11- Jin X., Wu L., Guo L., Yu H., Sun Y., *Eng Frac. Mech.* 76 (2009) 1800
12- Jin X., Wu Li., Sun Y., Guo L, *Mat. Sci*. *& Eng* A 509 (2009) 63.
13- Zhou S., Li Q., *Mat. Lett.* 62 (2008) 4022.
14- Ajdari A., Canavan P., Nayeb-Hashemi H., Warner G., *Mat. Sci. & Eng. A* 499 (2009) 434.
15- Jin X., Wu Li., Sun Y., Guo L., Yuguo S., *Comp. Sci & Technol.* 69 (2009) 1587.
16- Jin X., Wu L., Guo L., Yu H., Sun Y., *Eng. Fract. Mech.* 76 (2009) 1800.
17- Shahrjerdi A., Mustapha F., Bayat M., Sapuan S., Majid A., *J. Phys. Sci.* 6 (2011) 2258.
18- He Z., Ma J., Tan G., *J All and Comp.* 54 (2009) 459.
19- Watanabe Y., Yamanaka N., Fukui Y., *Comp. Part A* 29A (1998) 595.
20- Duquea N., Melgarejoa, Z., Suarez O., *Mater. Charact.* 55 (2005) 167.
21- Torii S., Tanaka S., Yano, T., Watanabe, Y., *J Trans. Phenomena*, 6 (2004) 189.
22- Yeo J, Jung Y., Choi S., *J Europ. Ceram. Soci*. 18 (1998) 1281.
23- Cannillo X., Lusvarghi L., Siligard C., Sola A., *J Europ. Ceram. Soci.* 27 (2007) 2393.
24- Belmonte M., Gonzalez J., Miranzo, P., Osendi, M., *Acta Mat.* 57 (2009) 2607.
25- Mishina H., Inumaru Y., Kaitoku K., *Mat. Sci. & Eng.* A 475 (2008) 141.
26- El-wazery M., El-Desouky A., *J Appl. Sci. & Eng.* 12(2014) 313.
27- Li J., Zeng X., Tang J., Xiao P., *J Europ. Ceram. Soci.* 23 (2003) 1847.
28- Sun L., Sneller A., Kwon P., *Mat. Sci. Eng.* A 488 (2008) 31.
29- Meng F., Liua C., Zhang, F., Tiana, Z., Huanga, W., *J All. Comp.* 512 (2012) 63.
30- Gowtam D., Rao A., Mohape M., Khatkar V., Deshmukh V., Shah A., *J Self-Propag. High-Temp. Synth.* 17(4) (2008) 227.
31- Xiong H., Kawasaki A., Kang Y., Watanabe R., *Surf & Coat. Technol.* 194 (2005) 203.
32- Pan C., Xu X., *Surf & Coat. Technol.* 162 (2003) 194.
33-Mumtaz K A, Hopkinson N., *J Mater. Sci*. 42 (2007) 7647.