Fabrication, Characterization and Modeling of Al_2o_3/Ni Functionally Graded Materials

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ABSTRACT

Functionally graded materials (FGMs), with ceramic and metallic constituents, are frequently used for tremendous high temperature applications. In this paper, six sets of FGMs samples were designed and fabricated using powder technology technique. All FGMs were sorted according to the conditions of sintering (i.e. temperature and time). The ceramic constituents were represented by (Al_2O_3) and the metallic constituents were represented by (Ni).It is found that as the sintering temperature and time increased, the apparent density was increased and porosity was reduced. (F-FGM, sintered at 1350°C for 3 hrs.) sample seems to impart high and slight linear graded microhardness across the layers without any obvious jumps throughout the thickness. The interfacial microhardness values were found very close to the bulk microhardness of adjacent layers. The reason behind such behavior is the minimum porosities and improved apparent density due to the efficient sintering practices (i.e. 1350°C and 3 hrs.) and uniform mutual diffusion of (Ni) and (Al_2O_3) particles across the layer interfaces. As the sintering time and temperature increase, the microstructure becomes much denser and the interfaces become more homogeneous that lead to eliminate the discontinuity in microstructure. A Finite element method throughout the COMSOL Multiphysicswas used extensively in estimation of temperature distribution through the thickness as well as residual stresses that induced as a result of high temperature loading of fabricated FGM. The model also shows aclear fluctuation of stresses along the thickness that imparts a development of stress concentration regions near the interfaces of layers, especially at the lower half region of FGM that was enriched by (Ni). Stresses clearly become normal variables with thickness at the upper half of FGM that enriched with (Al_2O_3).
Keywords:Al_2O_3/Ni functionally graded materials, Design, Fabrication and Characterization.

تصنيع , دراسة خواص ونمذجة مواد متدرجة بالخواص ذات اساس نيكل – الومينا

الخلاصه

المواد المتدرجه وظيفيا (FGMs) التي تتكون من المواد السيراميكيه والمعدنية التي كثيرا ما تستخدم في تطبيقات درجة الحرارة العاليه. في هذه البحث ، تم تصميم و تحضير ست مجموعات من عينات المواد المتدرجه بالخواص (FGMs)باستخدام تكنولوجيا المساحيق.إن مكونات الماده السيراميكيه ممثله بالألومينا (Al_2O_3) والمكونات المعدنيه متمثله بالنيكل(Ni). لقد ثبت أن زيادة درجة حرارة وزمن التلبيد يعملان على زيادة الكثافه الظاهريه وتقليل نسبة المساميه.لقد اثبتت النتائج

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العمليه ان العينه(F-FGM التي تم تلبيدها بدرجة حرارة 1350 درجه مئويه وزمن 3 ساعات) قد اظهرت تدرجا خطيا واضحا وارتفاعا مرضيا في قراءات الصلادة الدقيقة بمقياس فيكرز عبر طبقات الماده. كما تم العثور على قيم الصلادة الدقيقة البينية (الحد الفاصل بين الطبقات) قريبة جدا من قيم الصلاده الدقيقه للطبقات المجاورة. ان الأسباب الكامنة وراء مثل هذا السلوك هي وجود الحد الادنى من نسبة المسامية والتحسن الجيد في قيم الكثافه الظاهريه في هذه العينه التي جاءت بسبب كفاءة التلبيد المعتمده في هذا البحث (1350°C وزمن تلبيد 3 ساعه). كما تجدر الاشاره الى ان البنيه المجهريه تصبح اكثر كثافه والحدود الفاصله بين الطبقات تصبح اكثر تجانسيه مع زيادة درجة حرارة وزمن التلبيد. لقد تم ايضا استخدام طريقة العناصر المحدده وذلك من خلال برنامج الكومسول (COMSOL)الذي استخدمت نتائجه للتثبت من تدرج الخواص ودرجات الحراره بفعل التوصيل الحراري. كما تشير نتائج نمذجة الاجهادات الى وجود تذبذب في نتائج الاجهادات على طول سمك العينه (F) وخاصة في المناطق القريبه من الحدود الفاصله بين الطبقات وبالخصوص في الجزء الاسفل من الماده والغني بعنصر النيكل. بينما تبدو النتائج اكثر سلاسه وخطيه في الجزء العلوي الغني بمادة الالومينا.

INTRODUCTION:

At present, functionally graded material (FGM) is oftendeveloped as a means of treating reliability and durability problems that ascend when dissimilar materials that have differentmechanical properties, such as variations in hardness, toughness, thermal and residual stresses, and strengths of the interfaces, are utilized within one application. FGMs are the third generation of composite material that classified by their graded structure. Specifically, an FGM typically consists of a composite material with a spatially varying microstructure designed to optimize performance through the corresponding property distribution. Property distributions are found in a variety of common products that must have multiple functions (i.e., Multifunctional), such as gears, which must be tough enough inside to withstand the fracture, but must also be hard enough on the outside to prevent wear. Gear teeth are in constant contact, and therefore their surface hardness becomes of primary concern to prevent them from deteriorating during use [1].

A traditional method to create a metal-ceramic package would be to simply combine two fabrics together with an adhesive or welding in suitable method such as shown in figure (1).The evolution of high residual stresses will be unavoidable in such a bonding.So, it is hoped in this paper to overcome such a problem by utilizing the benefits of powder technology in parallel with the computer simulation to design, fabricate and modeling of five layers functionally graded materials starting with single phase ceramic represented by (Al_2O_3) at the top and ending with a single phase metal represented by (Ni) at the bottom. In addition a gradient of (Al_2O_3/Ni) in the form of three layers is introduced between them.

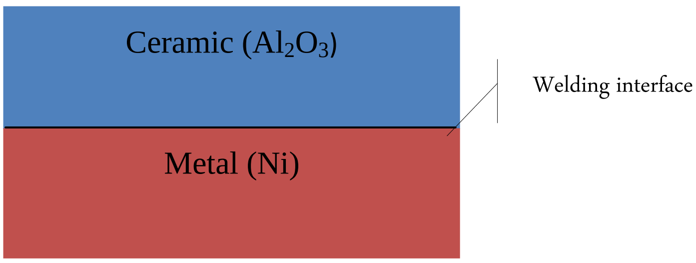


Figure (1): Exposing of Alumina to Nickel by welding.

The sharp interface between the (Ni) and (Al_2O_3) is a point of concern, so, this concern will decrease if it is possible to introduce of a graded interface rather than a sharp interface between the two dissimilar materials. The graded interface in these materials is a series of modifications in the microstructure of the composite that can be produced in discrete layers or as a continuously changing system, and is recognized as the gradient architecture.

Keiko Kikuchi et al. [2], have studied the microstructure of metal/ceramic functionally graded materials changes from disperse structure to continuous structure and then again into disperse structure, in turn the electrical, thermal, and mechanical properties in functionally graded materials change as the composition changes.The properties of the composite change as the relative amounts of the constituent materials vary with respect to one another.

In many cases, the property distributions in FGMs can be described by rule-of-mixtures (ROM) [3].There is often many ways to design a gradient materials, which are constrained by the materials involved and the intended purpose of the composite. A number of methods to describe the gradient structure are given by Markworth, et al. [5]. Jonathan G et al. [6],Kawasaki and Watanabe [7, 8] often used the power law distribution method in designing material gradients.Sintering of ceramic-metal are also studied by Alaa et al. [9], They used techniques of powder technology tofabricate FGMs materials that composed of five graded layers of Al2O3-Ti phases.The technique of powder technology is used to manufacture these materials that composed of five graded layers of (Al_2O_3/Ti) phases. Nandakumar et al. [10], an electrophoretic deposition has been used to synthesize Nickel–Alumina, functionally graded materials from NiO and alumina suspensions in ethanol.

According to above, super little literatures were found in the fabrication of such type of materials instep-wised manner by powder technology. So that, the paper at hand was coming to complete the knowledge of using powder technology technique and tunning the sintering conditions to achieve better physical and mechanical propertiesof five layers step-wise functionally graded materials. Across the current paper, the ceramic phase (Al_2O_3) was increasing linearly across the layers (i.e. 0, 25, 50, 75 and 100wt% respectively). The green specimens are composed of (Al_2O_3/Ni) layers and the sintered specimens are composed of graded (Al_2O_3/Ni). The vacuum furnace sintering technique is utilized for sintering of the graded green specimens.

Design of Al_2O_3/Ni -FGM

The first step in this work was the design of five layers FGMs, where the boundary condition of their structures depends on material selection and manufacturing process.The properties of materials used to build theFGMsmodel for high temperature application are denoted in the table (1).

Table (1): Physical and mechanical properties of FGM constituents [11].

Properties	Al_2O_3	Ni
Coefficient of thermal expansion (μm/m °c)	8.20	13.1
Density (gm/cm^3)	3.9	8.88
Melting point ^{0}C	2050	1455
Specific heat capacity(J/g.°c)	0.880	0.460
Thermal conductivity (W/m.°K)	12	60.7
Vickers hardness GPa	20.97	18.11
Young's modulus (E) GPa	370	207

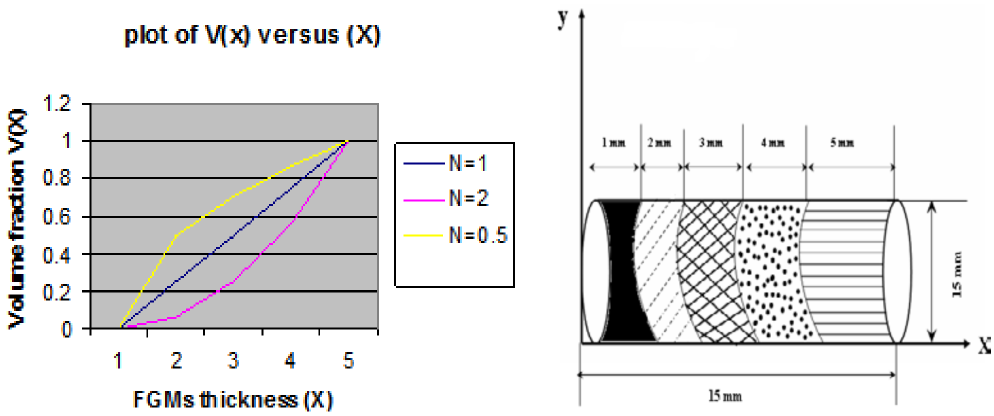
According to the FGM model, the dimensions and composition of each layer will be determined using the following formula [3]:

$$V1(x) = (\frac{(X2 - X)}{(X2 - X1)})^N \quad \ldots..(1)$$

Where, V1 (x) representsthe local volume fraction of Ni, while the volume fraction of Al_2O_3 is being according to the formula:

$$V2(x) = 1 - V1(x)X1 \quad \ldots..(2)$$

X_1 and $X_2$are the border regions of pure (Ni) and (Al_2O_3) respectively, (N) is a variable parameter, where its magnitude determines the curvature of$V_1(x)$. The solution of equations above at different values of N (i.e. 1, 2 and 0.5) is represented schematically in the following figure and curve.



(a) **(b)**

Figure (2): (a) - Design layout of (Al_2O_3/Ni); (b) -Volume fraction V (x) as a function of (FGM) thickness at variable (N),

Figure (2/a) represents the design of the (FGM)model indicates the thickness of each layer. Figure (2/b) represents the solution of volume fraction formula at different values of (N). It can be ascertained that the curvature can be made concave upward and concave downward, to a greater or lesser degree, by proper choice of (N). With higher values of (N) the FGM tends to be metallic nature (i.e. the lower surface phase is dominant) while lower values of (N) tend toward ceramic nature (i.e. the upper surface). Designers can vary the (N) value to tailor the (FGM) to specific applications at (N=0), the curve would actually be a smooth line corresponding to a volume fraction of ceramic equal to (1).

An adjusting of exponent (N) willcontrol the rate of transition between microstructures of base metal (Ni) and ceramic (Al_2O_3). The power law distribution is a versatile tool, as it can be used to construct a wide variety of distributions.As the exponent becomes much bigger or much smaller than one, the gradient tends to be smoother near either of the base materials. Additionally, a gradient exponent of one creates a linear distribution. For instance, in a general metal-ceramic material system, if a harder material is needed, the gradient can be designed for a gradual change in the microstructure of the ceramic regions, with a more rapid transition in the metallic portions of the composite.

Fabrication of (Al_2O_3/Ni –FGM)

Functionally graded materials in the present work were prepared according to the design input achieved in the above article. The fabrication of this type of material with multilayer and various chemical compositions of layers required a precise and careful dealing with the material types, tools and apparatus. The careful dealing includes a precise weighing practice of each FGMs constituent, checking materials, purity and then better cleaning of die surfaces in order to avoid any contamination of prepared materials with the iron of steel die surfaces.

Starting materials:

(Al_2O_3) and (Ni) powders were used as starting materials to fabricate the (FGMs). Knowing that, alumina powders (Baikowski, USA) with an average particle size of (<85µm) representing the pure ceramic layers. Nickel powders (Johnson Matthey, USA) with a mean particle size of (<55µm) representing the pure metallic layer.

FGMs Processing:

It was mentioned earlier, that FGM designed to consist of five layers as shown in figure (2/a). In addition to pure alumina and nickel layers at the two ends, the intermediate structure consisted of three layers with different ratios of ceramic and metal as shown in figure (3).

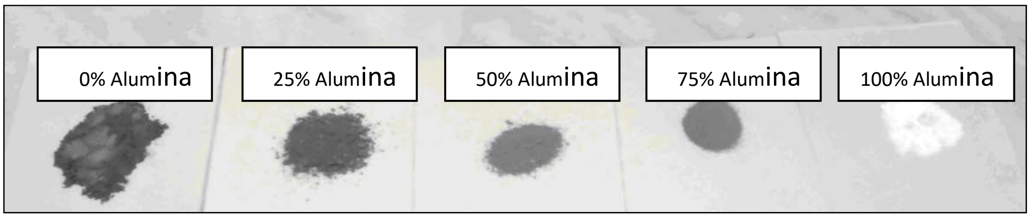


Figure (3): layers powder after mixing practices.

In the present work, the layers are termed as layer (1) to layer (5) startingfrom pure Ni end to pure (Al_2O_3) end. In order to find linear tailoring of the properties for system from pure (Ni) to pure (Al_2O_3),the graded in volume fraction will be determined depending on the simple power law equation (1) at power law index (N) equal to (1).Estimating the volume fraction of Nickel and the volume fraction of Alumina will be according to the following equation, [3]:

$$Vf(Al2O3) = 1 - Vf(Ni) \quad \ldots.(3)$$

The volume fraction of each layer is shown in the table (2). The weight of each layer is calculated by measurement of density and volume of each layer according to model'sprofile indicated in the table (2) then the mass of each layer is estimated accordingly.

Table (2): FGMs layer's chemical composition.

Layers no.	Volume fraction ofAl_2O_3	Layers	Mass of Al_2O_3 (g)	Mass of Ni (g)
1	0	100% Ni	0	1.57
2	0.25	75% Ni + 25% Al_2O_3	0.35	2.36
3	0.5	50% Ni + 50% Al_2O_3	1.05	2.36
4	0.75	25% Ni + 75% Al_2O_3	2.11	1.57
5	1	100% Al_2O_3	3.52	0
Total length =15 mm	100%	-	7.03	7.86

The six groups of samples were developed and fabricated according to the model's profile indicated in the table (2).Mixing of different powders and blending of same powders is the next step after preparing the weight of each layer. An efficient mixing is required to achieve uniform volume distribution of ingredients and the time required for mixing (depends on the amount of powders) about (90 min) using a ball mill is just enough to prevent agglomeration.Acetone is used as a binder because of its ability to vaporize at primary sintering temperature and also to protect Ni particles from oxidation during the sintering stage. The cylinder, steel die will be used to fabricatematerialmodel, the die has (15 mm diameter) as shown in figure (4). Compaction with (200 kg/cm^2) single action strokes press has been accomplished.

Figure (4): Cylindrical steel die with (15 mm) diameter.

Sintering practices including two steps; primary and secondary, knowing that all sintering practices were conducted by using vacuum furnace (type VDS/Ipsen).All FGMs were sintered primarily with 850°C for 2 hrs. Final sintering scheme for all prepared samples will be according to the following table (3):

Table (3): Sintering Data of prepared FGMs.

FGM	A	B	C	D	E	F
Final sintering Temperature (°C)	1250	1250	1250	1350	1350	1350
Soaking time (hrs)	1	2	3	1	2	3

Eventually, the cycle cools up and was set constant at a rate of 5°C/min in order to avoid any thermal shocks.The following photographs (figure 5) represent some of FGMs prepared in this work:

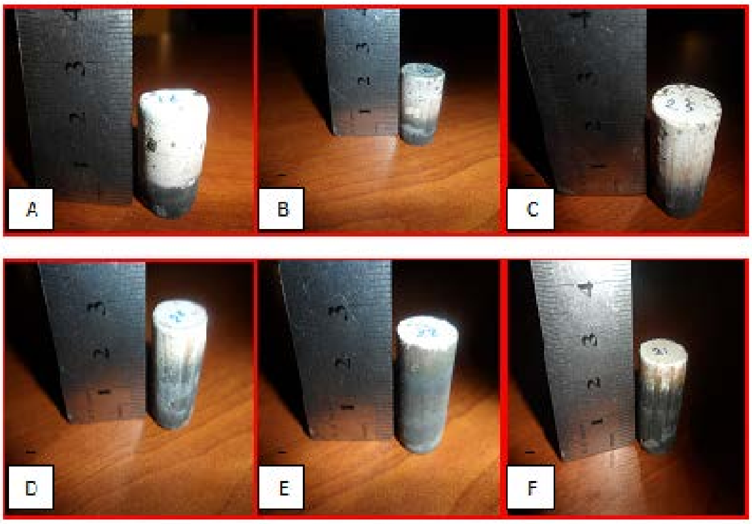


Figure (5): Photographs of some as-fabricated FGMs samples.

Characterization of (Al_2O_3/Ni) FGMs
Physical characterization:

The physical properties such are green, bulk and apparent density of prepared FGMs.The linear shrinkage and porosity were measured as well. Archimedes rule was the method used for measuring the values of apparent density and percentage of porosity. The sample weight was measured after sintering then immersed in warm water for 24 hours, followed by measuring the weight of test piece soaked and suspended in warm water. The bulk and apparent density were calculated according to the following formulas [12]:

$$\text{Bulk Density} = \frac{\text{Wd}}{\text{Wa} - \text{Wb}} \times \text{D} \qquad \dots.(4)$$

$$\text{Apparant Density} = \frac{\text{Wd}}{\text{Wd} - \text{Wb}} \times \text{D} \qquad \dots.(5)$$

$$\text{Apparant Porosity} = \left(1 - \frac{\text{Bulk Density}}{\text{Apparant Density}}\right) \times 100\% \qquad \dots.(6)$$

Where:

$W_{a:}$ weight of test piece soaked and suspended in air.
$W_{b:}$ weight of test piece soaked and suspended in immersion liquid.
W_d: weight of test piece.
D: density of immersion at temperature of test

Linear shrinkage: Thesinteredsample dimensions like (length and diameter), the characterization should be measured before and after before and after sintering.

Dimensional change for the sintered compact specimen is calculated from the following equation [8].

$$\text{Dimensional Change } \% = \frac{\text{Ds}-\text{DD}}{\text{DD}} \times 100\% \qquad \text{..... (7)}$$

Where:

D_D: diameter of mold cavity (mm).

Ds: the sintered specimen diameter (mm).

Expansion is indicated by a plus sign (+) and shrinkage is indicated by a minus sign (-).

Mechanical properties:

Microhardness: The microhardness along the sintered (FGMs) starting from pure nickel to pure alumina has been achieved in this study.An average of three readings for each layer was documented. Microhardness test was carried out to study the gradient of the mechanical property along the (FGMs) thickness. In the present study, load and time for the micro Vickers hardness test were (1.96 N) and (15 Sec.), respectively.

Compression test: (F-FGM)samples with (15 mm in diameter and 30 mm height) have been prepared and sintered according to the conditions that adopted in (F-FGM). The test has done at room temperature using a universal testing machine with (30KN) maximum load type (PHWYE), Marshal Compression machine. The specimens were carefully centered by eye and by ruler before being loaded steadily until failure. The test also repeated for each layer of (F-FGM) after reproducing layers samples at the same dimensions above.

Thermal properties measurement:-

Thermal conductivity is the property of a material that indicates its ability to conduct heat. Thermal conductivity is measured in watts per Kelvin per meter ($W \cdot K^{-1} \cdot m^{-1}$). Effective thermal conductivity of graded materials is essential for the calculation of the temperature profile and investigation of the thermomechanical behavior of these materials.One of the most accurate and convenient techniques for studying thermal transport properties is the Transient Plane Source (TPS) method.It is an advanced technique, providing data on thermal conductivity, thermal diffusivity as well as the specific heat per unit volume of the material under study.

A calibrated (Hot Disk Thermal Constants Analyzer TPS 2500, made in Sweden), is used to measure thermal conductivity.This apparatus is suited to calculate thermal conductivity from (0.005 to 500 W/m.°K).For each layer two samples have been developed in order to measure thermal conductivity coefficient (K).Thermal conductivity of multilayer (F-FGM) composite (K_{multi}) in the direction normal to the layer interfaces was predicted, according to the following formula, using thermal conductivity of each layer and with the assumption that there is no reduction in thermal conductivity of interfaces [13]

$$\frac{1}{\text{K multi}} = \sum_{t}^{1} \frac{\text{ti}}{\text{Ki}} \qquad \text{.... (8)}$$

Where, (t_i): is the thickness fractions of the FGMs layers, and (Ki) is the thermal conductivity values for different layers.

Thermal stresses by COMSOL package

Finite element method used extensively in this work through the COMSOL Multiphysicspackage to examine the developmental stresses, displacements, and temperature distribution of the FGM sample that shows an acceptable microhardness development along the thickness. The following Boundary conditions are assumed:

1. The sample consists of five layers starting from pure (Ni) at the bottom (1mm thickness) and graded towards pure (Al_2O_3) at the top (5mm thickness).
2. The sample is fixed at the bottom and free consider at the top.
3. Thermal load is applied at the top of the sample (1000°C) and room temperature at the bottom (25°C).
4. The value of the power index used is (N=1).
5. Physical and mechanical input data were taken from experimental characterizations of (F-FGM).

Microstructure observations:

The microstructure of fabricated FGMs is observed by light optical microscopy after the microstructure specimens are sectioned longitudinally, hot mounted with Bakelite as shown below in figure (6). Sectioning with wire cut and mounted was done in the Faculty of Materials Science &Technology /Freiberg University-Germany.

Figure (6): Sectioning and hot mounted of FGMs samples for metallographic observations.

Wet grinded by (Mopao - 160 – E) grinding device and polished according to (ASTM E-11).Microstructure was observed via optical microscopy (Bel- Photonic-Italian).

Results of experimental work:

The following section in this paper presents extensively the results and discussions of experimental findings:

Physical Characterizations:

The density difference between the primary constituents of FGMs (i.e. Al_2O_3 and Ni) powder and resulted layers densities especially at graded region is one of the most important physical properties to understand the formation mechanism of graded microstructure within the FGM fabricated by powder technology. According to the table (4), it is clearly shown that, the results of physical properties of fabricated FGMs; almost all FGMs are exhibiting the same values of green density. These results are fairly expected due to the using of single compacting load. It is noticeable that as the sintering time was increased at constant sintering temperature (i.e. A, B, C-

FGMs) and (i.e. D, E, F-FGMs) respectively, an apparent density was improved slightly. The reasons behind such improvement are the increasing of sintering efficiency as the soaking time was increased at each temperature. The results of apparent density of prepared FGMs are accompanied by a decreasing of apparent porosity as the sintering or soaking time increased at constant sintering temperature. Inappropriately, the lateral shrinkage of (F-FGM) is higher than other materials.

Table (4): Physical Characterization results of prepared FGMs.

Sample	Green density (g/cm^3)	Bulk density (g/cm^3)	Apparent density (g/cm^3)	Apparent porosity %	Lateral Shrinkage %
A	3.37	4.05	4.22	48.86	0.26
B	3.29	2.81	4.25	33.88	1.37
C	3.21	2.3	4.35	26.98	1.72
D	3.34	2.79	4.97	24.66	0.71
E	3.18	2.55	5.04	22.18	3.17
F	3.25	2.50	5.00	21.86	3.58

Mechanical Characterizations:
Vickersmicrohardness:

The microhardness distribution across the FGMs layers after sintering practices is presented in figure (7) according to ASTM E-384 standard. As expected, an increasing in microhardness is observed with the increasing of (Al_2O_3) content in each of FGMs sample layers. (F-FGM) sample seems to give a high and slight linear graded microhardness across the layers. The interfacial microhardness values in this sample were found very close to the bulk adjacent layers. The minimum jumps in microhardness readings as in (F-FGM) that imparts minimum residual stresses. That indicates (F-FGM) sample can impart almost linear graded mechanical properties among the other FGMs.

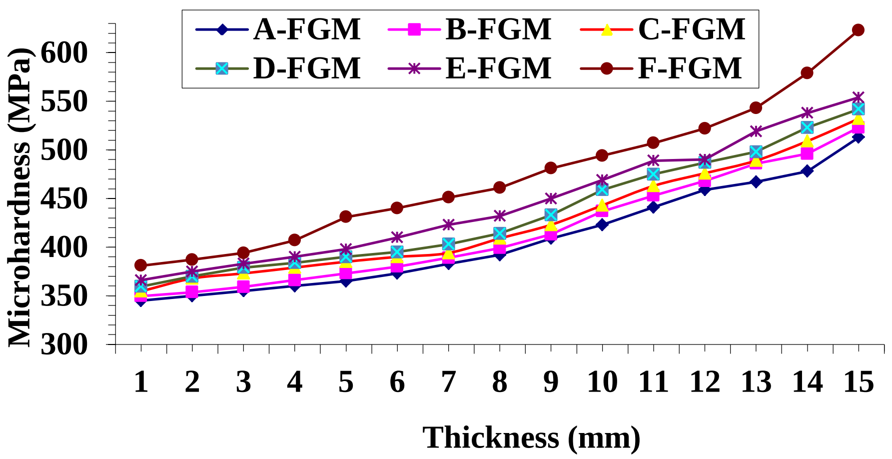


Figure (7): **Microhardness variation along the FGMs thickness.**

Compression Test results:

Figure (8) shows the modulus of elasticity results of each layer. Knowing that, the compression test samples were manufactured and sintered according to the sintering schemes that adopted in the case of (F-FGM) sample (i.e. sintering at 1350°C for 3 hrs.).

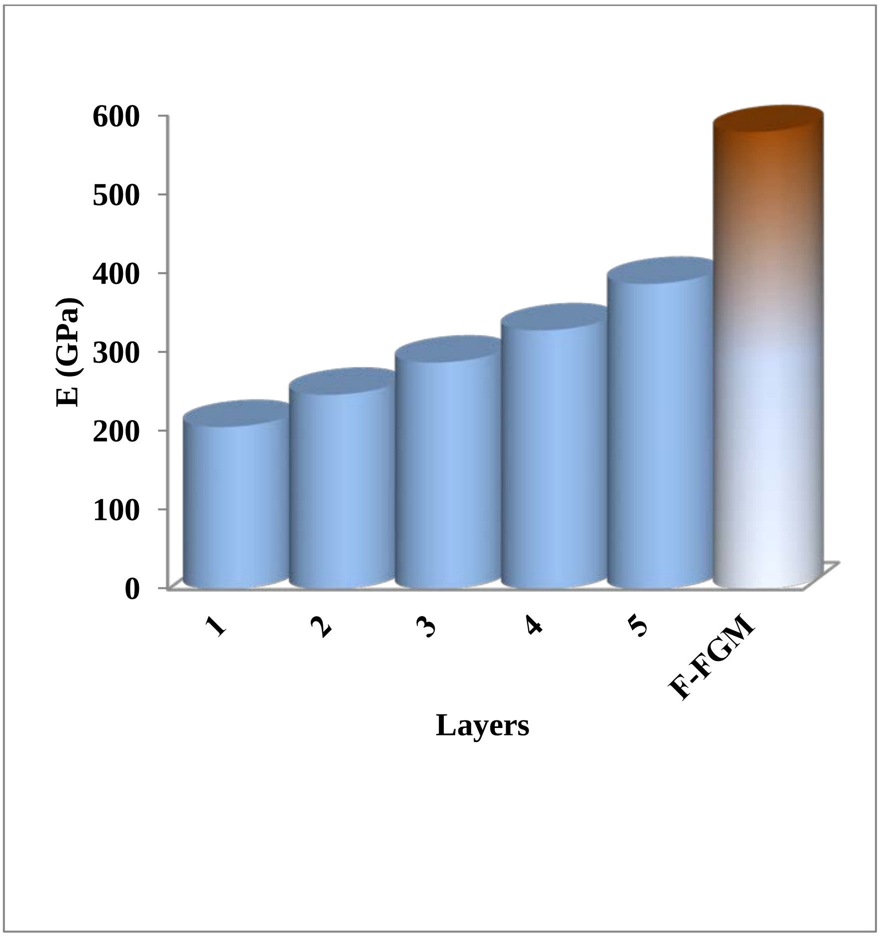


Figure (8): Modulus of elasticity results of (F-FGM) layers.

Figure (9)shows, the stress-strain curve of (F-FGM). The presents a linear relationship in the elastic stage, and then the FGM materials come into the plastic deformation stage. But the stress increases as the strain increasing.

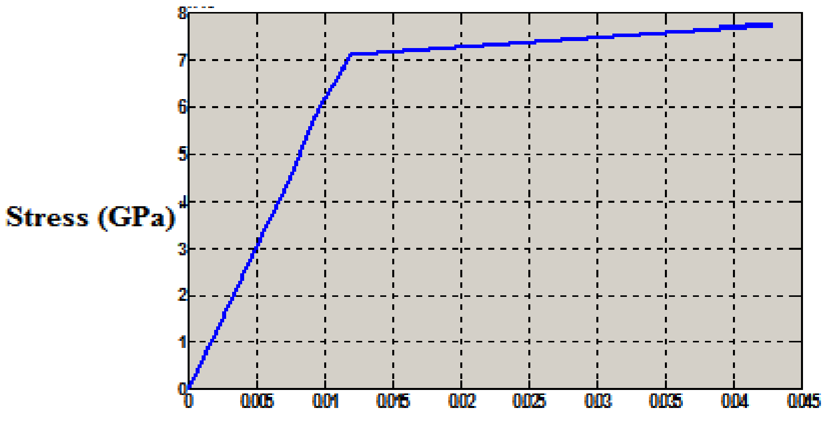


Figure (9): Stress-strain diagram of F- FGM samples.

Furthermore, the intensity of compression of (F-FGM) specimens is(680 GPa) when the strain is about (0.013); then the FGM specimen present plastic deformation; and when the strain was (0.02), the FGM specimens appear macroscopically cracked and the intensity of compression is increased.It shows that the plastic deformation is non homogenous. The reasons are (Al_2O_3)particulates prevent the plastic flow of (Ni) matrix, and the differences of (Al_2O_3) content in every layer and also because the variation of the volume fraction of (Al_2O_3) is not continuous, the deformation of each layer is not the same.

Thermal Characterizations:

Since (F-FGM) is the best properties among the prepared alloys, a thermal characterization of this sample was carried out.Table (5) shows the thermal characterization that includes the measurements of thermal properties like thermal conductivity, thermal diffusivity and thermal expansion of each layer of (F-FGM). Obviously shown from these results, that as the weight percentage of (Al_2O_3), thermal properties were altered accordingly. Thermal conductivity values were increased linearly as

Table (5): Thermal characteristics of F-FGM.

Layer	L (mm)	K (W/m.C)	Specific heat (J/g.C)	Thermal Expansion α (µ / m.C)
1	1	0.61	0. 46	8.2
2	2	0.49	0.57	9.43
3	3	0.36	0.67	10.65
4	4	0.24	0.78	11.88
5	5	0.22	0.88	13.1
Total	**15 mm**	**0.0188**	**0.047**	**11.28**

Results & discussion of COMSOL modeling of F-FGM

Figure (10) representsthe contour of normal stresses that developed during exposure of (F-FGM) to high temperature (i.e. 1000 °C) on the upper surface of pure Alumina while the other side nickel have been set at room temperature. Figure (11) represents the curve by which the normal stresses that developed along the sample thickness are varied. However, there was a clear fluctuation of stresses along the thickness that imparts a development of stress concentration regions near the interfaces of layers, especially in the half lower region of FGM that enriched in (Ni). Stresses are clearly becoming normal variably with the thickness at the upper half of FGM that enriched with (Al_2O_3).

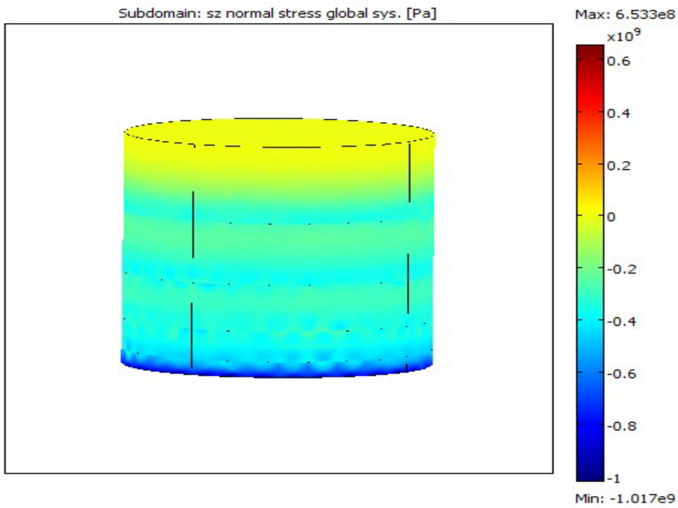


Figure (10): Three dimensional stress distribution contour of normal stresses that developed during exposure of F-FGM to high temperature (i.e. 1000 °C).

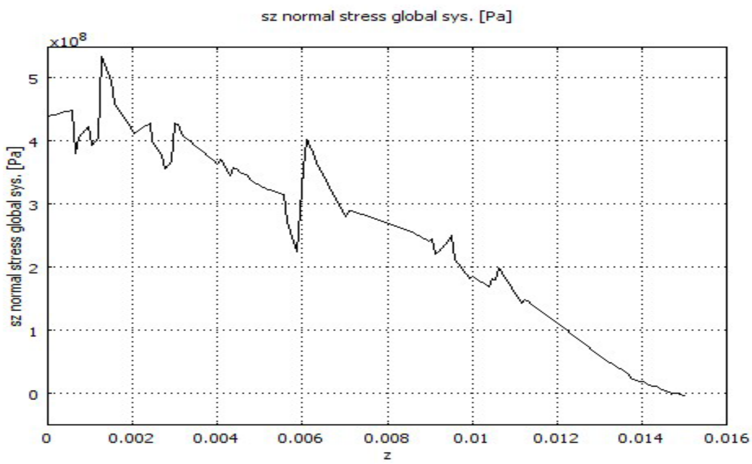


Figure (11): Variation of normal stresses that developed along the F-FGM sample thickness.

Displacement along the model as a result of temperature loading is represented as shown in figure (12). The figure shows the values of displacement versus (Z) distance starting from pure nickel to pure alumina.Consequently, the values of displacement at any point along the model can be found. The maximum displacement (i.e.Expansion) can be found at the surface of pure alumina of about (0.075 mm) as shown in figure (12).

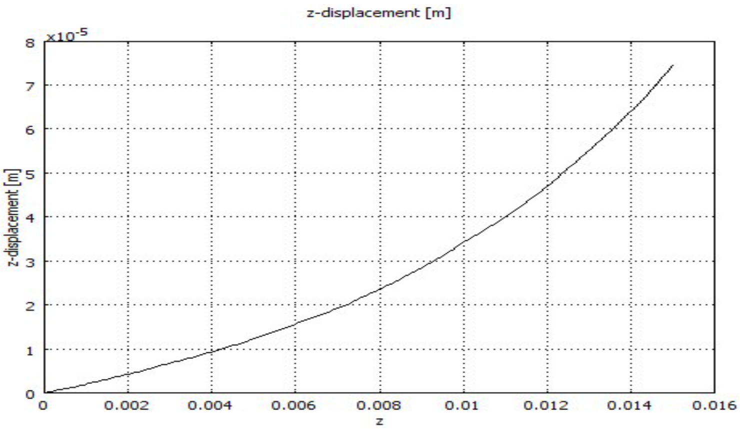


Figure (12): Z-displacement through thickness of F-FGM.

Temperature distribution of (F-FGM)has been represented as shown in figures (13 and 14). The maximum temperature as indicated on the upper surface of pure Alumina as denoted with red color, and temperature was falling down across layers of the sample reach to the minimum value at the base of the sample as denoted with blue color. The temperature distribution in one dimension from pure aluminum oxide into pure (Ni) considering the base surface insulated was shown in figure (14). The temperature distribution is linear along the thickness. These results are in conformance with the microhardness linear gradation along the thickness of (F-FGM).

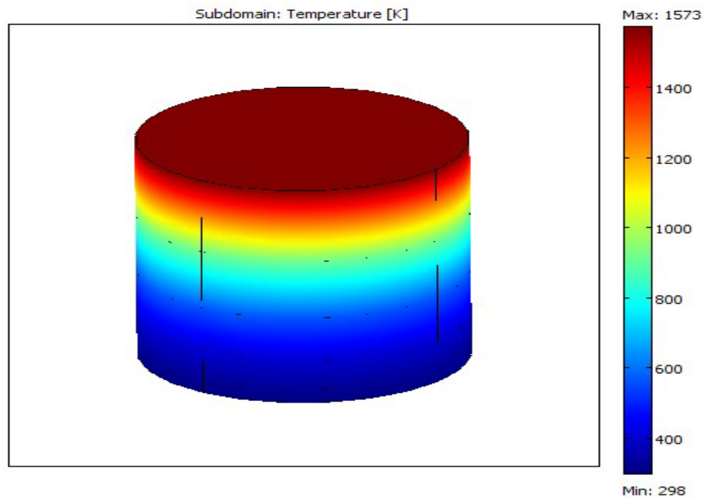


Figure (13):3-D temperature distribution of F-FGM.

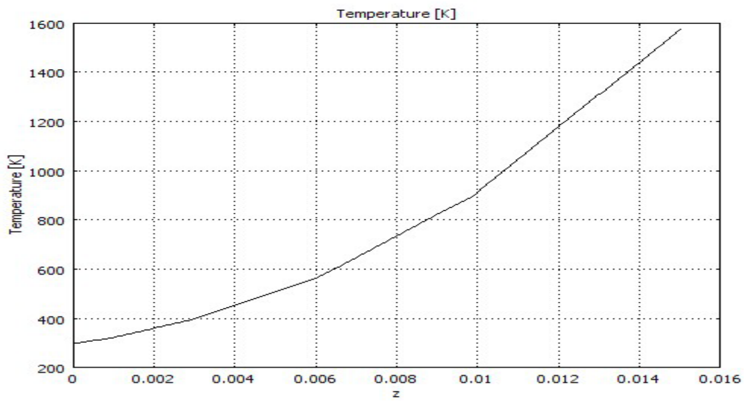


Figure (14): Temperature distribution along the thickness of F-FGM.

Microstructure observation:

According to figure (15), it can be inferred that the cross section of each FGM shows a well-defined five layer microstructures starting from the upper layer that consists of 100% (Al_2O_3) to the bottom layer which consists of (100% Ni). The dark areas represent the ceramic (Al_2O_3) phase, while the bright areas represent the metal (Ni) phase. The first layer from the FGMs bottom is dense with noticeable micro porosities. Alumina phase was introduced in the second layer at 25% and uniformly distributed in the (Ni) matrix. Micro porosities still appear in this layer. The microstructure becomes more dark and dense in the z direction as a result of introducing more (Al_2O_3). As the sintering time and temperature increase (i.e. 1350°C for 3 hrs.), the microstructure becomes much denser and the interfaces become more homogeneous that lead to eliminate the discontinuity in microstructure as can be seen in (F-FGMs).

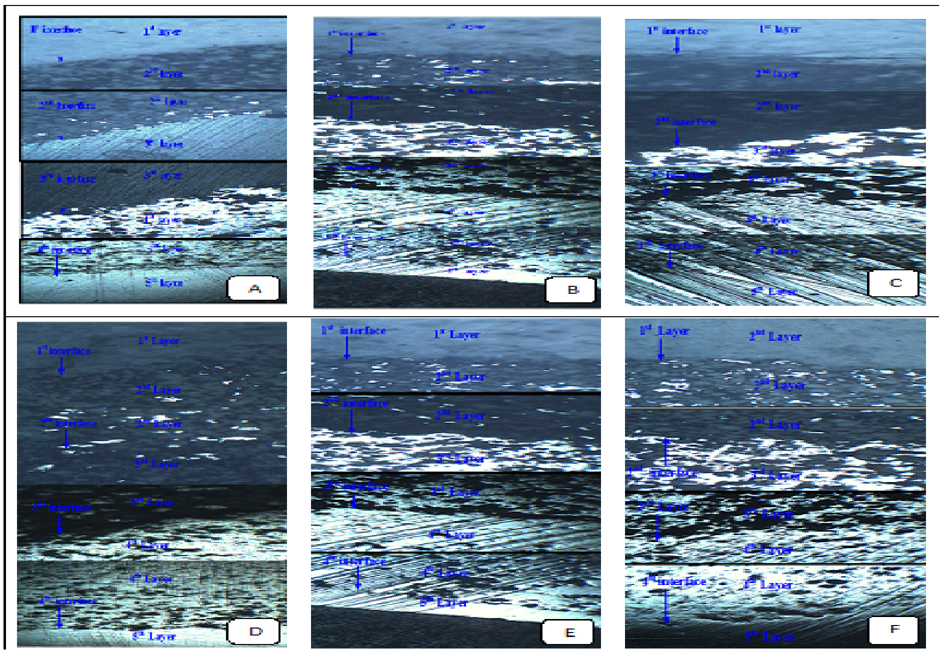


Figure (15): LOM microstructure observations along the FGM samples (500 X).

CONCLUSIONS:

Five layers (Al_2O_3/Ni) functionally graded materials were successfully fabricated by using powder technology route. The effects of increasing the sintering temperature and time as well as the physical and mechanical characteristics were investigated. Based on the present study, the following conclusions were made:

1. All prepared FGMs are almost exhibit an acceptable graded increasing of microhardness along the thickness.
2. Apparent density of prepared FGMs is supported by a decreasing of apparent porosity as the sintering or soaking time increased at constant sintering temperature.
3. The lateral shrinkage of (F-FGM) is higher than other materials.
4. F-FGM sample seems to impart a slight linear graded microhardness across the layers with minimum jumps. The interfacial microhardness values were found very close to the bulk adjacent layers.
5. The minimum jumps in microhardness values as in (F-FGM) imparts the minimum residual stresses achieved by the COMSOL simulation.
6. Compression tests results of prepared (F-FGM) gives a higher modulus of elasticity during the compression test among the other prepared materials. The reasons behind such behavior are the minimum porosities due to the efficient sintering practices.
7. As the sintering time and temperature increase, the microstructure becomes much denser and the interfaces become more homogeneous that lead to eliminate the discontinuity in microstructure.
8. A clear fluctuation of stresses along the thickness that imparts a development of stress concentration regions near the interfaces of layers, especiallyin the half lower region of FGM that enriched in (Ni).
9. Stresses are clearly becoming normal variably with the thickness at the upper half of FGM that enriched with (Al_2O_3).

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