Finite Element Analysis Of Thermally Induced Residual Stresses In (Ni/Al_2O_3) Functionally Graded Materials

T.Lavanya, L.Rasidhar, Aditya Vikas Rawat

Abstract— These instruction functionally graded materials (FGMs) are advanced materials and their main characteristic is microstructure and composition variation over the volume of the specimen. In graded metal/ceramic components incompatible properties like strength, toughness and machinability of metal are coupled with heat, wear and corrosion resistance of ceramic in a single part. Sintering is the main technique to manufacture these types of materials. Distribution analysis of these thermally induced stresses in the cuboid metal-ceramic (Ni/Al_2O_3) functionally graded material has been analysed. Finite element package ANSYS (Work-Bench 14.0) has been used in order to simulate the distribution of the thermal residual stresses in the materials. In order to achieve the optimal design for different geometries the parametric study also has been performed. The influences of number of layers, thickness variation, and dimensional changes have been investigated.

Index Terms--- Functionally graded materials, cuboid FGM, thermal residual stresses, Von-Mises effective stresses

1 INTRODUCTION

Functionally graded materials (FGMs) are advanced materials in which the material properties vary with position in the component. These materials are used where there is a need for different material characteristics in the same component, such as weldable wear components or electrical conductive components with an insulating surface.

Dimorph AB a world leading producer of smart materials uses sintering technique in order to produce these graded materials. In this sintering technique layers of powder mixtures are added to a sintering mould, a uniaxial pressure is applied, and the material is heated through and electric current, which transforms the powder mixture into a solid component with a gradually changing microstructure. Arash Hosseinzadeh Delandar [1], studied the Performance of FGM's and described the thermal residual stresses in the metal-ceramic FGM component of both cuboid and cylindrical in the form of Von-Mises effective Stresses and Maximum Principal Stresses. These studies related on the influence of thickness, linear and non-linear approach, inter lay ers and amount of porosity can be considered. Cho and Oden [2], analyzed the thermal-stress characteristics of (Ni/Al2O3) functionally graded materials (FGM), the newly introduced layered composite materials with great potential as next generation composites. It provides insight into the concept of FGM and lays the foundation of FGM optimization to control thermal stresses

. Alaa et al. [3], reviewed the Fabrication of Ceramic-Metal Functionally Graded Materials; high order step wise functionally graded materials Al2O3-Ti are fabricated. The best sintering conditions is found at 1500°C for 30 minute of sintering that gives apparent density of 4.25 g/cm3, Porosity of 1.28% and diametric expansion of 1.58%. This study shows the Material combination of linear and linear approach composition variation, amount of porosity in terms of weight density of materials can be carried out. Padmanabhan et al. [4], Investigated on the Comparison of mechanical properties of Al2O3 and low density Polyethylene (LDPE) is a artificially made material system consisting of two or more phases. It proved an excellent strength to weight ratio and stiffness to weight ratio could be achieved using these materials. Chung et al. [5], presented the High thermal conductive diamond/Cu-Ti composites fabricated by pressure less sintering technique. The fabrication method adopted in this study provides a simple and low-cost method for producing diamond/metal composites. Aran [6], In these Manufacturing Properties of Engineering Materials are classified and the most important properties of the engineering materials are listed. The properties covered here are especially those properties, which are most important in the manufacturing of the Functionally Graded Materials

In the present investigation FE method is employed to analyze the distribution of thermally induced stresses within the functionally graded materials that result from the sintering process. The cooling down phase in the manufacturing process will be simulated in order to predict the distribution of thermal residual stresses within the material. Parameter study will be performed. The influence of mixing ratio variation and layer thickness on the resulting thermally induced stresses have been investigated.

2 ANALYSIS OF FUNCTIONALLY GRADED MATERIALS

2.1 Manufacturing of Functionally Graded Materials

The manufacturing process of FGM can usually be divided in building the spatially inhomogeneous structure (“gradation”) and transformation of this structure into a bulk material (consolidation). Most suitable fabricating technique for functionally graded materials is Powder Processing. This method is extremely capable of accommodating graded layers. Every individual layer should have a certain and fixed mixture ratio of metal and ceramic powders. After mixing of different powders the next step is deposition of layers of powder mixtures with gradual changing

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in composition in the die. Placing the different layers of powder mixtures into the sample holder (die) is called "powder stacking".

In fact by powder stacking the component has been prepared for forming into the required shapes. Pressing is a main technique to form the powders and obtain a desired shape. Applying pressure to the die results in packing and forming of the powder component. Uniaxial pressing and iso-static pressing are two main forming methods for powders. In uniaxial pressing, the compaction and packing of the powder component is achieved by applying pressure on the compacting die along a single axial direction. In iso-static pressing, pressure is applied on the compacting die from all directions instead of one direction, by using this technique and application of pressure from all directions more uniform compaction of the part will be achieved.

Material failure due to Residual Stresses

In manufacturing of functionally graded materials by sintering technique, thermal residual stresses are generated due to the cooling process from the sintering temperature to the room temperature. In metal-ceramic FGMs, the two constituents have different thermal expansion coefficients. Hence, as the material cools down from the sintering temperature, the contraction of the different layers will not be uniform but will change with the mixing ratio. This effect will in turn cause thermal residual stresses in the material, and this may cause delamination and hence failure of the material as shown in Fig.2.1. Therefore, it is necessary to analyze and optimize distribution of these thermal residual stresses in order to fabricate FGMs without damage.

Figure 2.1 Cracking of metal-ceramic FGM due to thermal residual stresses

The Finite element package ANSYS (Work-Bench 14.0) has been used to analyze the distribution of thermal residual stresses in the Nickel and Aluminium Oxide (Ni/Al_2O_3) cuboid metal-ceramic carbide FGM. Models were assumed to cool from sintering temperature (Ti=1091.25˚C) for Metal of Nickel (Ni) and (Ti=1537.25˚C) for Ceramic of Aluminium Oxide (Al_2O_3) to room temperature (Tf=25.4˚C), with a uniform temperature field with respect to the sintering time were assumed to around four hours.

Stiffness properties like Elastic modulus, Poisson's ratio, Coefficient of thermal expansion (CTE), Melting point and thermal conductivity of pure ceramic and metal which were used in the Finite element analysis are listed below:

Table.1. Material Properties

Properties	Material	
	Ni	Al2O3
Elastic modulus,E GPa	200	370
Poisson's ratio , v	0.31	0.22
CTE, α (K- 1)	13.4*10-6	8.2*10-6
CTE, α (K- 1)	91	12
Melting point (K)	1445	2050

2.2 6 Layers cuboid FGM of uniform thickness

Finite element analysis results of thermally induced stresses for cuboid metal-ceramic FGM consist of following:

1. σ1: Maximum principal stress
2. σe: Von Mises effective stress

As per ANSYS (Work-Bench 14.0) the design criteria of (Ni/Al_2O_3) metal and ceramic carbide FGM and the influence of thermal residual stresses for 6 Layers to both uniform and non-uniform thickness, 10 Layers with dimension variation is as follows:

Standard dimension of (40*20*35) mm of cuboid 6 layersFGM geometry is length (a) =40 mm, width (b) =20 mm and height or thickness (c) =35 mm.

Table 2 Composition, height and materials properties of different layers.

Layer	Composition (Vol %)	Height (mm)	Elastic modulus, E (GPa)	Poisson's ratio, v	Coefficient of thermal expansion (CTE), α(K-1)	Thermal Conductivity, K (w/mk)
1	Metal 100	15	200	0.31	13.4*10-6	91
2	Metal 80, Ceramic 20	4	234	0.29	12.12*10-6	75.2
3	Metal 60, Ceramic 40	4	268	0.274	11.14*10-6	59.4
4	Metal 40, Ceramic 60	4	302	0.256	10.16*10-6	43.6
5	Metal 20, Ceramic 80	4	336	0.238	9.18*10-6	27.8
6	Ceramic 100	4	370	0.22	8.2*10-6	12

3 Results and Discussions

3.1 Geometry Of 6 Layers Cuboid FGM:

Finite element analysis of ANSYS (Work-Bench 14.0), the geometry of 6 Layers cuboid metal-ceramic FGM dimensions (40*20*35) mm of uniform thickness Fig.2 shows upper layer is 100% Metal and bottom layer is 100% ceramic and then the remaining 4 Layers in the middle portion is the graded region of variation of composition as listed in the Table 2.

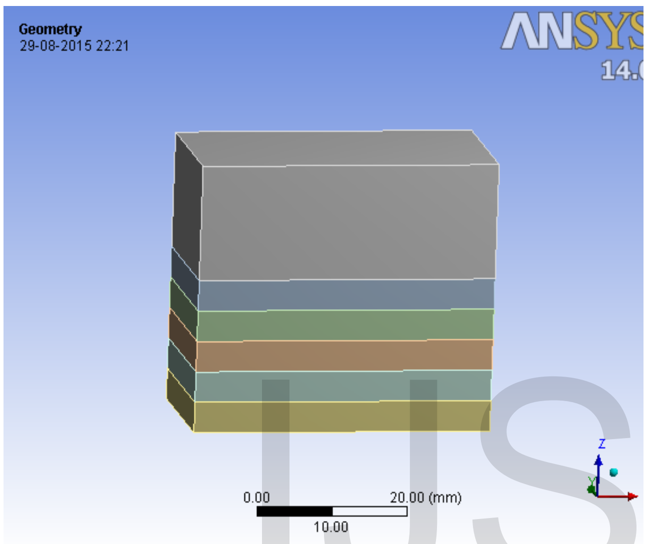

Fig.2 Geometry of 6 Layers cuboid FGM

FE analysis of Time-Temperature graph:

Cooling of the specimen from sintering temperature to room temperature has been analyzed. Models were assumed to cool from sintering temperature (Ti=1091.25˚C) for Metal of Nickel and (Ti=1537.25˚C) for Ceramic of Aluminium Oxide (Al2O3) to room temperature (Tf=25.4˚C), with a uniform temperature field with respect to the sintering time were assumed to around four hours means 14608 seconds.

Fig.3 & Fig.4 shows the geometry and related input graph of series 1 is Al2O3 is the maximum and series 2 is Ni is the minimum sintering time-temperature of metal & ceramic is as follows:

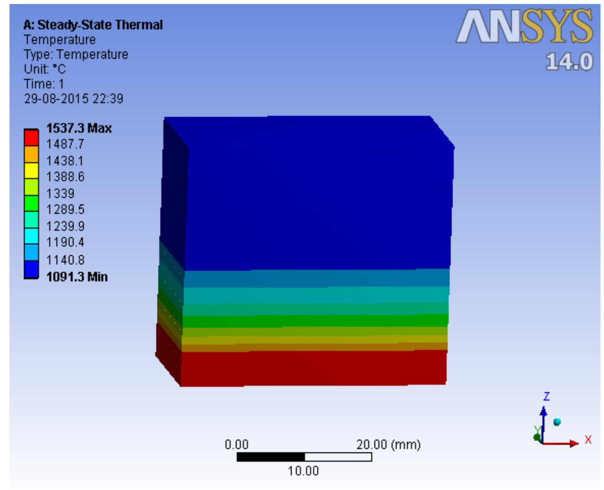

Fig 3 Maximum & Minimum sintering temperature

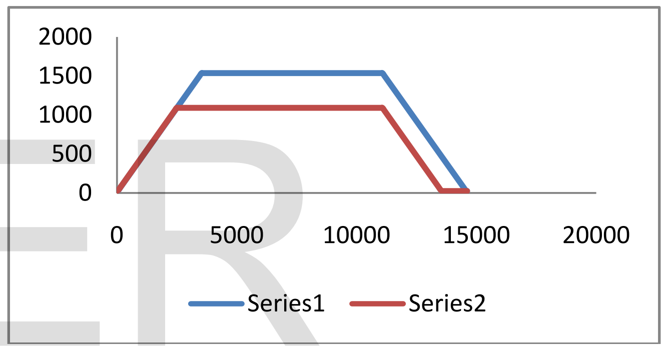

Fig 4 Graph between sintering Temp-Time

FE analysis of Thermal Residual stresses:

The resulting stresses are the Thermal Residual stresses in the Fig 5 shows the maximum and minimum Von-Mises effective stresses (σe) in the 6 Layers cuboid FGM of uniform thickness with respect to the time interval. This analysis shows the layer 1 (Metal 100%) is the layer, where Von - Mises effective stresses are high. For this model (Max σe=2.0377 MPa and Min σe=0.01301 MPa).

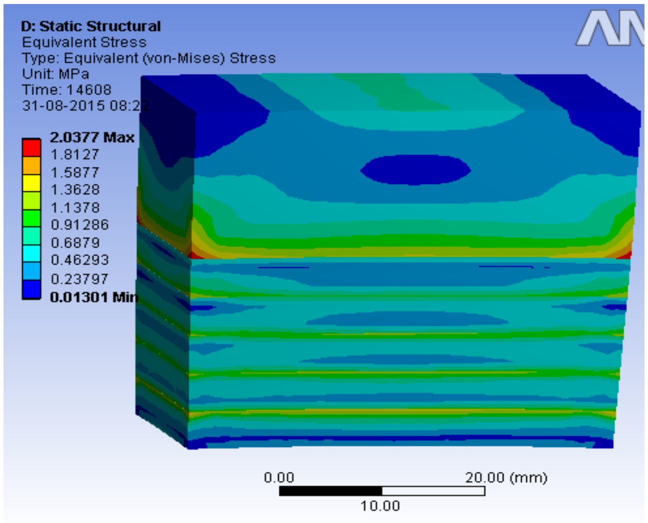

Fig 5 Maximum & Minimum Von-Mises effective stresses (σe)

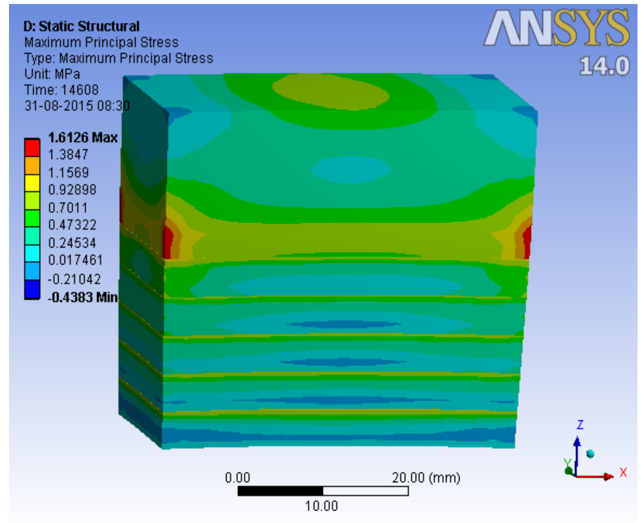

Fig 7 Maximum and Minimum Principal Stresses (σ1)

Graph shows the output transient thermal analysis of stress Vs time that are thermal residual stresses where the maximum and minimum Von-Mises effective stresses of both Ni & Al2O3 with respect to the time distribution from sintering to room temperature with the time interval around 4 hours as shown in the Fig. 6

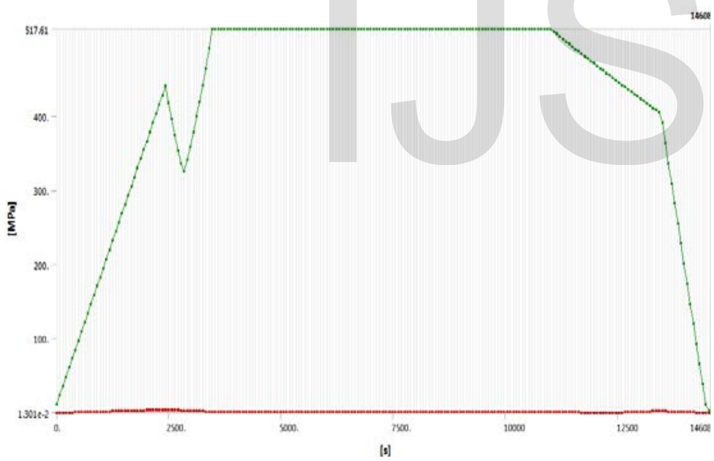

Fig .6 Graph between Max & Min Von-Mises stresses Vs time

The resulting stresses are the Thermal Residual stresses in the Fig.7 shows the maximum and minimum principal stresses (σ1) in the 6 Layers cuboid FGM of uniform thickness with respect to the time interval. This analysis shows the layer 1 (Metal 100%) is the layer, where principal stresses are high. For this model (Max σ1=1.6126 MPa and Min σ1=-0.4383 MPa).

Graph shows the output transient thermal analysis of stress Vs time that are thermal residual stresses where the maximum and minimum Principal stresses of both Ni & Al2O3 with respect to the time distribution from sintering to room temperature with time interval around 4 hours as shown in the Fig. 8.

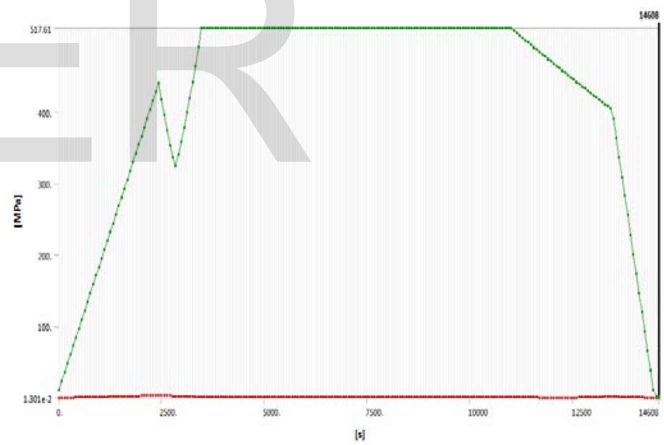

Fig.8 Graph between Max & Min Principal stresses Vs Time

- Based on the Finite Element analysis results of thermal residual stresses in 6 Layers cuboid FGM dimensions (40*20*35) mm of uniform thickness the model as shown in the Fig.9 layer 1 (Metal 100%) is the layer, where Von - Mises effective stresses (σe) are high. For this model (Max σe=2.0377 MPa).

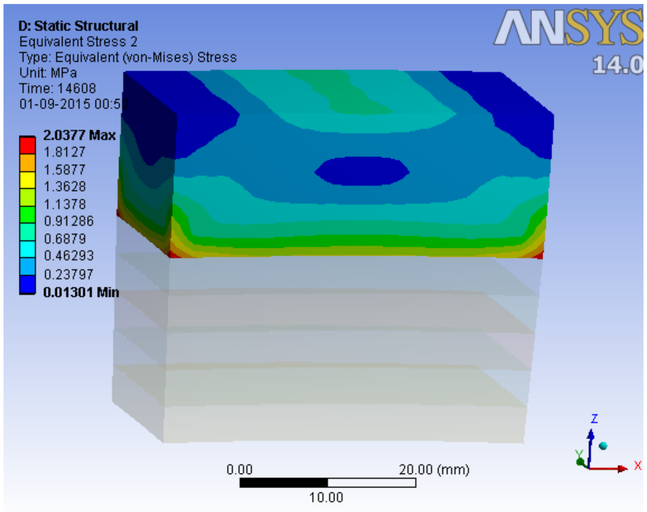

Fig .9 Maximum Von-Mises effective stress (σe) of Layer-1

Graph shows the output transient thermal analysis of stress Vs time that are thermal residual stresses in the layer 1 where the maximum and minimum Von-Mises effective stresses of both Ni & Al2O3 with respect to the time distribution from sintering to room temperature with the time interval around 4 hours as shown in the Fig 10.

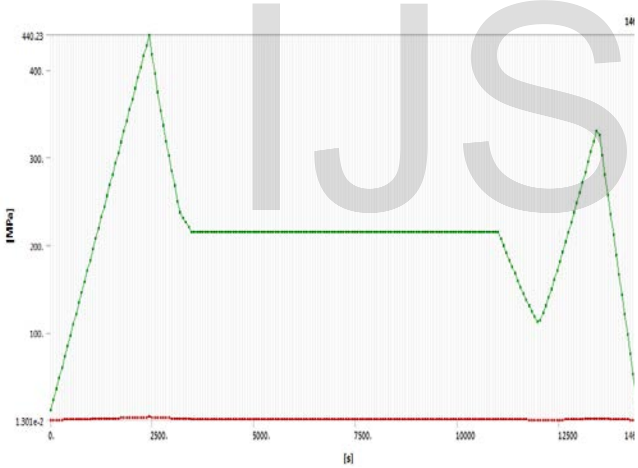

Fig.10 Graph between Max & Min Von-Mises stresses Vs Time in layer

- Based on the Finite Element analysis results of thermal residual stresses in 6 Layers cuboid FGM dimensions (40*20*35) mm of uniform thickness the model layer 1 (Metal 100%) is the layer, where Maximum Principal stresses (σ1) are high. For this model (Max σ1=1.6126 MPa) as shown in the Fig.11.

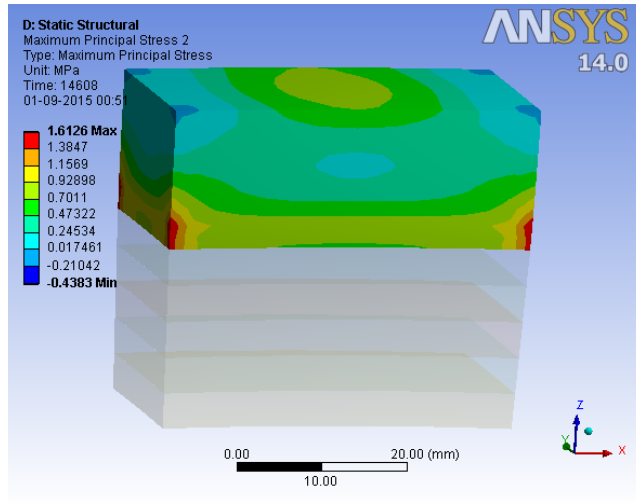

Fig.11 Maximum principal stresses (σ1) of Layer-1

Graph shows the output transient thermal analysis of stress Vs time that are thermal residual stresses in the layer 1 where the maximum and minimum Principal stresses of both Ni & Al2O3 with respect to the time distribution from sintering to room temperature with the time interval around 4 hours as shown in the Fig .12.

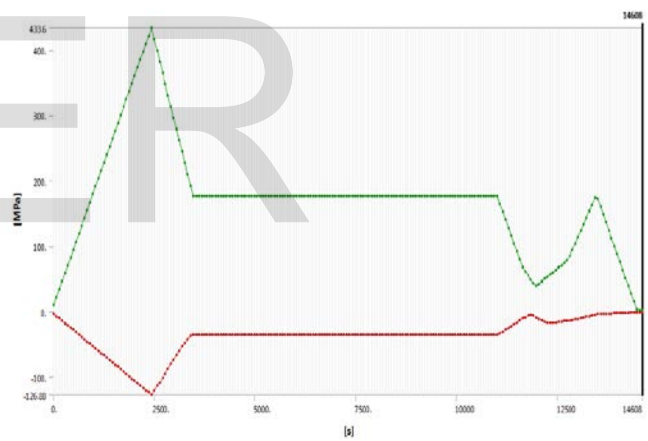

Fig.12 Graph between Max & Min Principal stresses Vs Time in layer 1

3.2 Results of Comparisons in Cuboid FGM

6 layers with dimension (40*20*35mm) and linear composition variation table3.

Table.3 Comparisions in cuboid FGM

Equivalent (Von-Mises) Stress(σe) MPa	Maximum Principal Stress(σ1) MPa
Max σe= 2.0377	Max σ1= 1.6126
Min σe= 0.01301	Min σ1= -0.4383

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CONCLUSION

By using FE-method to analyze the distribution of thermal residual stresses it is possible to design and manufacture FGMs, with optimum magnitude and distribution of thermal stresses. This optimum distribution of thermal residual stresses helps to fabricate a final product without cracking or delamination.The finite element analysis results for cuboid metal-ceramic (Ni/Al2O3) Functionally Graded Material indicate that, thermal residual stresses will be reduced when 8 intermediate layers are placed between the two metal and ceramic layers. Moreover, the results illustrate that decreasing the number of inter layers has no improving effect on the resulting thermally induced stresses.The performance objective for both the Von-Mises effective stresses and Maximum Principal stresses is achieved in the form of thermal residual stresses when the thickness variation has been considered in the cuboid metal-ceramic (Ni/Al2O3) .

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