Design and Preparation of Stepwise Functionally Graded Materials Used for Internal Combustion Engine Piston Applications

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ABSTRACT

This work includes the design and preparation of a(Low carbon steel / AL_2O_3) stepwise functionally graded crown part of an internal combustion engine piston. Powder technology technique, has been studied to improve engine thermal efficiency by creating semi adiabatic combustion chambers, where ceramic phase facing the hot combustion gases, while metallic phase assembling with other parts of the piston. Finite element method ABAQUS program had been used to minimize nucleated residual stresses generated under fabrication process and service work conditions by designing the compositional graded of stepwise FGM within specific dimensions, in addition to temperature distribution across FGM thickness. Then the fabricated specimens had SEM imaging, physical and mechanical property inspection. The results also show that linear transition from metal to ceramic structure can provide minimum residual stresses under all conditions, using stepwise FGM can improve engine heat efficiency by doubling the crown surface temperature,(622) ºC, comparing with steel crown, (322) ºC, under the same applied heat flux. Physical inspections show limited relative density, (48.5) %, with high total porosity structure, (53.3) %, can be performed by this fabrication method. Mechanical tests results show that the layers' hardness increase with increasing ceramic content, and decrease with increasing pores percentage. Compression test shows the ability of suggested stepwise FGM to withstand service work stresses of combustion chamber without failure.

INTRODUCTION

While only around (30) % of fuel energy which supplied to engines is used to perform useful work, the residual amount is lost through friction and cooling activities. This directs engines researches during the last two decades toward improving thermal efficiency of engines [1]. Improving heat efficiency can lead to; decrease consumed fuel by reducing the incomplete fuel combustion percentage, reduce the pollution gases as reduction of consuming fuel, enhance thermal fatigue resistance as reduction of thermal stresses of underlying metallic surfaces, consequently, increase the estimating work life of the cylinder, finally boosting engine power by improving mechanical and thermal loads limits [2, 3]. Lining the combustion chamber with low thermal conductivity, and high temperature resistance ceramic phase by thermal coating have a discussion by may researcher, however, these procedures can provide only limited

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heat insulations because the limited thickness that can be applied. In this work, it's suggested to prepare bulk thermal barrier stepwise FGM to use as crown part of piston by powder technology

method to provide thermal insulation for combustion chamber, where ceramic part of FGM facing the hot combustion gases, while metal part is connected with remain parts of piston body.

Literature survey

Using (ceramic/metal) for the thermal barrier purpose had been discussed by many researchers, in 1997 (316 stainless steel/ alumina) was studied by (M. Grujicic et al.), this research, optimizes compositional graded through seven layers, the research found that nonlinear structural graded (n=4) had lowest residual stresses during the fabrication stage [4]. In 2004, (Tadeusz et al.) had used ABAQUS FEM code for analysis functionally graded thermal barrier coating on(Al-Si) alloy piston to estimate stress distributions throughout the entire working cycle [5]. In 2007, (Buyukkaya) had used ANSYS FEM code for analysis functionally graded thermal coating on (Al-Si) alloy and steel piston [2]. In 2009, (Zeming He et al.) had studied fabrication and characteristics (alumina/iron) stepwise FGM [6]. In 2010, (Hideaki Tsukamoto) had presented a methodology of analyzing and design functionally graded thermal barrier coatings taking into account the time-independent and dependent inelastic deformation, such as plasticity of metals, creep of metals and ceramics, and diffusional mass flow at the ceramic/metal interface for Ni/Zr_2O system [7].

Problem description

Using stepwise FGM instead ceramic-metal direct connection will help reduce the extreme residual stress, which create at the interface surface between two phases. The source of these stresses is the difference in thermal and mechanical properties between the two phases, especially at elevated temperatures during fabrication process or through service work. The challenges of this work are optimizing the compositional graded of stepwise FGM to get minimum generated residual stresses, and ensure that the suggested part has ability to withstand service conditions through much of physical and mechanical inspections addition to SEM images.

Theoretical part

Although this work isn't concerned with engine designing field, real dimensions of steel diesel engine piston have taken into the count infinite element method stresses analyzing. Five equals' layers' thickness with(15) mm total height, and (125) mm diameter (width) axisymmetric model, is used as shown in figure (1)

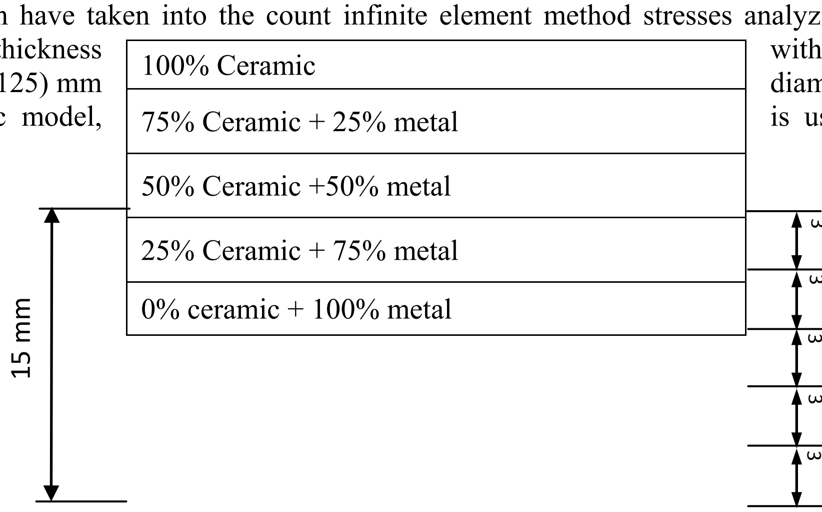

Figure (1) stepwise FGM

Specify constituents 'volumes' fractions in each layer is the most important FGM designing variable that decided the nucleated residual stresses. volumes' fractions is calculated according to the following relation [8].

$$V_2(z) = \left(\frac{z-z_1}{z_2-z_1}\right)^n \quad ...(1)$$

Where

V_2 (z): volume fraction of second phase at specific high

Z_2: total thickness (cm or mm)

Z_1: phase one thickness (cm or mm)

Z: any height within graded direction (cm or mm)

n: exponent of graded equation

The exponent value (n), decides the compositional graded mode as shown in figure (2).For (n > 1) FGM composition deviation toward metallic structure, the metal is the main structural constituent, and for (n < 1) FGM composition deviation toward ceramic structure, the ceramic is the main structural constituent. As shown in figure (2) below.

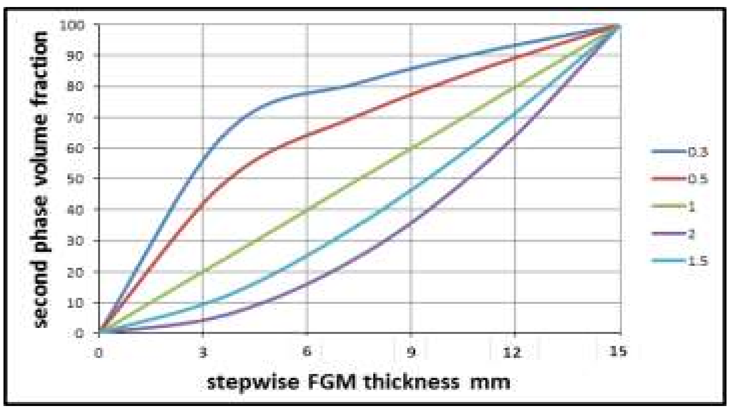

Figure (2): Stepwise FGM with different (n) values

Different (n) Values have studied, (0.3, 0.5, 1, 1.5, and 2), on order to optimize compositional graded. The volumes' fractions percentage of the second phase (ceramic) all (n) modes, is shown in table (1) below

Table (1): Second phase volume fraction for studied (n) values

Layer number	n=0.3	n=0.5	n=1	n=1.5	n=2
Layer 1	0	0	0	0	0
Layer 2	65.9	50	25	12.5	6.25
Layer 3	81.22	70.71	50	35.35	25
Layer 4	91.7	86.6	75	64.95	56.25
Layer 5	100	100	100	100	100

FGM raw materials' properties are highly dependent upon its temperatures. The following table (2) shows the ceramic and metal properties developments with increasing temperatures.

Table (2): Development of materials' properties with temperatures

Low carbon steel properties [9,10]			
(°C)	modulus of elasticity (GPa)	Poisson ratio	Th. Expansion co. (10^{-6}) m / °C
25	201	0.285	11.7
100	198	0.303	12.2
200	190	0.326	12.8
300	185	0.356	13.4
400	170	0.38	13.9
500	149	0.395	14.3
600	120	0.399	14.8
700	77.62	0.387	15.07
800	36.49	0.38	15.57
900	26.6	0.407	15.63
Al_2O_3 [4]			
(°C)	Modulus of elasticity (GPa)	Poisson ratio	Th. Expansion co. (10^{-6}) m / °C
25	385.4	0.26	5.6
100	383	0.258	5.9
200	380	0.256	6.4
300	376	0.254	6.85
400	373	0.252	7.15
500	369	0.25	5.42
600	364	0.247	7.65
700	359	0.244	7.8
800	352	0.24	7.95
900	342	0.235	8.05

For estimation effective properties of each stepwise FGM layer individually, the following relations depend on:

1. Effective elastic modulus [11]

$$k_e = \frac{k_p\,(3k_m+4f_p\mu_m)+4\mu_m k_m(1-f_p)}{3(1-f_p)k_p+3f_p k_m+4\mu_m} \qquad \ldots(2)$$

Where: (f_p) is the volume fraction of particle phase
(k_p, k_m) are the bulk elastic modulus of the particles and the matrix respectively
(μ_m) is the shear modulus of matrix, which calculated by relation[12]:

$$\mu_m = \frac{k_m}{2(1+v_m)} \qquad \ldots(3)$$

2. Effective coefficient of thermal expansion [11]

$$\frac{\alpha_p K_p - \alpha_m K_m}{K_p - K_m} = \frac{\alpha_e K_e - \sum_{k=p,m} f_k \alpha_k K_k}{K_e - \sum_{k=p,m} f_k K_k} \qquad \ldots(4)$$

Where: (α_m,α_p) are thermal expansion coefficient of matrix and reinforced phases,

(k_m, k_p): are bulk modulus of elasticity of the matrix and reinforced phases,
(f) : is the volume fraction
(α_e) : is the effected thermal expansion coefficient of composite.
3. Poisson ratio [12]

$$v_z = f_p v_1 + (1 - f_p) v_2 \quad \ldots(5)$$

Finite elements analyzing:

For analyzing developmental stresses during the fabrication process, under service conditions, addition to thermal analyzing, the following steps had been done

1. Stepwise FGM has represented by axisymmetric model, (15) mm height and (112.5) width, as shown in figure (3), and it is supposed that all edges of the model are free to allow all possible deformation forms.

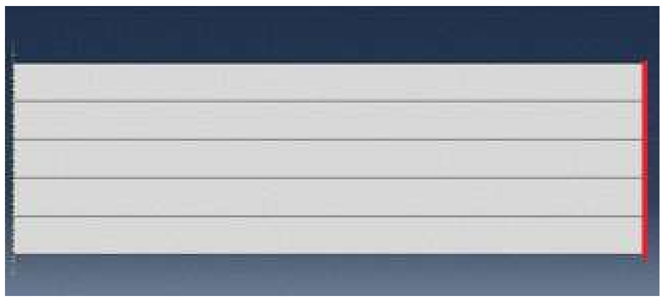

Figure (3) Axisymmetric model

2. General analysis-static-nonlinear analysis type, has used for analyzing residual stresses through fabrication process, while "coupled temp-displacement-steady, state-nonlinear analysis type, has used for analyzing residual stresses under service conditions, and "heat transfer-transient" was used to monitor the heat flux and temperature distribution along the FGM thickness.
3. For service conditions' stresses analyzing, It's considered that the upper layer of the model is at (622) C° while the bottom layer is at (80) C°, also it's supposed that the upper layer expose to uniform distribution pressure equals (2000) KN/m^2[13].
4. For thermal analyzing to the model, it's proposed that top surface layer subjected to ($5*10^6$) W/m^2 heat flux [3].
5. Meshing process is done in graded way, where elements size decrease toward free edge and interfaces between layers to get more accurate results as shown in figure (4).In case of fabrication residual stress analyses, (CAX4T) elements had been used, while (CAX4RT) types for analyses stresses under service conditions effects, and (DCAX4) elements type for temperature distribution monitoring. The total number of elements was (5589)

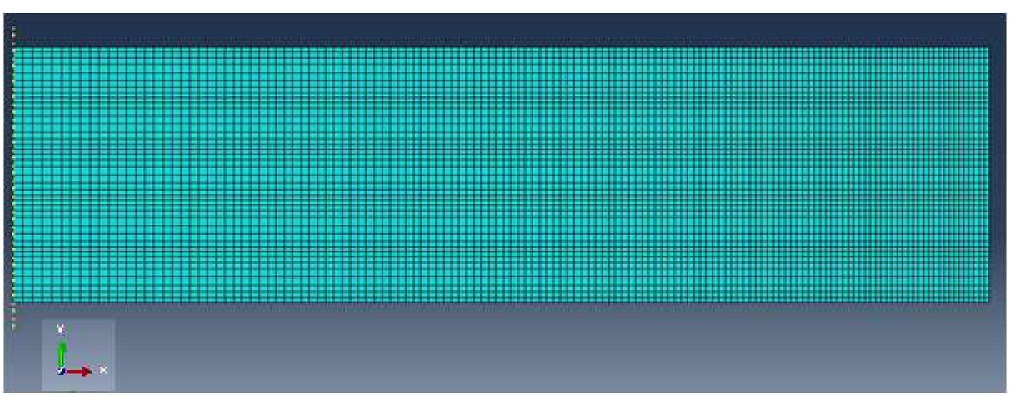

Figure (4): gradual meshing axisymmetric model

Results Analysis:

1. Fabrication residual stresses

The expecting fabrication stresses during the sintering process for all (n) values at free edge of model can be seen in following figure (5)

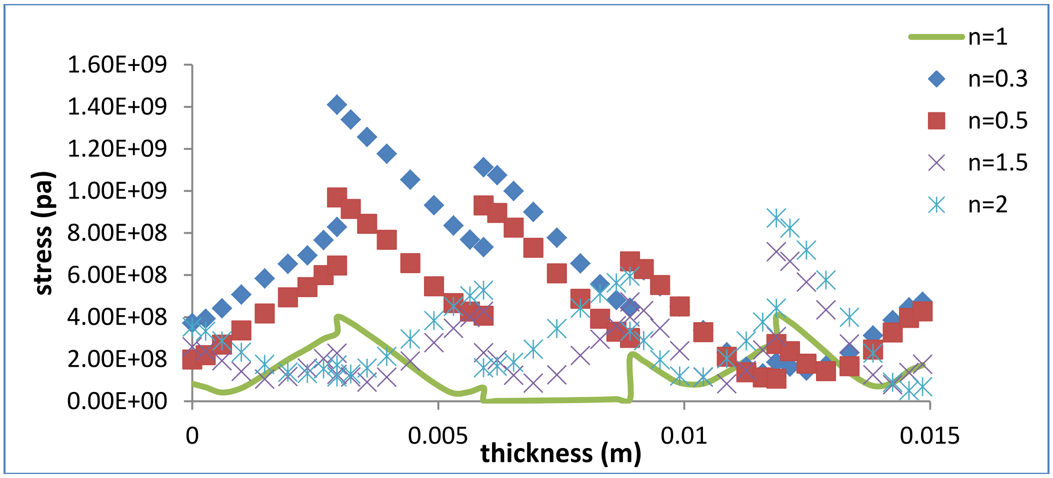

Figure (5):Nucleated stresses at free edge through fabrication process

For all (n) values, stresses curves have zigzag paths where tips of these curves are located at interfaces between adjacent layers regions, as difference of materials properties of neighbors' layers. However, the results show that (n = 1) curve has minimum expected fabrication stresses. The expecting stresses under service conditions also show that the (n=1) is the best choosing as shown in figures (6)and

(7)

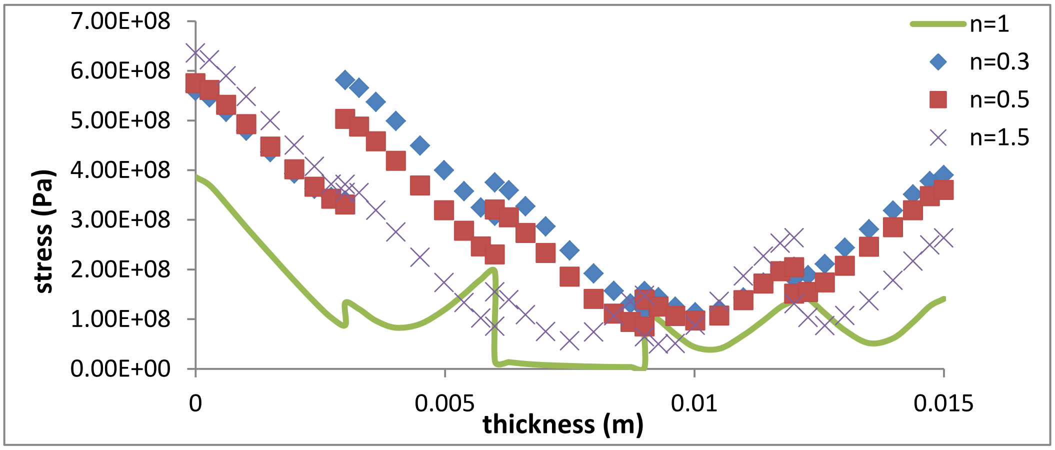

Figure (6):Nucleated stresses at free edge through service work

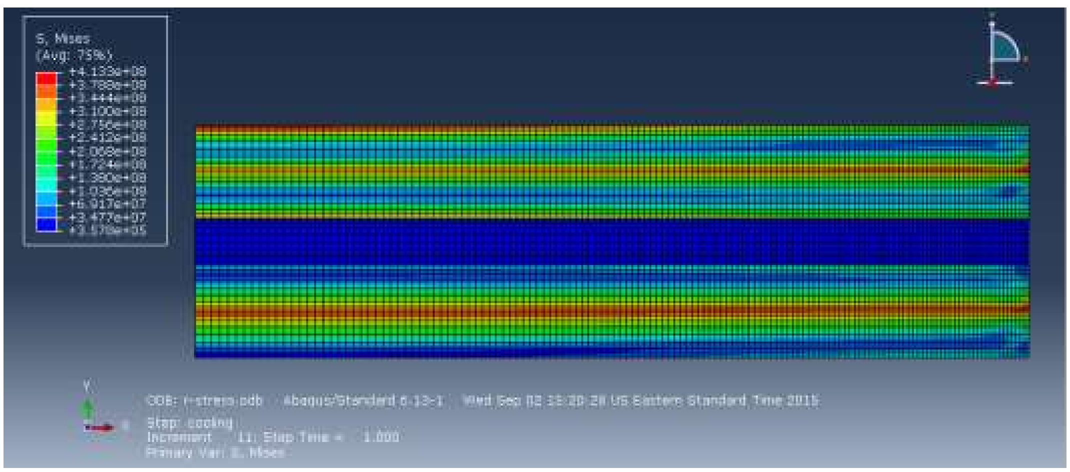

Figure (7):Nucleated stresses at free edge in case (n=1) under service conditions

Temperature distributions across stepwise FGM thickness comparing with same dimensions steel part is shown in figure (8).

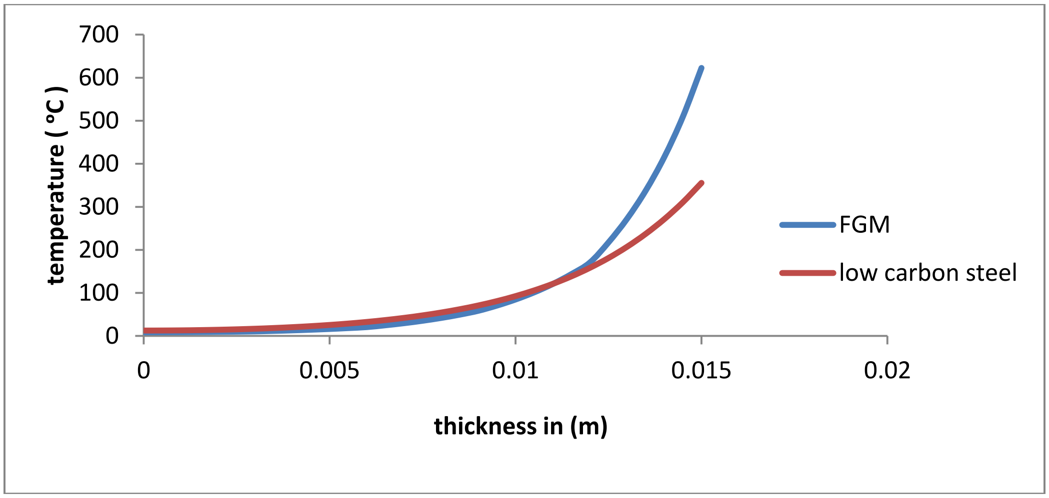

Figure (8):Temperatures distribution across the FGM thickness

The chart shows that the surface temperature of stepwise functionally graded materials, (622) ºC, is much higher than that of low carbon steel, (355) ºC, when receive the same amount of heat flux, as low thermal conductivity of ceramic phase. This improves heat efficiency of the combustion process and provides more useful energy instead to dissipate heat by cooling systems.

Specimen preparation and inspection tests:

Sticking layers by powder metallurgy technique have used to fabricate stepwise FGM. Raw powder materials had dry mixed for (3) hours for each layer individual, then packing into (15) mm steel mold without addition, any bonding additive, specimen have compact under (270) MPa Pressure, while the sintering process had down at (1400) ºC for (3) hours directly without drying process [6] in a tube furnace under low inert gas flow (0.5) bar (argon). Finally cooling process had done by turn off the furnace.

Inspections tests includes:

1. Scanning electrons microscope SEM

SEM instrument type "inspect S50", had used to monitoring microstructure gradient along thickness as shown in figure (9) below

The images show free cracks structure with continues transition in structure from full ceramic layer at the top specimen, image (A), to full metallic structure at bottom, image (D), without evidence to exist cracks or interface surface between adjacent layers.

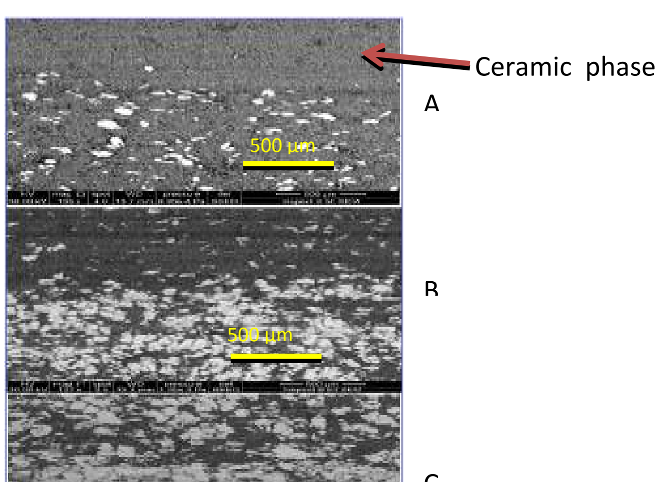

Figure (9) SEM image of stepwise FGM

2. Physical properties inspections had performed according ASTM C-3738-88 [14]. The tests results is shown in Table (3)

Table (3): physical properties of stepwise

Bulk density	2.86
apparent porosity %	26.66 %
Total porosity	53.36 %
Theoretical density	5.893
Relative density %	48.53 %

The results show that the fabrication stepwise FGM by powder technology method can offer only limited relative density, bulk density to theoretical density ratio, as high porosity percentage inside the sintered body. However experimental show that increase of sintering temperatures or sintering time can cause flow metallic phase or sticking with furnace wall as results of viscous behavior at elevated temperatures instead of improve sintered density.

Mechanical tests results:

The compression and macro hardness tests had been performed to the stepwise FGM specimen. Compaction test was done by using (50)Tan capacity computerized press machine. Where pressure was applied in normal direction against the upper surface according to according to ASTM-E9. The result of the test is shown in figure (10).

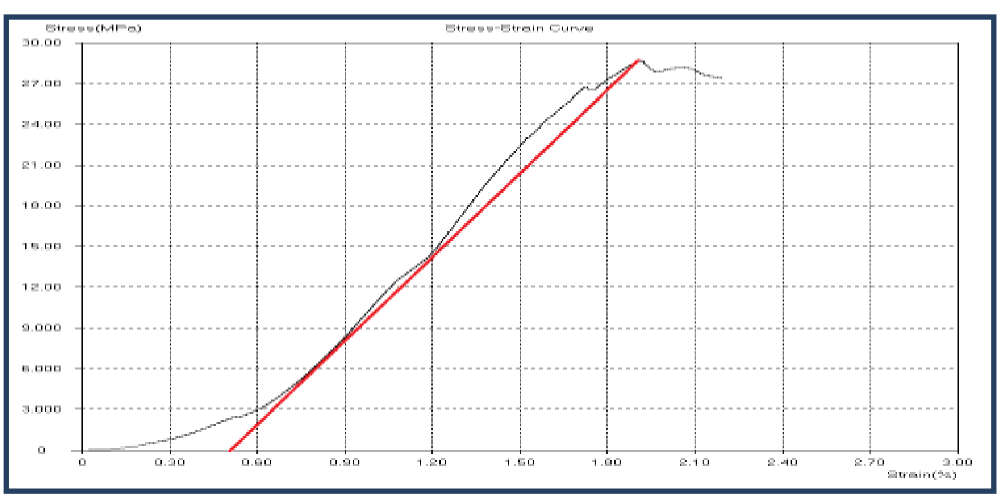

Figure (10): Stress-strain curve of compression test

The stress-strain curve shows approximately a brittle behavior, where the strain directly proportion with applied stress till the specific point (28. 71) MPa Behind this value, specimen has fractured as shown in figure (11).

Figure (11) Crashed stepwise FGM specimen

However, this magnitude is much lower than the pressure, which subjected through service operation by combustion gases (1.629) MPa. Also the figure (11) shows that the failure occurs by fragmentation top, ceramic layer, and cracks propagation in normal direction from top brittle ceramic layer to lower layers, which have a more metallic content percentage. Finally the non-proportional part of the stress - strain curve, is usually occurring as a result of the sliding between specimen and jaws of machine which usually occur at starting of the test.

Macro hardness test across stepwise FGM thickness is shown in figure (12)

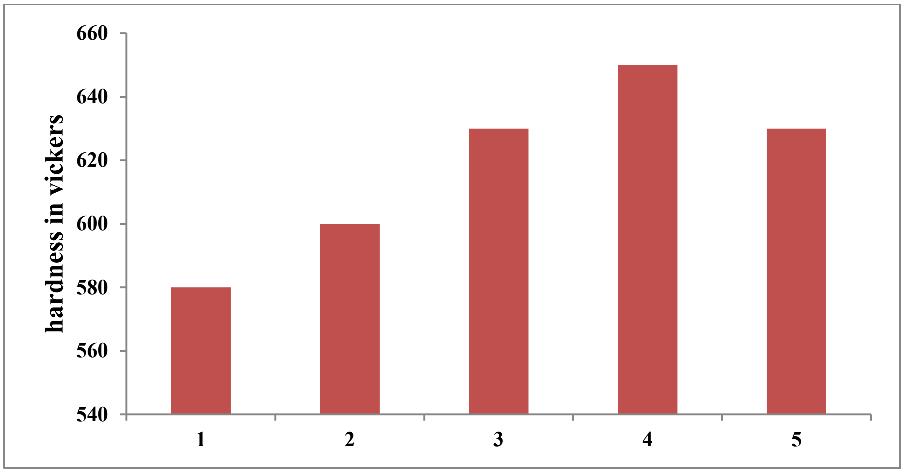

Figure (12): Macro-hardness stepwise FGM

Hardness results show increasing hardness with increasing ceramic phase content. Hardness value for each layer is related to porosity content in this layer and hardness of constituent materials. This can explain hardness with increasing hard ceramic phase content except to the hardness of layer five which has the highest porosity content as the absent of viscous metallic phase in this layer

CONCLUSIONS:

1. Linear compositional transition through FGM thickness has minimum developed residual stresses under both fabrication and service work conditions of combustion chamber conditions.
2. Using stepwise FGM instead steel can doubling crown top surface under same duty, that mean decreasing rejected heated by cooling system.
3. Physical properties tests show limited relative density that can achieved by powder technic.
4.SEM images show overlapping layers without cracks.
5. Hardness tests that performed across the thickness at each stepwise FGM layers show that hardness increases with increasing ceramic content, and decreases with increasing porosity percentage
6. Compression test shows that stepwise FGM can withstand applied combustion gases pressure.

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