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THE THERMO-MECHANICAL FINITE ELEMENT ANALYSIS OF FUNCTIONALLY GRADED MATERIAL

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ABSTACT: Functionally Graded Materials (FGMs) are materials that can be characterized by the variation in composition and structure gradually over volume along at least one specific direction. These variations can occur as a result of the chosen manufacturing process and they cause corresponding changes in the properties of the material. Functionally graded materials can be designed for specific function and applications. Nowadays, the possibilities of using FGM seem to be almost limitless. According to the literature these materials can be used in engineering, optical, power, and even in nuclear physics and medicine applications. The problem of thermal residual stresses creation in sintered FGM material during cooling from sintering temperature was presented in this paper. The influence of transition zone layers number on the distribution of residual stress was analysed. The thermo-mechanical analysis was performed using the finite element method (FEM). During performed analyses the maximum principle stress distributions were investigated in order to estimate the risk of material failure.

Keywords: Functionally Graded Materials, Finite Element Method, residual stress

1 INTRODUCTION

Functionally Graded Materials (FGMs) are an advanced, a novel and an artificial class of a new generation of engineered materials. These materials have been known for centuries, although their current name appeared recently. FGMs are materials that can be characterized by the variation in composition and structure gradually over volume along at least one specific direction. These variations can occur as a result of the chosen manufacturing process and they cause corresponding changes in the properties of the material [1÷3]. Functionally graded materials can be designed for specific function and applications. Gradual, controlled transition between the properties of constituent materials enables an adaptation of the product for the foreseeable conditions of its operation (Figure 1). Functionally graded materials have very useful physical properties, for example the resistance to thermal corrosion in combination with high mechanical strength (in comparison with composites FGMs have lower thermal and residual stress) [1, 3÷5]. In recent decades, intensive studies of FGM various applications have been conducted. Nowadays, due to their versatility of behaviour, the possibilities of using these materials seem to be almost limitless. According to the literature the main application range of the FGMs include: engineering, thermoelectric, optical, power, and even nuclear physics and medicine applications [1÷5]. The functionally graded materials in dependence of used gradient nature may be divided into following types [3]:

- fraction gradient type,
- shape gradient type,
- orientation gradient type,
- size (of material) gradient.

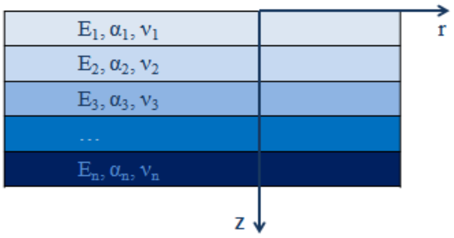

Figure 1: Segmented functionally graded material with n layers - polar coordinates

The differences in thermo-mechanical properties between metals and ceramics cause the occurrence of residual stresses in regions of ceramic-metal interfaces. The residual stresses arise during fabrication as well as under thermal and mechanical loading of material. These stresses affect performance and the lifetime of the ceramic-metal bonded systems. The residual stresses can cause a number of adverse effects such as: cracking within ceramic, plastic deformation accompanied by formation and growth of the voids in metal and ceramic/metal decohesion. In recent years, many researchers presented numerous experimental and theoretical investigations of residual stresses [7]. A lot of the literature data indicates the relationship between the magnitude and the distribution of residual stresses, the failure mechanisms, materials thermo-mechanical properties and specimen/structure geometry [7÷13].

The ceramic/metal residual stresses can be reduced in magnitude and redistributed in a desired manner by introducing an intermediate layer. This layer has some specific character of microstructure and properties, i.e. they varied in a more gradual fashion from those of one material to the ones of the other [7].

2 METHODOLOGY

The problem of thermal residual stresses formation in sintered FGM cylindrical samples during cooling from sintering temperature of 1000°C was presented in this paper. The finite element method FEM) was used to investigate that problem for 316 stainless steel/Al_2O_3 graded material model. The influence of transition zone layers number on the value of residual stress in cylindrical samples with diameter of 24 mm and height of 20 mm was analysed. During performed analyses the maximal principle stress distributions were investigated.

A continuous variation of the materials volume fractions throughout the graded region is practically unattainable via powder metallurgy processing. Therefore, the graded region of material had been modelled in the form of a finite number of layers, each with fixed volume fractions of the two materials. Different grading profiles that were used in investigations were obtained by varying the number of layers. In this work, the following material systems were modelled:

- no intermediate layers,
- one intermediate layer (fraction: 50%) with a thickness of 8 mm,
- three intermediate layers (fractions: 75%, 50%, 25%) with a thickness of 3 mm,
- four intermediate layers (fractions: 80%, 60%, 40%, 20%) with a thickness of 2 mm,
- nine intermediate layers (fractions: 90%, 80%, 70%... 10%) with a thickness of 1mm,
- nineteen intermediate layers (fractions: 95%, 90%, 85%... 5%) with a thickness of 0.5 mm.

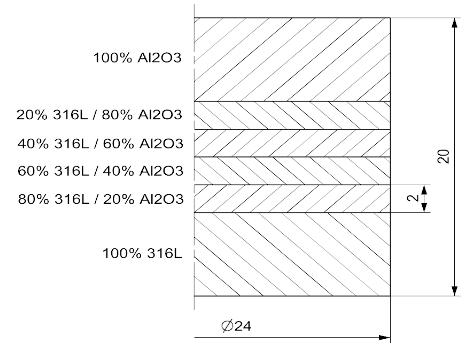

Figure 2: Exemplary modelled material system (4 intermediate layers with a thickness of 2 mm)

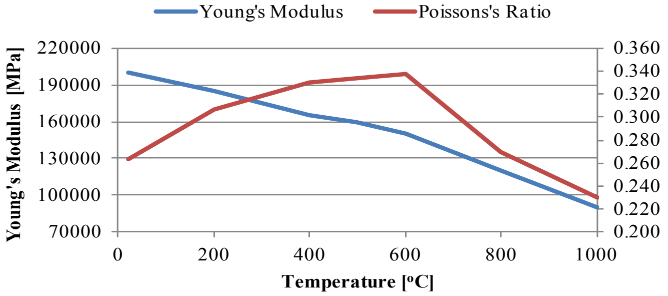

Figure 3: Young's modulus and Poisson's ratio data as a function of temperature for 316L [7]

Figure 2 shows an exemplary modelled material system used during investigations.

Figures 3 and 4 present Young's modulus and Poisson's ratio data as a function of temperature respectively for 316L and Al_2O_3. The thermal expansion coefficients vs. temperature for both materials are presented in Figure 5.

Widely used in the modelling of FGMs a "mixture rule" was applied in order to create the gradient of the investigated materials. A material having two components, denoted as A and B, is considered. The well-known Voigt-type estimate for the effective value, P, of the property of FGM was used [14]:

$$P = f \cdot P_A + f \cdot P_B \qquad (1)$$

where: the P is the effective value, P_A and P_B are the values of some particular property, f_A and f_B are the values of volume fractions (where $f_B = 1 - f_A$ assuming that the material is 100% dense) for pure A and pure B, respectively.

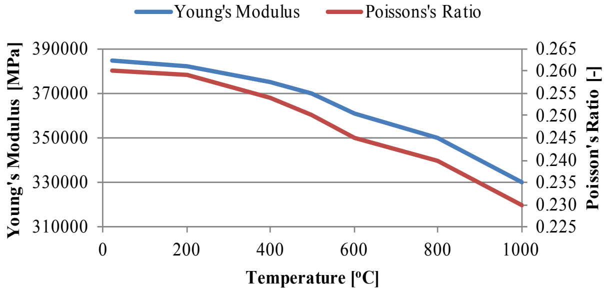

Figure 4: Young's modulus and Poisson's ratio data as a function of temperature for Al_2O_3 [7]

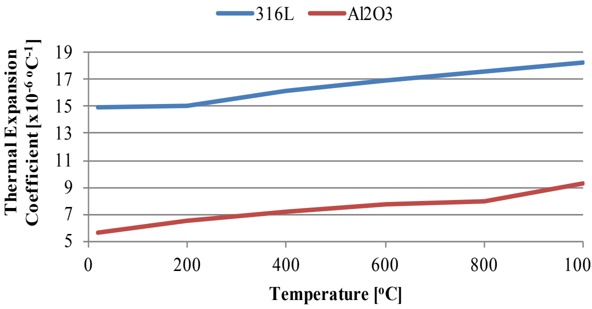

Figure 5: The thermal expansion coefficients as a function of temperature for 316L and Al_2O_3 [7]

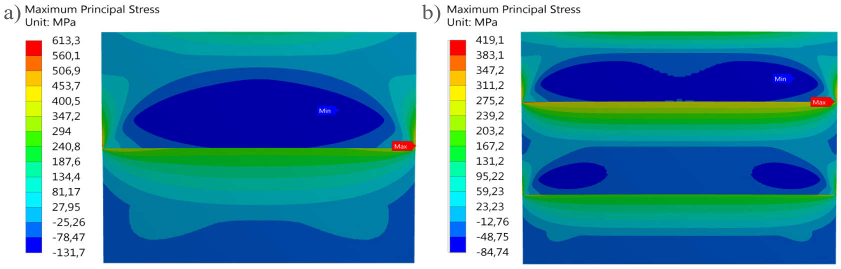

Figure 6: Maximum principal stress distribtions: a) no intermediate layers, b) 1 intermediate layer

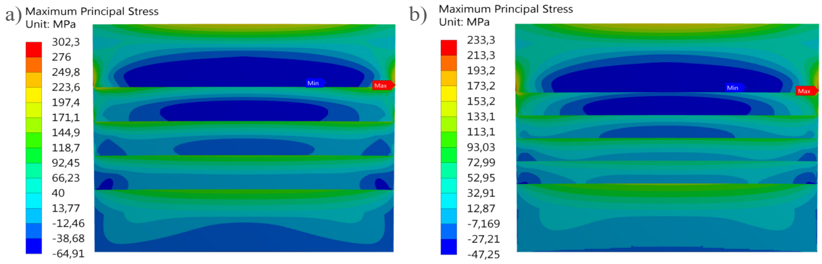

Figure 7: Maximum principal stress distribtions: a) 3 intermediate layers, b) 4 intermediate layers

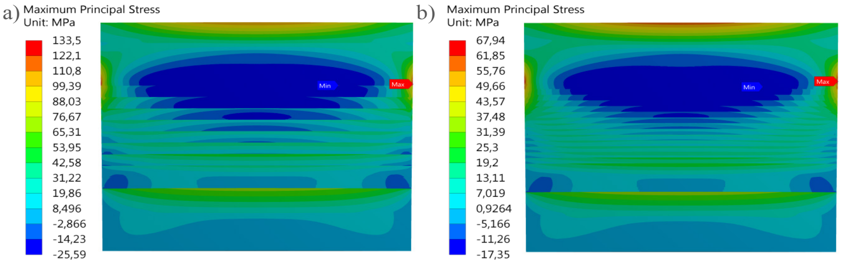

Figure 8: Maximum principal stress distribtions: a) 9 intermediate layers, b) 19 intermediate layers

Since the tensile strength of Al_2O_3 can be about ten times lower than its compressive strength, the maximum principal stress failure criterion was used in the investigations. A critical stress for 316L was 300 MPa (yield stress) and 250 MPa (ultimate tensile strength) for Al_2O_3. Due to lack of data concerning the failure of 316L-Al_2O_3 composites, a "mixture rule" was again used in order to investigate the damage of intermediate layers of FGMs.

3 RESULTS

Figures 6, 7 and 8 show the cross sections of the modelled FGM systems with distribution of maximum principal stresses calculated by FEA. The stresses are ranged from 67.9 MPa (FGM with 19 layers) to 613.3 MPa (sample without graded region).

In all cases, maximum stresses are located in the external surface area of 100% Al_2O_3 near the layer interface. Furthermore, in all graded layers the tensile stresses arise on that side which is bonded to another layer with higher content of Al_2O_3. On the opposite side the layers are being compressed. This is due to the fact that the greater content of the Al_2O_3, the smaller value of thermal expansion coefficient of the layer is.

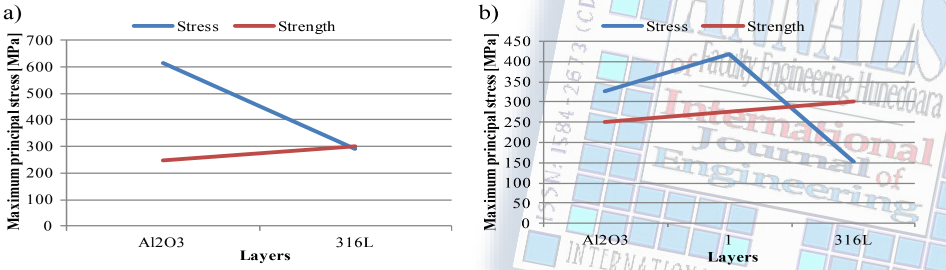

Figure 9: Maximum principal stress in each layer: a) no intermediate layers, b) 1 intermediate layer

Figures 9, 10 and 11 presents the maximum principal stresses in each layer. In three cases, FGM with no layer, 1 layer and 3 layers, the stresses exceed the material strength, which indicates the risk of cracking. The curve in the Figure 12 indicates that the greater the number of intermediate layers, the lower the stresses are.

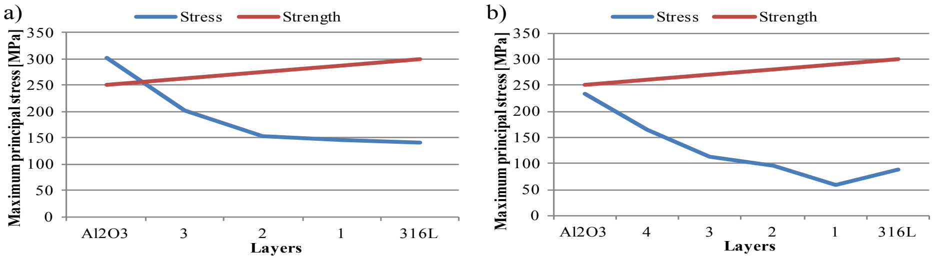

Figure 10: Maximum principal stress in each layer: a) 3 intermediate layers, b) 4 intermediate layers

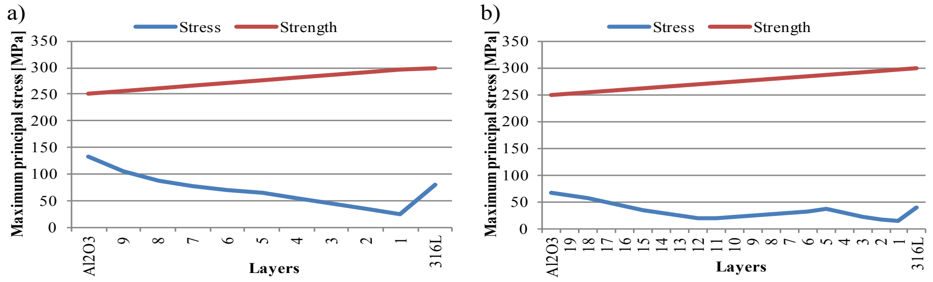

Figure 11: Maximum principal stress in each layer: a) 9 intermediate layers, b) 19 intermediate layers

4 CONCLUSIONS

The Finite Element Analysis was used to estimate and compare the three-dimensional residual stresses in various FGM samples. On the basis of the performed analyses for the investigated model of 316L/Al_2O_3 FGM material it can be concluded that:

- The number of the intermediate layers in sintered FGMs has a significant impact on the magnitude and distribution of residual stresses. An appropriate choice of the intermediate layers number can significantly reduce the risk of material damage.
- The FEM analyses are especially useful for graded materials where the residual stresses cannot be or are difficult to measure experimentally.

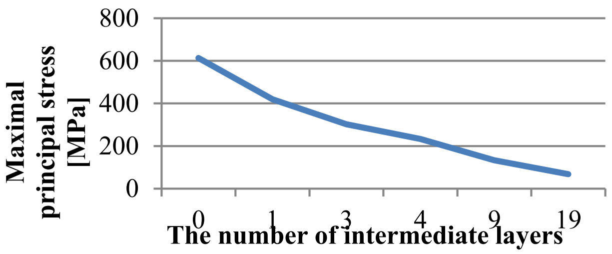

Figure 12: Maximum principal stress as a function of the nuber of intermediate layers

NOTE: This paper is based on the paper presented at the 9th International Conference for Young Researchers and Phd Students - ERIN 2015, May 4-6, 2015, Monínec, Czech Republic, referred here as[7].

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