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Journal of the European Ceramic Society 27 (2007) 1281–1286
www.elsevier.com/locate/jeurceramsoc

Interlayer of Al_2O_3–Cr functionally graded material for reduction of thermal stresses in alumina–heat resisting steel joints

Katarzyna Pietrzak *, Dariusz Kaliński, Marcin Chmielewski

Institute of Electronic Materials Technology, 133 Wolczynska Str., 01-919 Warsaw, Poland

Available online 12 June 2006

Abstract

The present paper analyses the influence of an interlayer's construction and thickness on thermal residual stresses generated in ceramic–metal joints.

Numerical calculations (the finite elements method—FEM) of the state of thermal residual stresses, as well as the verifying technological tests, were made for the following pair of materials: the Al_2O_3 ceramics–heat resisting steel. The model reference system was the direct joint of these materials. The results presented in this paper concern the influence of the type of a gradient material (various thickness, various construction profile—understood as the number of layers, various Al_2O_3–Cr composition and mutual position) on the state of residual stress in the joint. The numerical calculations carried out on the state of residual stresses showed that for the assumed composition and thickness of the gradient material it is possible to further lower the level of stresses in the ceramic element of the analyzed joint by modifying the profile of a gradient material's inner structure.

It was found that the dangerous stresses concentration area was shifted from the bonding line ceramic/FGM layer (of relatively low strength) further into the FGM's layer, i.e. to the dividing line layer I ($75Al_2O_3/25Cr$)/layer II ($50Al_2O_3/50Cr$), of much higher strength.

Keywords: Al_2O_3–Cr composites; Joining; Sintering; Mechanical properties; Functionally graded materials

1. Introduction

In many branches of modern industry, be it power, aviation, space, electronic, automotive or chemical, it is necessary to create joints combining advanced ceramics and metal alloys, of very complex shapes and consisting of many elements. Extremely diverse properties (α, Re, E, ν, λ) of these materials result in great thermal residual stresses in joints.[1–4] The most frequent method to reduce thermal residual stress is choosing the proper shape of linked elements or using compensation interlayers, either hard (Mo, Nb, Kovar) or soft-plastic ones (Cu).[2,4–8] The problem might be solved by applying a ceramic–metal gradient type material as an interlayer.

Gradient materials (FGMs) are characterized by functional change in atleast one of their properties. It can be, for instance, a change in chemical composition, structure, grain size, texturization level, density. In the case under study the most important is a change in physical, (i.e. thermal expansion coefficient α) and mechanical properties, by which the stress level in the joint is lowered. The production technology of FGMs influences both the structure of individual layers it consists of (except for the chemical composition of these layers) and, what is also important, the profile character of the FGMs structure (Fig. 1). It stems from the above that, besides the microstructure of individual layers, FGM properties depend on their quantity, thickness and also are a function of the structure profile. The profile of a gradient material inner structure can be described by the following relationship:[10,11]

$$f_X = \left(\frac{y_i}{t}\right)^p \quad (1)$$

where f_X is the variation in the volume friction of X material, y_i the distance of the ith layer from the gradient material surface, t the total height of the gradient material, and p is the material concentration exponent.

A close analysis of relationship (1) for various layers of a gradient material, their different thickness and thickness interrelationship between different layers (the FGMs profile), allows to optimize the structure of a gradient material so as to lower the level of residual stress in ceramic–metal joints.

* Corresponding author.
E-mail address: Pietrz_k@sp.itme.edu.pl (K. Pietrzak).

0955-2219/$ – see front matter
doi:10.1016/j.jeurceramsoc.2006.04.102

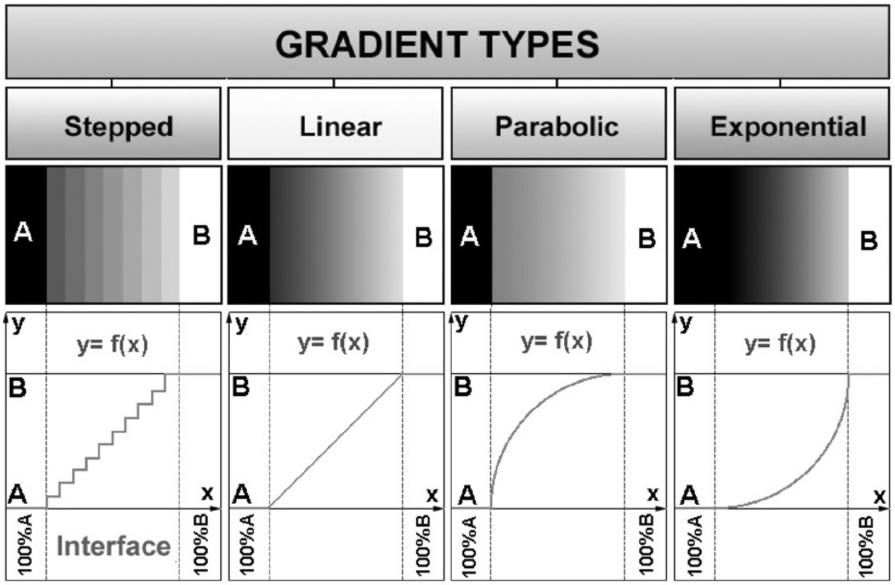

Fig. 1. Graphic representation of basic gradient types.[9]

For a material to meet the required properties it has to have the proper structure including such elements as: shape, size, proportion of reinforced elements to overall size and their mutual position, which determine most of the physical and mechanical properties.

Due to the fact that the studies and technological investigations carried out by the authors were focused on producing joints consisting of the Al_2O_3 ceramics–heat resisting steel, capable of working, i.e. under cyclically changeable thermal stress, the results and solutions presented in the paper concern the gradient material obtained from Al_2O_3–Cr composites of various proportions.

In order to design and obtain the required Al_2O_3 ceramics–heat resisting steel joint, various theoretical models were developed, for which thermal residual stresses were calculated (by the finite elements method—FEM).

2. Experimental procedure

The models of Al_2O_3–heat resisting steel joints used to calculate thermal residual stresses were shown in Fig. 2. They can be best characterized as:

- direct alumina ceramics–heat resisting steel joint—model I (Fig. 2(a)),
- alumina ceramics–heat resisting steel joint, with a gradient interlayer consisting of three composite Al_2O_3–Cr layers: $75Al_2O_3/25Cr$, $50Al_2O_3/50Cr$, $25Al_2O_3/75Cr$ (in vol.%), each of which was of equal thickness. The total gradient layer (g_{FGM}) was 0.3, 0.6, 1.5, 3.0, 4.5 mm thick, respectively)—model II (Fig. 2(b)),
- alumina bonded with heat resisting steel through a gradient interlayer consisting of seven Al_2O_3–Cr composite layers of

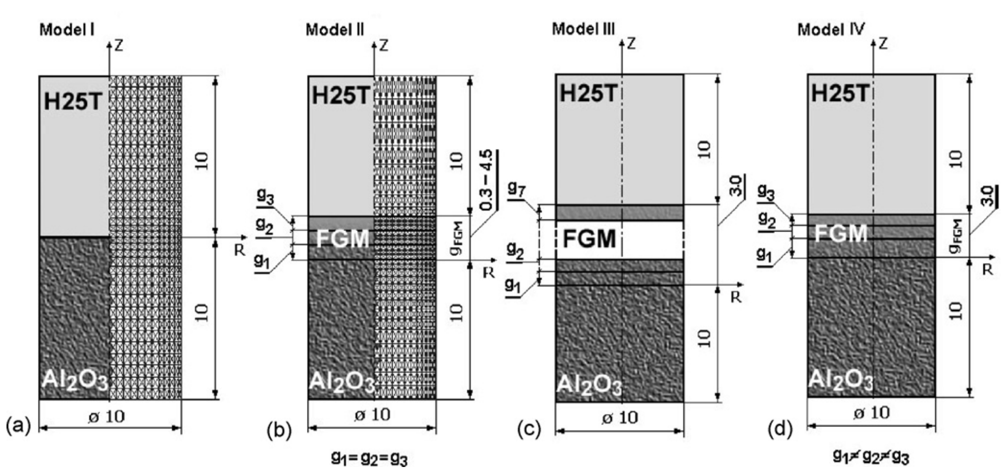

Fig. 2. The joint models of Al_2O_3–heat resisting steel and meshes of finite elements use in the residual stress calculation by FEM: (a) direct joint—model I; (b) joint with the three-layered (g_{LAYER} = constant) FGM (Al_2O_3–Cr)—model II; (c) joint with the seven-layered FGM (Al_2O_3–Cr)—model III; (d) joint with the three-layered ($g_{LAYER} \neq$ constant) FGM (Al_2O_3–Cr)—model IV.

Table 1
The properties of materials (at room temperature) used for numerical calculation of residual stresses[11–13]

Materials	E (GPa)	Re (MPa)	α ($\times 10^{-6}$/°C)	ν
Al_2O_3	318	–	5.6	0.22
H25T Steel	206	400	9.0	0.30
Cr	321	300	7.2	0.22

different ceramic composition: 87.5Al_2O_3/12.5Cr, 75Al_2O_3/25Cr, 62.5Al_2O_3/37.5Cr, 50Al_2O_3/50Cr, 37.5Al_2O_3/62.5Cr, 25Al_2O_3/75Cr, 12.5Al_2O_3/87.5Cr (in vol.%), each of which was equally thick. The thickness of the total gradient layer was g_{FGM} = 3.0 mm—model III (Fig. 2(c)), and

- alumina bonded with heat resisting steel through a gradient interlayer consisting of three Al_2O_3–Cr composite layers of different ceramic composition as model I but with each layer of different thickness. The thickness of the whole gradient layer g_{FGM} = 3.0 mm—model IV (Fig. 2(d)).

The level and distribution of the residual stresses in the adopted joints model were analysed using the numerical program the TSP,[1] which realised the finite element method.

Due to axial symmetry, our calculations concerned half the model accepted. The meshes were made denser in the region where, in the ceramics element, the stresses were expected to concentrate, i.e. on the outer cylindrical layer and near the ceramics/metal joining line.

The material properties accepted for residual stress analysis (Young's modulus E, thermal expansion coefficient α, yield point Re, Poisson ratio ν—Table 1) varied with temperature, except for the Poisson ratio, which was accepted as constant, independent on the temperature. The properties of Al_2O_3–Cr composites, constituting FGM layers, were estimated in compliance with the role of mixture—Voigt's. The loading conditions assumed for the models resulted from the designed joining process (diffusion bonding). The temperature load assumed for calculations was in the 900–20 °C range. The criterion for obtaining a crack-free joint, assumed in calculations, was that the analyzed level of residual stress could not exceed the bending strength for alumina ceramics, i.e. 250 MPa, approximately. In all cases considered in model IV, g = 3.0 mm were the total thickness of a gradient material assumed for calculations. As a result of our calculations, the thickness of individual layers of the gradient material was defined depending on coefficient p (Table 2).

The assumptions (properties of materials, heat load) made to calculate the state (distribution and level) of residual stresses in Al_2O_3–FGMs–heat resistant steel joints were the same as those described in detail in.[14]

3. Numerical calculations

Taking into account numerical calculations of residual stresses in the directly jointed model of an Al_2O_3–heat resisting steel (H25T type—chemical composition: 0.15% C, 0.8% Mn, 24–27% Cr, 1% Si, 0.6% Ni, 0.8% Ti, rest of Fe) joint, tensile stress concentration σ_{MAX} was found in the ceramics, up to the value of about 550 MPa (Fig. 3). It may lead to cracks in the ceramic element.

Among stress components one can distinguish axial stress σ_Z, whose distribution and level in the ceramics is quite close to σ_{MAX}.

The distribution of σ_Z on the diameter of a ceramic element indicates that the stress is tensile on its outer layer and compressive stress inside. This occurred when the bending moment affecting the ceramic element was greater than radial contraction in the ceramics and circumferential contraction of the steel element while the joint was cooled.

[1] The 'TSP' numerical program developed at the Joining Engineering Department, Warsaw University of Technology.

Table 2
Thickness of FGM layers (mm) constituting the gradient material for different exponent p values

Layer composition (vol.%)	Material concentration exponent p						
	0.25	0.50	0.75	1.00	1.50	2.00	4.00
75Al_2O_3–25Cr	0.04	0.33	0.69	1.00	1.44	1.73	2.28
50Al_2O_3–50Cr	0.56	1.00	1.05	1.00	0.84	0.68	0.43
25Al_2O_3–75Cr	2.44	1.67	1.36	1.00	0.71	0.55	0.29

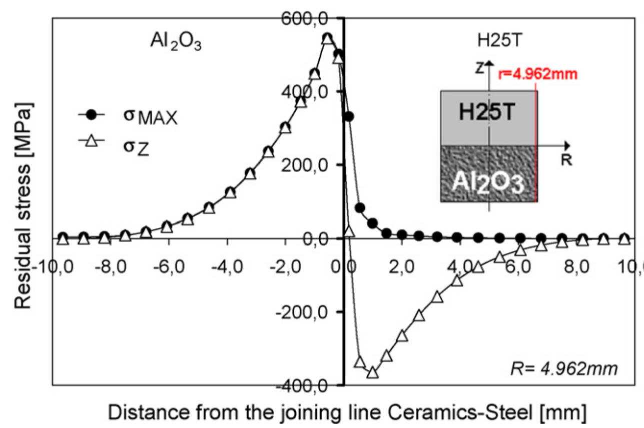

Fig. 3. Axial distributions of residual stress σ_{MAX} and σ_Z in selected cross-sections of a directly jointed model of the Al_2O_3–steel joint.

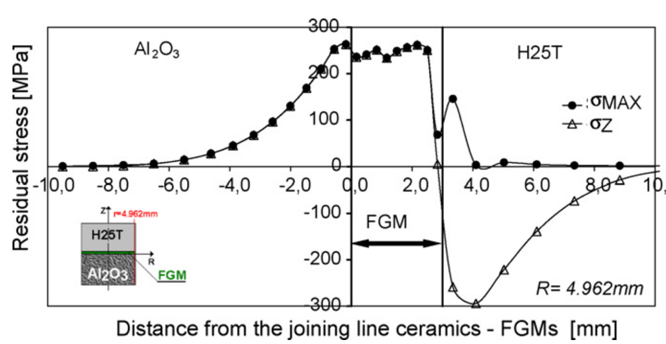

Fig. 4. Axial residual stress distributions σ_{MAX} and σ_Z in selected cross-sections of the Al_2O_3–FGM–steel joint.

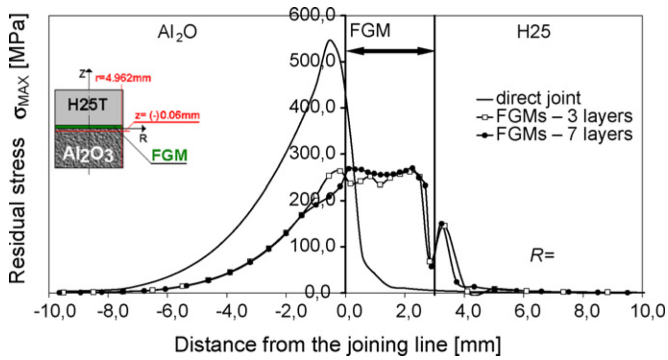

Fig. 5. Influence of the number of the gradient material (Al_2O_3–Cr) layers on the level and distribution of stresses σ_{MAX} in Al_2O_3 ceramics–FGM–steel joint models.

The remaining stress components: σ_R, σ_{RZ}, σ_T and minimum principal stress σ_{MIN} do not have any significant influence on the ceramic element effort, and by the same token, on the entire joint.

The σ_R stresses are negative in ceramics (compression) and their maximum absolute values are lower than the principal maximum stress values σ_{MAX} analyzed above. Also peripheral stresses σ_T and minimum principal stresses σ_{MIN} (constituting a pair with a similar distribution in the ceramic element) are negative in the ceramics. Their values are the lowest inside the ceramic element, close to the joining line with the metal. The values of tangential stress σ_{RZ} in the ceramics are also negative.

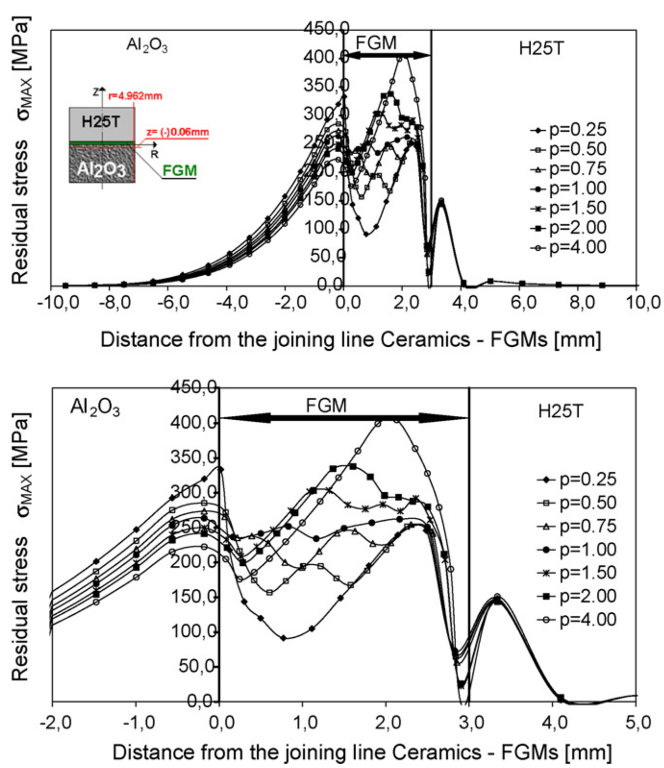

Fig. 6. Influence of the profile of the gradient material inner structure (material concentration exponent p) on the level of residual stresses in the Al_2O_3 ceramics–FGM–steel joint model (model IV—Fig. 2).

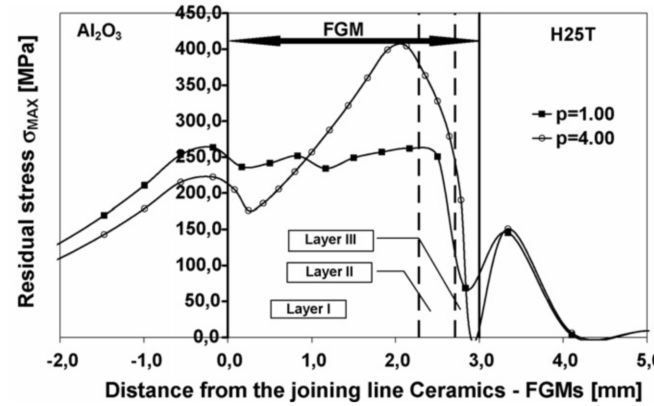

Fig. 7. Comparison of stress value and distribution stress σ_{MAX} in the Al_2O_3 ceramics–FGM–steel joint model for the material concentration exponent $p = 1.0$ and 4.0.

Fig. 4 presents axial distributions of residual stresses σ_{MAX} and σ_Z in selected cross-sections of the assumed bonding model (alumina–heat resistant steel with the gradient interlayer), consisting of three Al_2O_3–Cr composite layers, each of which was equally thick (model II, Fig. 2).

In this case of bonding, the calculated residual stresses σ_{MAX} in the area of their highest concentration, attained the level of about 260 MPa (Fig. 4) and were over 50% lower than in the direct joint (550 MPa). It should be observed that the residual stress distribution σ_{MAX} throughout the FGM layer was relatively even. The stresses maintain a constant level of about 248 MPa, on the average.

Extending the gradient material by further four layers did not result in a significant drop in the level of residual stresses in the joint under study. As compared to the joint with a gradient interlayer consisting of three Al_2O_3–Cr composite layers, the calculated residual stresses σ_{MAX} were only about 10% lower and equalled 236 MPa (Fig. 5). One may conclude that the application of a gradient material consisting of three layers is a satisfactory solution for the assumed bonding model. A further build-up of the gradient material by additional layers complicates its production technology considerably.

The calculations concerning the level of residual stresses showed that for the assumed composition and thickness of a gradient material it was possible to lower the level of stresses in the ceramic element of the Al_2O_3 ceramics–FGM–steel joint by modifying the profile of the gradient material inner structure

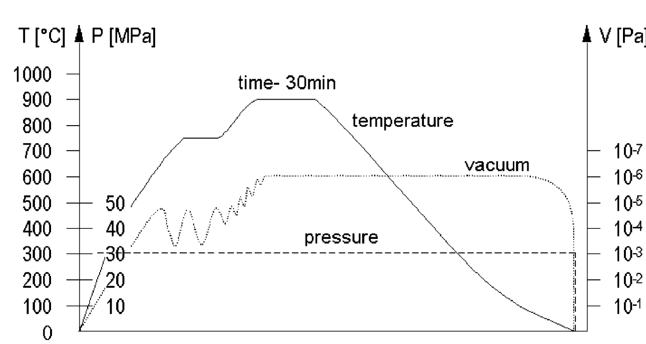

Fig. 8. The conditions of joining process for Al_2O_3–FGM–steel joints.

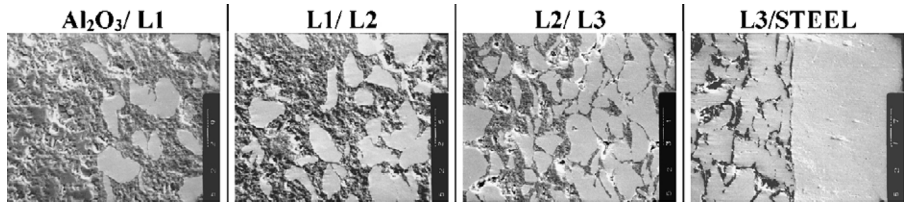

Fig. 9. Microstructure of Al_2O_3–FGM–steel joints: L1, $75Al_2O_3/25Cr$; L2, $50Al_2O_3/50Cr$; L3, $25Al_2O_3/75Cr$ (vol.%).

Table 3
Bending strength σ_b of pressure sintered Al_2O_3–Cr composites

Composite (vol.%.)	Strength σ_b (MPa)
Al_2O_3	~250
$25Al_2O_3+75Cr$	392.4 ± 20.3
$50Al_2O_3+50Cr$	349.9 ± 4.2
$75Al_2O_3+25Cr$	301.9 ± 3.7

(model IV—Fig. 2 and Table 1). It is the thickness of the gradient material close to the ceramic bonding element that has the biggest influence on the level of residual stresses in the ceramic element of the joint (Fig. 6).

As compared to the joint model where all layers are equally thick (material concentration exponent $p = 1.0$), making the layer ($75Al_2O_3/25Cr$) adjacent to the ceramic element of the joint thicker—from 1.0 mm to, for instance, about 1.73 mm (material concentration exponent $p = 2.0$) resulted in about a 10% drop in the stress level σ_{MAX}. For the material concentration exponent $p = 4.0$, a 16% drop in residual stresses σ_{MAX} was obtained (Fig. 7).

For material concentration exponent p greater than 1, there is a shift in the concentration area of dangerous stress from the bonding line ceramics/FGM layer of relatively low strength deeper inside the FGM layer, i.e. to the line dividing layer I ($75Al_2O_3/25Cr$) and layer II ($50Al_2O_3/50Cr$) of decidedly higher strength (Figs. 6 and 7). Bending strength tests σ_c of pressure-sintered Al_2O_3–Cr composites, constituting the gradient interlayer in the Al_2O_3 ceramics–FGM–steel joint (Table 3) proved that the strength of a composite increases as its chromium content goes up. Bending strength σ_c of the composites under study is, respectively, about 20% ($75Al_2O_3/25Cr$), 40% ($50Al_2O_3/50Cr$) and 56% ($25Al_2O_3/75Cr$) higher than the strength of pure Al_2O_3 ceramics.

The shift of maximal stresses deeper inside the FGM layer is very significant from the point of the entire joint strength.

4. Joining of alumina to heat resisting steel

In the tests (the diffusion bonding method) to joint Al_2O_3 ceramics and H25T steel, in compliance with the joint scheme from Fig. 2, the gradient interlayer 3.0 mm thick was used. Before joining with steel, the interlayer materials were sintered on ceramic substrate (temperature $T = 1400\,^{\circ}C$, time $t = 30$–60 min, pressure $p = 30$ MPa, in argon atmosphere).[15] The joining conditions of the studied Al_2O_3–steel joints were presented in Fig. 8.

Joining Al_2O_3 ceramics directly with steel did not yield positive results. Soon after the joining finished, the joints were damaged as their ceramic element cracked. The crack of a ceramic element occurred close to the dividing surface Al_2O_3–steel. It confirms a considerable concentration of tensile residual stresses in this particular welding area and their high level, far exceeding the bending strength of alumina ceramics.

The application of Al_2O_3–Cr gradient material as an interlayer in the joint (Fig. 9), even with the FGM layer 3.0 mm thick, allowed to obtain a alumina ceramics–steel joint of sufficient strength. Residual stresses (σ_{MAX}) calculated for the gradient material of the above thickness attained the value of about 260 MPa, only slightly exceeding the ceramics bending strength. Probably, the real level of residual stresses in the Al_2O_3–FGM interlayer–steel joint, with the FGM 3.0 mm thick, is much lower than calculated. It may stem, among others, from too rough an estimation (the mixture rule) of the Al_2O_3–Cr composite properties assumed for the numerical analysis.

5. Summary

The calculations made and described in the present paper proved that the application in Al_2O_3 ceramics–heat resistant steel joints, interlayer of pre-designed special properties (total thickness, α, Re, E, ν) results in lowering residual stresses generated in joining process. The comparison of numerical calculation results for direct joints and joints with the FGMs interlayer shows that the satisfactory solution is to use an interlayer consisting of three Al_2O_3–Cr gradient layers, 3 mm thick altogether (all layer equally thick). The application of such an interlayer resulted in a 50% drop in the value of residual stresses, and what is very important, brought about the shift of their maximal value from the surface deeper inside, which was characterized by higher strength of the gradient material. Further research proved that, besides the chemical composition of individual layers, the profile of the gradient material structure was quite essential—understood as the number of layers, thickness diversification and their respective positioning in the gradient. It was concluded that the best solution is when the FGM layer close to the ceramics is the thickest.

Summing up, it must be stated that, although from the technological and economic point of view obtaining gradient materials of a higher number and thicker layers is more difficult, the possibility of applying FGMs interlayer of an adequate profile is the optimal solution when it is essential to lower stresses in the designed joint even by 1%.

Acknowledgements

The authors would like to thank the Polish State Committee for Scientific Research for the financial support under the Project no. 3T08A 080 27.

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