Journal of Ceramic Processing Research. Vol. 17, No. 8, pp. 803~814 (2016)

J O U R N A L O F
Ceramic
Processing Research

Modeling the effect of interface characteristics and layer compositional parameters on the residual stress distribution in FG-TBC system: FEM and FIS approach

N. Nayebpashaee[a,*], S. H. Seyedein[a], M. R. Aboutalebi[a], H. Sarpoolaky[b] and M. M. Hadavi[c]
[a]*Materials Processing Simulation Laboratory (MPS-LAB), School of Materials and metallurgical Engineering, Iran University of Science and Technology (IUST), Narmak, Tehran, Iran*
[b]*School of Materials and metallurgical Engineering, Iran University of Science and Technology (IUST), Narmak, Tehran, Iran*
[c]*Department of Materials Science and Engineering, materials and energy research center (MERC), Karaj, Iran*

Thermal barrier coating using turbine industries, application of pre- process simulation and on-line subsequent control based on physical knowledge are greatly advantageous in order to develop the material performance despite of the time and cost efficiency. Fuzzy linguistic- based model is one of the most accepted and promising approaches that is currently used in the control systems of various engineering fields and applications. As for need of industrial units, physical simulation strategies are too compound for industrial use and less efficient than soft computational techniques. A combination of fuzzy linguistic-based model and finite element method (FEM) has therefore been developed in the terminology of a combined or "hybrid model" in this study. The hybrid model was applied to predict residual stress during thermomechanical process in functionally graded thermal barrier coating (FG-TBC). Results show that, interface shape amplitude and ceramic constituent in composite layer have significant effect in distribution of residual stress in interface regions and can be considered as potent zones for both vertical and horizontal cracks. In addition, this study shows excellent potential of such finite element-artificial intelligence hybrid approach for analysis of high temperature imposing of these protective coatings.

Key words: Thermal barrier coating (TBC), functionally graded (FG), Fuzzy logic (FL), Finite element method (FEM).

Introduction

In high temperature combustion applications, achieving better performance for aircraft engines working in such elevated temperatures has always been a challenge for involved scientist. Higher performance means bearing quite elevated temperatures in important combustion engine components [1]. Thermal barrier coatings (TBCs) are one of the most conventionally- used protective materials which are introduced as insulation materials that takes the duty of shielding underlying metallic substrate of a turbine blade form thermal damages.

The classic TBC is composed of double layers including the bond coat and top coat. The bond coat is MCrAlY (where M = Ni and/or Co) and the ceramic-based top-coat is often made of yttria stabilized zirconia (YSZ) [1]. Problems such as phase transformation, sintering induced volume shrinkages and increasing of elastic modulus cause a limited operating temperature of maximum 1473K for long-term use and This is the main drawback of YSZ. To find a solution for this, the search for new materials has been intensified in the recent years and since then, zirconate-based TBCs are considred to be a good candidate materials for the future application in turbine and other high temperature. Low thermal conductivity, high stability and high sintering resistance ability at mentioned limiting temperatures are some of the outstanding standpoints of this modern materials. $La_2Zr_2O_7$ (LZ) is one of the candidate materials. So far, little investigation was focused on the thermal shock behavior of the double-ceramic-layer (DCL) TBCs [2-4].

Each of mentioned layers has distinctly different thermal and mechanical properties which usually amplify the complexity of investigating about this ceramic- metallic high temerature resistance materials.

Some of the main threats with put lifetime of these coatings into danger are: residual stresses stemmed from technical process, mismatch between different materials in layers and finally compound and rough character of the TBC/BC boundary [5]. Residual stresses itself can be caused throughout three occurrence in real conditions of application which are stresses induced during phase transformation, solidification and further contraction of splat droplets from spraying temperature to the room temperature and stresses com from the difference between the linear Coefficient of Thermal Expansion (CTE) of two materials at two side of interfaces in substrate / BC or BC / TC. This matter is worse and more hazardous when coating system is cooling down from high temperatures to ambient

*Corresponding author:
Tel : +98-21-77240480
Fax: +98-21-77240480
E-mail: Nayebpashaee@iust.ac.ir

temperatures and drastically decrease the lifetime of protective layer [5].

In thermal barrier coatings fabricated using thermal spray technique, the rough interface is left after sand blasting procedure. These sub- micron rough interfaces created between layers have both advantage and also weakness. As good point, it improves the layer adhesion by mechanical inter- locking and this can significantly rise the service lifetime of a plasma-sprayed coating system that experience many thermal cycle. In another hand, non- flat surfaces can be considered as a proper bed to non- uniform stress distribution and concentration comparing to flat surfaces which can cause more crack initiation zones [6].

One of the conventional phenomena seen conventionally in failure of TBC systems is the growth of thermally growth oxides (TGO) with different thicknesses and morphologies that have been taken into consideration in many studies. At higher temperatures and at the interface of BC/TC, diffusion is activated and simultaneous migration of aluminum and oxygen takes place and this can gradually leads to formation of brittle phase of aluminum oxide layer that usually constraint expansion. This resistance to free expansion and contraction induce residual stress at this interlayer boundary and put them to the risk of fracture and fatigue crack.

This is a major failure mechanism developed at the interface formed as a result of bond coat oxidation at about 900 ^{o}C. The effect of formation of this oxide layer was investigated and several parametric study was done considering alumina oxide layer, interface shape morphology and non- homogeneity of thermal loading as affecting parameters of TBC performance [7].

Another foremost limitation in this high temperature protective system is the interfaces between substrate/ BC and BC/TC. These interface regions undergo high stresses due to the mismatch of thermal expansion between materials and due to interface sub- micron roughness which is the main [8].

Functionally gradient thermal barrier coatings (FG-TBCs) propose a solution for tackling the problems of stress concentration. Their application reduces the mismatch effect, thermal expansion, and interfacial stresses. These categories of coatings comprise a conventional top coat and a metallic bond coat as well as intermediate coatings with different number and amounts of ceramic and metallic constituent. It is worth noting that, stress mismatch at the interface and various defects in the coating materials can be reduced by replacing the sharp interface composition with a graded composition layer. In this kind of materials, the microstructure and properties change from ceramic to metal gradually from ceramic region to metal region and enhance adhesion and fatigue life in addition to residual stress decrease [9-10].

Presence of an intermediate layer between surface ceramic and metallic layer cause outstanding increase in hot corrosion of coating system [11]. Existence of Cr and Al in composite layer of BC + TC leads to the formation of $AlVO_4$ and $CrVO_4$ as other products of hot corrosion that reduce the contact area of YSZ with molten salt and less reaction take place between them. The consequence of that can be considered as less extent of phase transformation in ceramic layer, less volume change and induced stresses and better lifetime of TBC [12]. In addition, thermal fatigue life of functionally graded coatings is approximately five times better than conventional coating with identical thickness and also better oxidation resistance was seen FG-TBC protective layers [13].

The purpose of the current study is to assess the influence of the sub- micron interfaces roughness on stress distribution using finite element ABAQUS commercial code of functionally graded TBC systems. FE modeling of TBC systems on functionally graded thermal barrier coating is rare and most recent researches were about simulation of conventional coating. In addition to that, this study also implements a useful fuzzy logic model for evaluating the effects of process parameters namely; layer composition, layer thickness and interface feature of coating on the residual stress variation of FG-TBC during heating.

Finite Element Analysis

In order to numerically simulate the temperature distribution and consequent induced residual stress in the new functionally graded thermal barrier coating, a

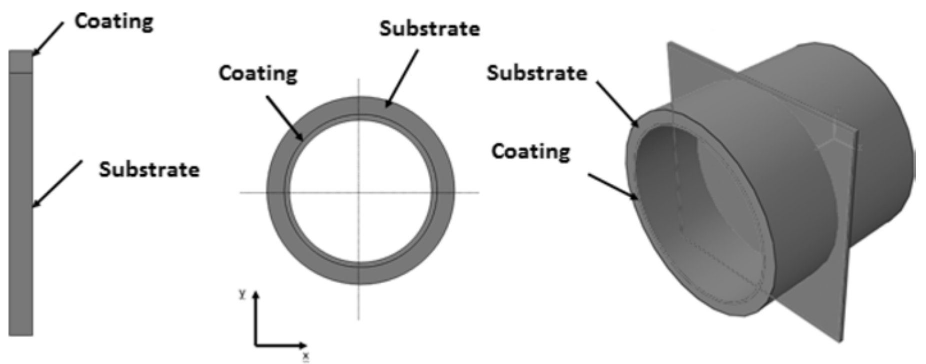

Fig. 1. TBC calculation domain.

Fig. 2. thermal barrier coating with two protective ceramic coating.

two dimensional finite element model was used fro this research. The schematic illustration in Fig. 1 indicates trends for selection of proper substrate/coating calculation domain.

As mentioned and aslo illustrated graphically in Fig. 2, The new design of functionally graded protective system is assembled of the metallic and ceramic layers with the different thickness of 100, 150 and 200 μm as following: Inconel 738 metal substrate, NiCoCrAlY metallic bond-coat (BC), functionally graded layer (50% BC + 50% YSZ , 25% BC + 75% YSZ , 75% BC + 25% YSZ) and at last, ceramic layer of Yttria Stabilized Zirconia (YSZ) on top of all.

Proposed model used in the current research have four layers and considered as calculation domain for coupled temperature- displacement numerical calculation. In order to construct the model with the maximum accuracy, all interfaces were modeled by a sub- micron asperity (here with constant wavelength of 100 micrometer) with sinusoidal interface with different amplitude i.e. 10, 20 and 30 microns. Three metallurgical postulation was taken into consideration in the modeling and implemented to ABAQUS commercial finite elemnt package. 1. Perfect bonding between layers is presupposed in all interfaces and

2. The presence of porosity in structure was overlooked and

3. No thermal resistance was implemented in the cohesive contact between layers.

Not violating the latter limitation, a meshing technique called tie constrant in the software was implemented. In this method, the connection between nodes of sections in two side of boundary line is stayed in touch during thermal loads and consequent distortion. In another word,

Table 1. Material Properties of the Graded Coating [8].

Material	T (K)	E (GPa)	P (Kg/m^3)	α ($\times 10^{-6} \times K^{-1}$)	ν	K (W/(mk))	Cp (J/Kg • K)
Inconel	276	200	8220	14.4	0.3	11.5	431
	673	179	8220	14.4	0.3	17.5	524
	1073	149	8220	15.6	0.3	23.8	627
	1473	140	8220	15.8	0.3	24.4	712
MCrAlY	276	225	7320	11.6	0.3	4.3	501
	673	186	7320	14	0.3	6.4	592
	1073	147	7320	16	0.3	10.2	781
	1473	134	7320	20.8	0.3	11.3	764
50% BC + 50% YSZ	276	217.5	6360	10.35	0.25	500.5	2.68
	673	195.5	6360	12.29	0.25	584	3.6
	1073	164	6360	13.56	0.25	709	5.43
	1473	148	6360	14.65	0.25	707	5.96
25% BC + 75% YSZ	276	213.75	5880	9.73	0.225	500.25	1.87
	673	200.25	5880	11.44	0.225	580	2.2
	1073	172.5	5880	12.35	0.225	673	3.04
	1473	155	5880	11.58	0.225	678.5	3.29
75% BC + 25% YSZ	276	221.25	6840	10.975	0.275	500.75	3.49
	673	190.75	6840	13.15	0.275	588	5
	1073	155.5	6840	14.78	0.275	744	7.81
	1473	141	6840	17.73	0.275	735.5	8.63
YSZ	276	210	5400	9.1	0.2	10.6	500
	673	205	5400	10.58	0.2	0.8	576
	1073	181	5400	11.13	0.2	0.65	673
	1473	162	5400	8.5	0.2	0.62	650

a point-to-point coincidental constraint was used for every two nodes at the different sides of the boundary. Since the effect of temperature is quite influential in material response at elevated tempaeratures, the properties of each materials were assigned to the software with temperature dependent together with isotropic homogenous mode . Elastic modulus, density, coefficient of thermal expansion, thermal conductivity, and specific heat for different coating layers at defined temperatures were exxtracted from related publications for computation. The results of these properties are shown in Table 1. Having a real picture, two boundary condition of symmetry and Multi-Point Constraint (MPC) was utilized and assigned to the left and right edges of coating domain, respectively. Multi point constraint allows all nodes of edge to be in simultaneous motion in every horizental direction. Fig. 3 indicates the mentioned consideration in the model for establishment of finite element meshing geometry. Element used in this study is two dimensional triangular quadratic six nodes with mechanical plane strain mode and reduced integration. This element selected from library is one of the most efficient element with the ability of calculation and reporting both primary (temperature) and secondary (heat flux) in theramal analysis and displacement iteratively.

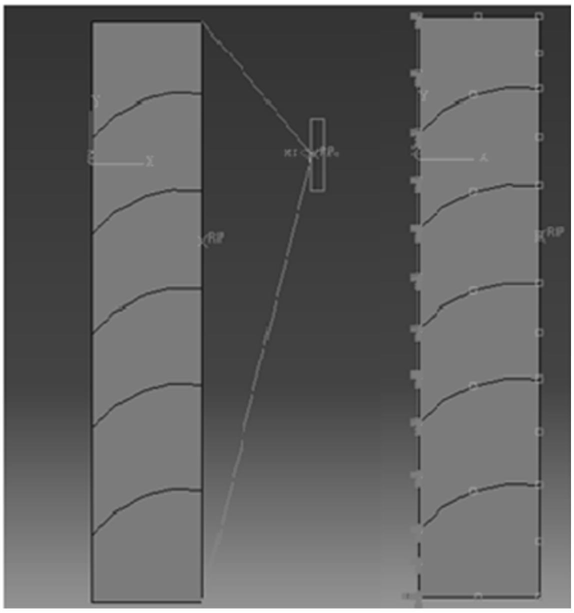

Fig. 3. Symmetrical and periodic multi point boundary condition used in this study.

To develop and extract the required outputs with the utmost accuracy and confidency in interfaces, this regions as seen in Fig. 4 were discretized with quite smaller element size using one- sided biased mesh technique.

Deigned thermal cycle during exposing, the thermal cycle on the top-coat surface consists of three stages as illustrated in Fig 5: the heating stage from 25 C to 1400 C in 300 s, followed by a service at 1300 C and finally, a cooling stage from1300C to 25C in 300s. In the other

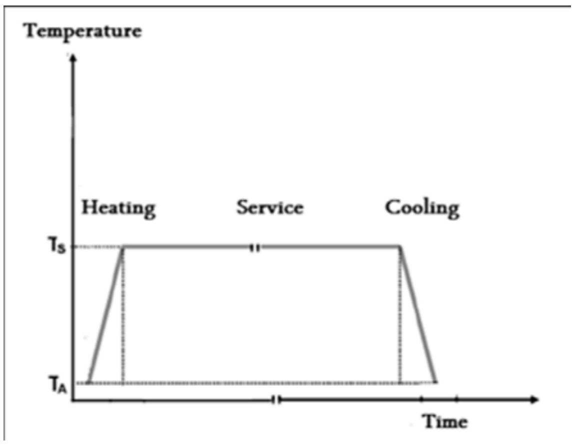

Fig. 5. Thermal cycle strategy loaded to the top ceramic coating.

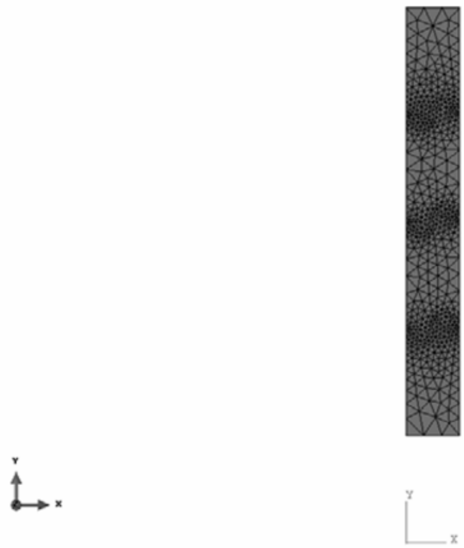

Fig. 4. Biased mesh generation in the interfaces of FG-TBC.

side, convective transfer by with the surrounding air is utilized with a coefficient of convection equal to18 W/ m^2 K.

Fuzzy logic Modeling

The use of numerical methods in new fields of manufacturing and engineering subjects is getting raised day to day. Soft computation methodology based on the knowledge of artificial intelligence has recently found its place in advanced materials engineering applications. Artificial neural network (ANN) is the most renowned method in prediction and classification of multifaceted and multi-dimensional properties of materials with its astounding ability of learning from sets of examples and generalize the knowledge to new conditions [14] .However, this technique has many negative aspects which may get the simulation process into difficulty; very slow convergence, entrapment in the local minimum and of course requirement of a large number of data sets are some of occurring problems. In this regard, fuzzy logic can be used as a advanced modeling approach [15] which was first introduced by L. A. Zadeh in 1965 [16]. Fuzzy logic is a powerful problem-solving methodology with many applications in embedded control and materials processing such as prediction of roughness [17] and hardness [18] of components, mechanical properties of FGM [19] and composites materials [20-21]. Fuzzy concepts provide a remarkably straightforward method to describe explicit conclusions from vague and ambiguous information. In a sense, fuzzy inference system uses human decision-making process with its ability to work from approximate data and find precise solutions. Just unlike classical logic which needs a profound understanding of situation by using exact equations, and precise numeric values, this logic have as a feature an alternative way of thinking, using a higher level of abstraction compromised from past experiences [18]. Therefore, it simplifies design complexity and problem solving. In fuzzy logic, numbers replaced with linguistic variables whose representations are linguistic- based and uses specific rules. The conventional coding of a classical set (crisp set) has only two values: one uses when a member is in the set; and zero, when it is out of it but in fuzzy logic theory, everything is a matter of degree .Membership function is used for clarifying the value of each element in fuzziness. Considering above concepts, deterministic uncertainty in fuzziness may be confused with nondeterministic probability [16]. Fuzziness describes event ambiguity but probability describes event occurrence. Whether an event occurs is random, the degree to which it occurs is fuzzy. The fuzzy logic based modeling is much more in-line with the human's interpretation system, which implements an 'if–then' code. In the fuzzy theory texts, 'If' usually named premise and 'Then' is the subsequence. Basically, fuzzy logic has three steps: fuzzication, rule evaluation and defuzzication process. Fuzzication is a process that switches decimal values into fuzzy sets. The rule evaluation step includes "if...then" phrases that form the linguistic formation of rules. Finally, a defuzzication procedure transforms the fuzzy outputs to crisp ones that can be interpreted for later applications.

Fuzzy logic is a very useful and outstanding computational tool in different complex and nonlinear engineering problem. Since any logical system can be fuzzified and a general logical relationship exists between residual stress and above affecting factors, a fuzzy logic (FL) approach would be very gifted and effectual for this problem. Fuzzy sets and membership is the key approach in decision making when faced with uncertainty. Fuzzy set can be defined as a set of crisp values that can be group together with an associated fuzzy term and contains objects that satisfy imprecise properties of membership. So, a fuzzy set is totally characterized by a membership function. In a Formal definition, a fuzzy set A in X is expressed as a set of ordered pairs according to equation 1[21].

$$A = \{(x, \mu_A(x))\} | x \in X | \tag{1}$$

Where, A is the fuzzy set, x and μ_A(x) are the member of the universe and its related membership function, respectively and X is universe of discourse. There are basically two types of fuzzy sets: normal and subnormal. A normal fuzzy set is one whose membership function has at least one element x in the universe whose membership is unity and on the other hand, A subnormal fuzzy set is one whose membership function doesn't have an element x in the universe whose membership is unity. All information contained in a fuzzy set is described by its membership function. For crisp sets an element x in the universe X is either a member of some crisp set, say A on the universe or it is not that means A is not in the universe. (Binary membership) but, in a fuzzy membership, the notion of binary membership has been extended to accommodate various "degrees of membership" on the real continuous interval between zero and one, where the endpoints conform to no membership and full membership, respectively. The sets on the universe X that can accommodate "degrees of membership" are referred as "fuzzy sets" [22].

Results and Discussion

Stress distribution analysis

As a general rule, the failure takes place in and subsequent cracking thermal barrier coating depends upon two factors of sign and\magnitude of residual stresses and that value should be compared with the that specific yield stress of coatings. Reported results of finite element analysis for this research will be evaluate in terms of normal stress components to the interface and designated by S22. The novel FG-TBC modern system is embedded to the top free surface where is in contact with the hot gas experiencing temperature varying from 273 k to 1490 k. Heat is transferred through the system by conduction mode and cooling is constantly done from bottom border of the coating by convection. During losing thermal energy, a normal stress induces at the layer interface due to the temperature gradient in TBC stemming from high heat flux. During a heating/cooling cycle, stresses are relaxed or developed because of thermal mismatch between interfaces that can be finally led to formation of cracks and spallation consequently. In this regards, the major factor mainly used for failure analysis of TBC systems are tensile stress perpendicular to the interface resulting from thermal mismatch.

According to the achieved results reported by Ranjbar et al. [8] the failure process occurs in three stages. The first stage can be the initiation and growth of micro-cracks with no weight loss which formed gradually as a result of thermal mismatch between YSZ and BC. There is an interesting point here that, these micro- cracks can be a source of formation of new small cracks. As an external characteristic, the pimple-like spots on the surface of the sample due to the oxidation of Ni-based superalloy substrate at high temperatures are visible after about at least five cycles and cause considerable weight loss. When the small cracks passes a threshold amount to form a crack net, the atomic bond strength declined, and these spots began to spall.

As another point, fatigue crack initiation is usually considered as a surface phenomenon attributed to the residual stress left on the TBC surface. It was commonly found that the, cracks initiated from the surface and interfaces due to the high induced stress and propagated perpendicularly along the thickness direction, which resulted in the debonding of the coating. In a graded coating, these cracks originate from the most brittle layer, and propagate deeply into the adjacent layers, and finally extend to the entire coating.

For all the interfaces, there exist both tensile stress and compressive stress. The tensile stresses exist at the center and the most outside edges. The compressive stresses are located between these two regions. The alternate distribution of tensile stresses like a pair of scissors resulted in the formation of a remarkable shear stress at the boundary circles between the tensile and compressive stress regions. Through the thickness of the graded coating from the surface of the coating, both the average and the maximum values of the tensile and compressive stresses reduced gradually.

In FGM coating, more similarities in thermal expansion of FGM layers lead to better adhesion between layers and less stress concentration in interfaces which are weak regions of coating and this, delays the crack initiation and fatigue crack growth in the interface.

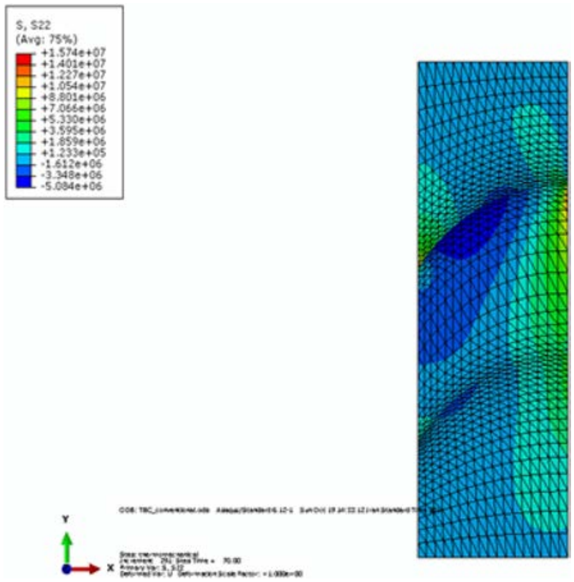

Fig. 6. Residual stresss induced after thermal cycle in the conventional TBC.

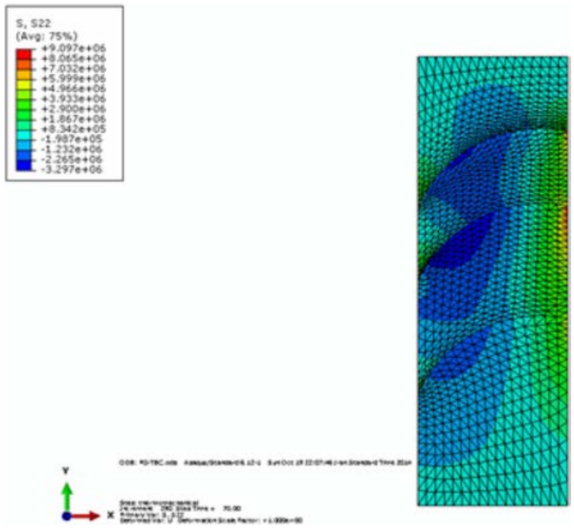

Fig. 7. Residual stresss induced after thermal cycle in the FG-TBC.

In this regard and as an outstanding point in FGM strategy, it was found from the current study that, the maximum stress in the structure is approximately half of conventional TBC systems and for that; it can be suggested as a new design of high temperature material. Figs 6 and 7 indicate the fifty percent difference in stress distribution in conventional and functionally graded coatings with the same total thickness and width.

In this study, different factors of functionally graded design such as thickness of layers, composition and interface amplitude of thermal barrier coating was taken into consideration using finite element analysis and results them introduced to fuzzy linguistic based fuzzy inference model. As mentioned before, three levels of variation was selected for each affecting parameters

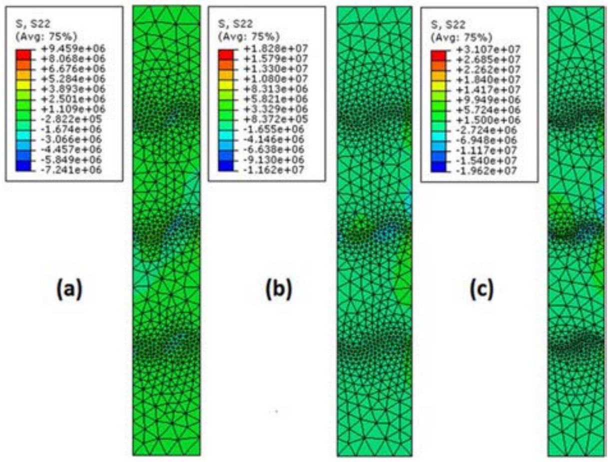

Fig. 8. Residual stress induced after thermal cycle in coating with (a) thickness of 100, composition 75% BC + 25% of and amplitude of 10 micron (b) thickness of 150 , composition 75% BC + 25% of and amplitude of 10 micron (c) thickness of 200, composition 75% BC + 25% of and amplitude of 10 micron.

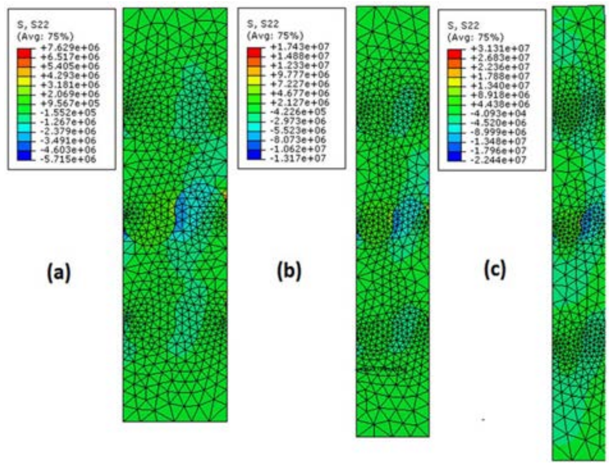

Fig. 10. Residual stress induced after thermal cycle in coating with (a) thickness of 100, composition 75% BC + 25% of and amplitude of 30 micron (b) thickness of 150, composition 75% BC + 25% of and amplitude of 30 micron (c) thickness of 200, composition 75% BC + 25% of and amplitude of 30 micron.

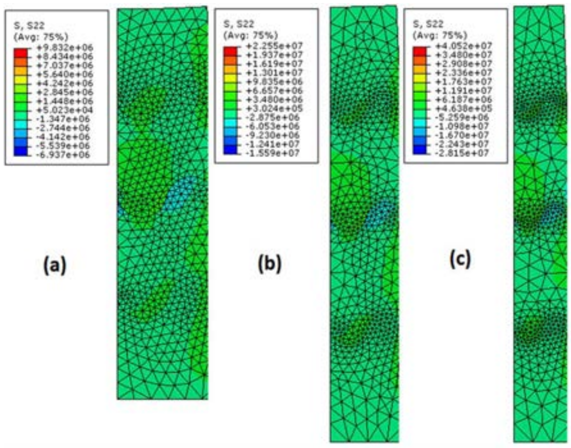

Fig. 9. Residual stress induced after thermal cycle in coating with (a) thickness of 100, composition 75% BC + 25% of and amplitude of 20 micron (b) thickness of 150 , composition 75% BC + 25% of and amplitude of 20 micron (c) thickness of 200, composition 75% BC + 25% of and amplitude of 20 micron.

and according to full factorial design of experiment, a total number of 27 tests were necessary to investigate the impact of parameters on design criteria, here residual stress in the interface of graded composite layer of BC/TC and upper top coat. Coupled temperature- displacement equations were solved by simulation using finite element approach and required residual normal stress was extracted at the critical point mentioned above. The effect of every individual parameter can be interpreted as following. As thickness of layers increases, the residual stress induced increases and this is because of much more residual stress stored in the thicker layer with relatively more materials. In other words, difference in thermal expansion leads to a thermal mismatch between layers that can be known as source of residual stress in the system and in systems with thicker layers, higher amount of stress accumulated and put the interface bonding into danger. For functionally graded coatings with composition of 25% BC + 75% YSZ, the residual stress seen in the interface of composite layer and top coat is less than other strategies of 50% BC + 50% YSZ and 75% BC + 25% YSZ and that is because of more matching and mechanical compatibility between layers containing 75% ceramic ingredients and fully top coat composite layer. According to mentioned reson and folowing this trend, induced stress at the interface of functionally graded layer and top coat reach its maximum value when composite layer contains only 25% of ceramic material. Just counter to two above factors, increasing of interface amplitude have two different effects on the residual stress induced at the interface that works inversely to regarding to each other.

As the amplitude of sinusoidal interface increases, more rough asperity creates between layers and this cause more non- uniformity and heterogeneous in distribution of stress. Just in counter way, higher peaks and deeper valleys are more potent to form stronger mechanical inter- locking of two neighbor layers at the interface that cause much adhesively. The improved adhesion between two layers postpone the initiation of cracks and further coalescence of them because of resistance of interface to inter-layer de-bonding and failure. As seen in the FEM simulation results of this study, residual stress increases as the amplitude increase and after a specific value of amplitude, it begins to decrease. Achievements of this study are in agreement with the abovementioned reasons that the residual stress of systems with amplitude of 20 micron is higher than ones with 10 and also 30 microns of interface amplitude. According to the full factorial design of experiment, 27 test runs were done using ABAQUS commercial package and essential outputs were extracted for using in fuzzy logic modeling. Figs. 8, 9 and 10 show a selection of stress distribution contours of FG-TBC protective system at different testing parameters.

Optimization of numerical simulation

In finite element analysis, solving a real engineering case in shorter runtime is more effective and economical due to occurrence of numerical errors as time of solve elongates. Since coupled processes have complex non-linear complicated natures, an exceedingly lengthy time is usually required for achievement of solution while not violating convergence criteria. Because of this; some adaptations have to be introduced to the model for reduction of time duration. One of the most conventional methods in reducing problem runtime is mass scaling technique which can be used in all problems that whether materials have strain dependency during process or not. Mass scaling is the most proper approach and so; an appropriate scale of element density variation was used for this problem after a series of trial and error simulations. Comparing the internal and kinetic energy of process at the end of step is the criterion of accuracy checking when using such quasi-static tricks and methods like mass scaling.

For assuring that the problem is quasi- static, the values of internal and kinetic energy should be checked versus each other in this trend that, the fraction of kinetic energy to internal energy should keep on approximately less than 5 to 10 percent all over process. For this purpose, history output for both internal and kinetic energy was requested from post- processing module of finite element code and subsequently, combined in one graph and the compared. Fig. 11 demonstrates the assessment of this two involved energies with respect to each other. Comparing the internal and kinetic energy, it can be evidently seen that in all steps of iterative solution, internal energy is considerably higher than kinetic energy in the graph and kinetic energy is only a small fraction of total consumed energy. Therefore, it can be concluded that, performed analysis can be taken into account as a quasi static type and proposed mass scaling method reduce solving time without putting numerical calculation error in problem. As another point, kinetic graph reaches its peak at the middle of the process and this means that point that, consumed energy at these times was used for accelerating the process.

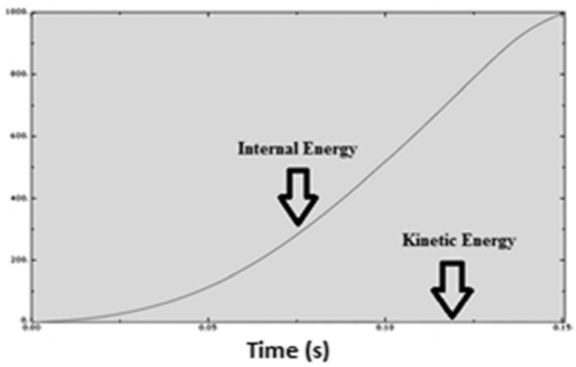

Fig. 11. Evaluation of kinetic and internal energy for quasi- static criteria.

As it was mentioned before, during high values of distortion especially in interfaces with small meshing region, strain values are induced into the materials during thermal stress and this can cause the solution procedure stop after a specific deformation attempt. For tackling this problem with considering material specific nature, ALE hybrid adaptive meshing is introduced as a proficient and helpful technique to keep element away from excessive distortion and prohibition of element mass to approach to zero which leads divergence and incomplete solution. In this approach, movements of element nodes become independent of geometry deformation and because of this matter, the quality and dimensions of elements remains in fine and acceptable situation. In another word, when strain induced to the model, only the node coordinates of elements alters and the geometry and topological feature of elements experience no change. Efficient avoid from excessive distortion, a significant and proper frequency and sweeping factor have to be considered while implementing adaptively to elements imposed to large destructive elements. The former identifies the number of increments after that, re-meshing takes place and the later parameter gives the number of orientation change in each re-meshing effort. A set of (10, 3) was decided to be used for frequency and sweep factor, respectively for analysis in this study.

Prediction of residual stress using fuzzy logic approach

Implementation of the Mamdani type fuzzy model applied to prediction of residual stress followed the steps listed below:

Fuzzification is the process of making a crisp quantity, fuzzy and converts definite data in the controller input to the format of linguistic variables. This is achieved by simply evaluating all the input membership function with respect to the current set of input values in order to establish the degree of participation of each membership function.

Rule evaluation: design of the related rule which link the three input variables to the single output variable and also assigning membership functions to them. Inference unit is a unit that performs fuzzy inference on fuzzy rules.

Defuzzication: After computing the fuzzy rules and evaluating the fuzzy variables, it is essential to translate results to the real world and make a fuzzy quantity, crisp, to obtaini a real number for next numerical interpretation. In the most conventional method, the so-called center of area, the weighted strengths of each output member function are multiplied by their

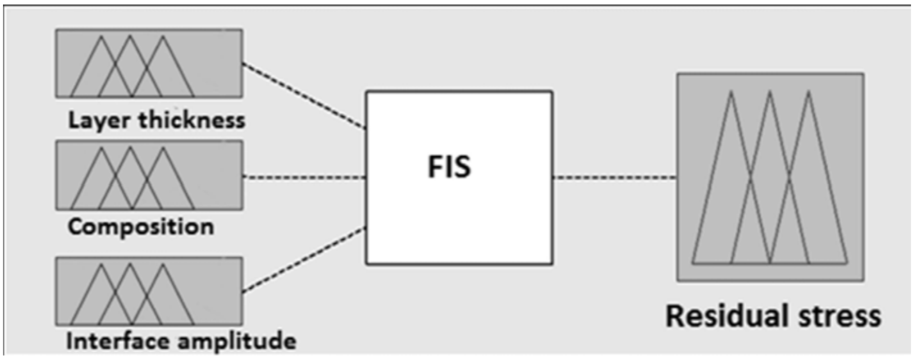

Fig. 12. fuzzy diagram for stress prediction in FG- TBC.

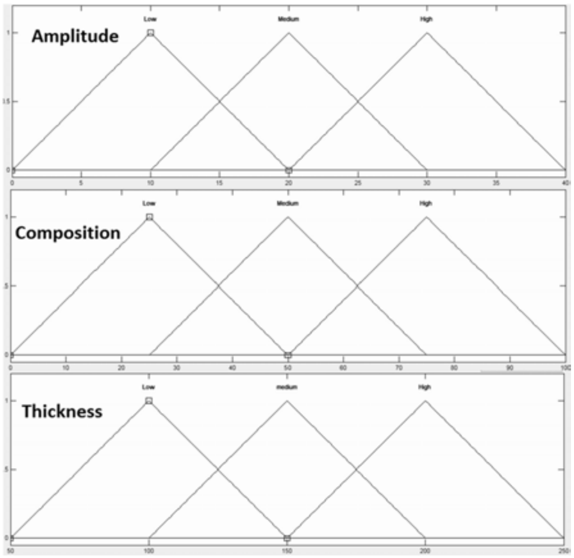

Fig. 13. Fuzzy membership functions for inputs of FG-TBC model.

respective output membership function center points and summed. Finally, this area is divided by the sum of the weighted member function strengths and the result is taken as the crisp output.

The first step in the fuzzy design is assigning a membership function to each variable. Different types of membership functions can be selected depending on the problem conditions and user's experience. Membership function can be in symmetrical or asymmetrical geometrical shape. In the current study, fuzzy triangular membership function was used because they are regularly applied because of their simplicity and ability for modeling non-linearity. Fuzzy membership converts the notion of binary membership to various degrees of membership value on a two-dimensional diagram. Fig. 12 illustrates fuzzy diagram for residual stress analysis of FG- TBC.

Fuzzy membership uses the perception of binary membership to accommodate a range of "degrees of membership" on continuous interval between zero and one, where the endpoints conform to no and full membership, respectively. Any kind of membership functions has different components which assign membership values to the corresponding variable considering function's configuration like type, number, shape and etc.

The core of a membership function is defined as the region (a single point in triangular membership factions) that is identified by complete and full membership in the set. The core consists of elements with unit membership value ($\mu(x) = 1$). Boundary is the section characterized by positive membership between zero and unity. The sum of all border regions is called support zone ($0\mu(x)$ 1) which supposed to be identical in triangular membership function. Fig. 13 and Fig. 14 illustrate membership functions used for inputs and output, respectively.

The amplitude of interface asperity is input 1 and has three member functions i.e. low, medium and high. It is ranged from 0 to 40 microns. The composition of composite layer is input 2, has three membership functions, i. e. low, medium and high. It ranged from zero to 100 of each YSZ and bond coat and layer thickness as third input has three membership functions, that is to say low,

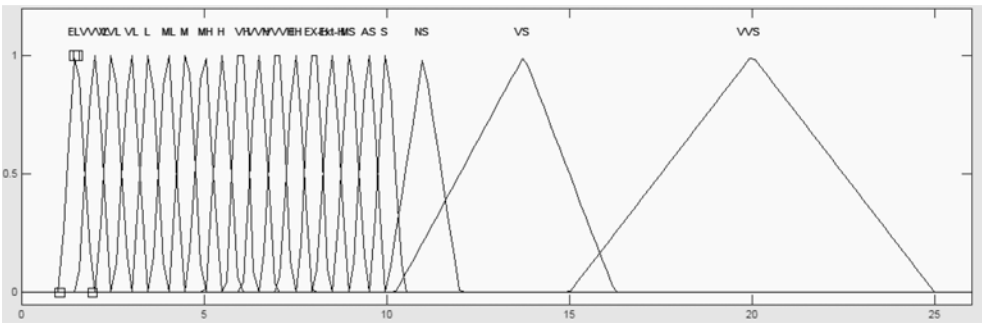

Fig. 14. Fuzzy membership functions for output of FG-TBC model.

Table 2. Linguistic rules for the fuzzy inference system.

No.	Rule definition
1	If (Amplitude is Low) and (Composition is Low) and (Thickness is Low) then (Stress is EL) (1)
2	If (Amplitude is Low) and (Composition is Low) and (Thickness is medium) then (Stress is ML) (1)
3	If (Amplitude is Medium) and (Composition is Low) and (Thickness is Low) then (Stress is VVH) (1)
4	If (Amplitude is Medium) and (Composition is Medium) and (Thickness is medium) then (Stress is S) (1)
5	If (Amplitude is Medium) and (Composition is High) and (Thickness is Low) then (Stress is VVVL) (1)
6	If (Amplitude is Medium) and (Composition is Medium) and (Thickness is High) then (Stress is ML) (1)
7	If (Amplitude is Low) and (Composition is High) and (Thickness is Low) then (Stress is VVL) (1)
8	If (Amplitude is High) and (Composition is Medium) and (Thickness is Low) then (Stress is H) (1)
9	If (Amplitude is High) and (Composition is High) and (Thickness is High) then (Stress is VS) (1)
10	If (Amplitude is High) and (Composition is Medium) and (Thickness is High) then (Stress is VVS) (1)
11	If (Amplitude is High) and (Composition is Low) and (Thickness is Low) then (Stress is L) (1)
12	If (Amplitude is High) and (Composition is Low) and (Thickness is medium) then (Stress is Ext-H) (1)
13	If (Amplitude is High) and (Composition is Low) and (Thickness is High) then (Stress is NS) (1)
14	If (Amplitude is Low) and (Composition is Medium) and (Thickness is High) then (Stress is VS) (1)
15	If (Amplitude is Low) and (Composition is Medium) and (Thickness is medium) then (Stress is VVVH) (1)
16	If (Amplitude is Low) and (Composition is High) and (Thickness is High) then (Stress is VVH) (1)
17	If (Amplitude is Medium) and (Composition is Low) and (Thickness is High) then (Stress is S) (1)

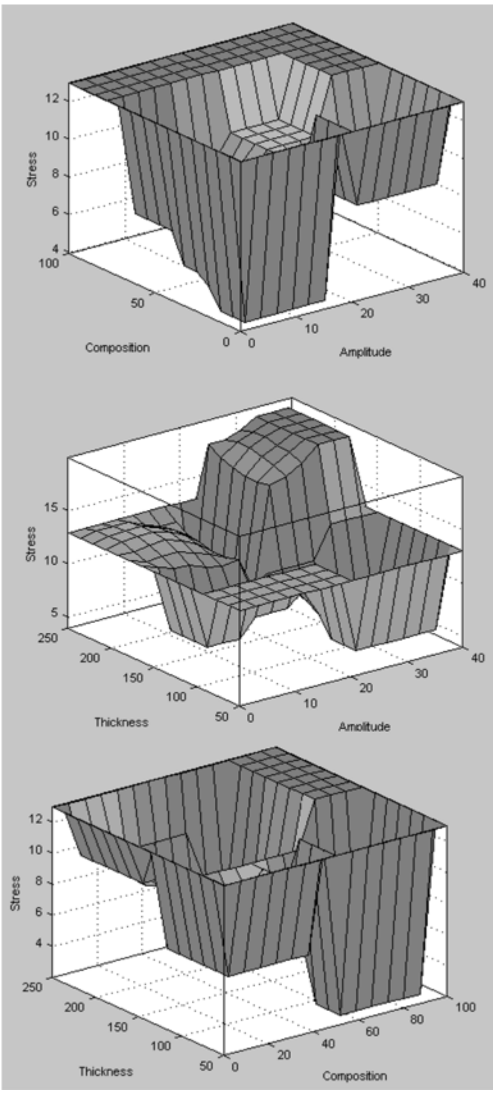

Fig. 15. Fuzzy surfaces for three inputs parameters of FG- TBC system model.

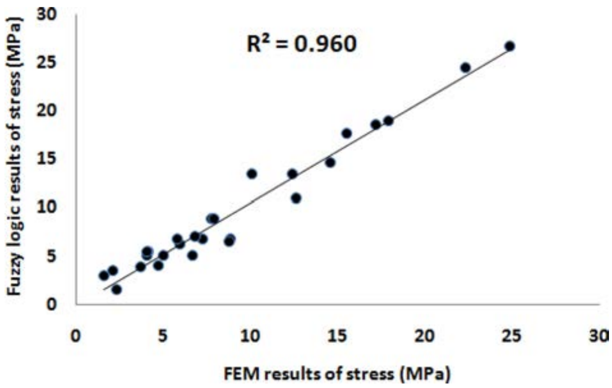

Fig. 16. Evaluation of actual results versus simulation results.

medium and high. It ranged from 50 to 250 microns. The only output, residual stress in FG-TBC system has 21 fuzzy terms. It ranged from 4 to 24 MPa includes extreme low (EL), very very very low (VVVL), very very low (VVL), very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H), very high (VH), very very high (VVH), very very very high (VVVH), extreme high (EH) and excessive high (Ex-H), Extra high (Ext-H), mild severe (MS), average severe (AS), severe (S), naturally severe (NS), very severe (VS), very very severe (VVS). Rule evaluation is the second step in constructing a fuzzy system. The goal is to establish a connection among multiple inputs and residual stress in coating. Table 2 shows 17 accomplishing 'if-then' rules. Deffuzification is the ending process in the fuzzy logic analysis. Many defuzzication methods can be utilized including centre-of-area, weighted average, Max-membership or height method and Center of sums. We choose the first one of the above as one of the most common defuzzication method named centre-of-area or centroid. Figs 15 shows the fuzzy surfaces achieved from fuzzy logic

Table 3. Comparison of FEM results and FIS results.

Test	Amplitude (μm)	Thickness (μm)	Composition A : MCrAly B : YSZ	FEM Stress (MPa)	FUZZY Stress (MPa)	Error (%)
1	15	125	10 A + 90B	3.2	4.1	–0.28
2	15	125	20 A + 80B	4.6	4	0.13
3	15	125	30 A + 70B	6.4	6.2	0.03
4	15	125	40 A + 60B	8.8	9.3	–0.06
5	25	175	60 A + 40B	13.6	14.6	–0.07
6	25	175	70 A + 30B	16.3	18.5	–0.13
7	25	175	80 A + 20B	24.4	25.8	–0.06
8	25	175	90 A + 10B	28.6	26.2	0.08

Table 4. validation of finite element simulation approach used in this research by experimental and numerical results reported by Chen et al [23].

Layer	Max. Stress Chen	Max stress Validation	Error percent
LZ / 80% LZ + 20% YSZ	491.7	512.1	4.0
80% LZ + 20% YSZ/ 60% LZ + 40% YSZ	465.7	483	3.6
60% LZ + 40% YSZ/ 40% LZ + 60% YSZ	455.6	474	3.9
40% LZ + 60% YSZ/ 20% LZ + 80% YSZ	438.7	458.2	4.3

modeling performed on FG- TBC system according to input-output relations extracted from FEM. The comparison of the actual and fuzzy model value with $R^2 = 0.96$ shows the trustable ability of proposed approach for evaluating the induced stress in thermal barrier coating system. Fig. 16 presents a regression graph which shows the fuzzy and FEM results compression and. Since all 27 possible combination of affecting parameters had been used in fuzzy model, interaction between inputs seems to be taken into account in analysis and improves prediction accuracy. There is no considerable difference between the predicted and the actual data. However, for having an effective and efficient modeling with fuzzy logic, it would be more acceptable to use the least number of rules which can get a good results instead of using all possible rules that can be implemented. (All rules that can be written for three inputs with three memberships for each). In conclusion, the fuzzy model showed better performance and accuracy rather than the regression model with the higher R^2.

As validation or model evaluation, the residual stress of some other FG-TBC systems were calculated via finite element with the same simulation procedure and same conditions and achieved information with corresponding data were implemented to fuzzy inference model. Table 3 presents a comparison between the FEM computed values and the FIS predicted results for the induced stress in the protective layer.

The percentage errors associated in each test run with respect to the experimental results are also given in the table. It is observed that the error in FIS prediction lies approximately in the range of 0-13% which establishes the validity of the fuzzy rule- based prediction.

Conclusions

Based on above results, the following results can be highlighted:

1. Linguistic concepts in the form of fuzzy logic are proven to be simpler, more efficient and effective in modeling multi-dimensional complex problems without using lengthy formulations which needs a large number of experiments.

2. The developed hybrid modeling approach combining finite element and linguistic fuzzy models has been successfully applied to express residual stress induction in FG-TBC and evolution of affecting variables during thermal cycle under application in hot section of gas turbine.

3. Comparison of the local distributions of stress conditions and distortion within TBC structure

Simulated by FEM and the developed hybrid model shows a very similar result, indicating that the hybrid modeling approach can be applied within FEM code. The linguistic-based components in the hybrid model facilitate extrapolation beyond process conditions utilized for the block-box components, and this is essential to model in service mechanical properties close to those for real processing conditions.

4. ANN modeling for predicting and optimizing mechanical properties can eliminate the need for time-consuming destructive tests applied on yields, which ultimately leads to lower manufacturing costs.

5. The procedure described in this paper is a very

good technical example of data mining in practice, where available data coupled with soft-computing tools are used to draw invaluable conclusions.

6. FGM strategy reduced the stress values in the coating to half of its value in conventional coating. Less difference in thermal expansion improve the adhesive bonding between different ceramic / ceramic and ceramic / metal interfaces with sub-micron asperity and also decrease the risk for crack initiation and propagation.

References

1. R. Vaßen, M.O. Jarligo, T. Steinke, D.E. Mack, D. Stöver, Surface and Coatings Technology, 205 (2010) 938-942.
2. L.Wang, Y. Wang, W.Q. Zhang, X.G. Sun, J.Q. He, Z.Y. Pan, C.H. Wang, Applied Surface Science, 258 (2012) 3540-3551.
3. S. M. Naga, Ceramic matrix composite thermal barrier coatings for turbine parts, in: Advances in Ceramic Matrix Composites, Woodhead Publishing Limited, 2014, pp. 524-533.
4. M. Ranjbar-far, J. Absi, G. Mariaux, D.S. Smith, Materials & Design, 32 (2011) 4961-4969.
5. M. Ranjbar-Far, J. Absi, S. Shahidi, G. Mariaux, Materials & Design, 32 (2011) 728-735.
6. M. Bia³as, Surface and Coatings Technology, 202 (2008) 6002-6010.
7. P. Bengtsson, C. Persson, Surface and Coatings Technology, 92 (1997) 78-86.
8. M. Ranjbar-Far, J. Absi, G. Mariaux, F. Dubois, Materials & Design, 31 (2010) 772-781.
9. S. Widjaja, A.M. Limarga, T.H. Yip, Thin Solid Films, 434 (2003) 216-227.
10. S. Widjaja, A.M. Limarga, T.H. Yip, Materials Letters, 57 (2002) 628-634.
11. J.J. Sobczak, L. Drenchev, Journal of Materials Science & Technology, 29 (2013) 297-316.
12. B. Kieback, A. Neubrand, H. Riedel, Materials Science and Engineering: A, 362 (2003) 81-106.
13. A.S. B. Saeedi, A. Ebadi,A.M. Khoddami, J. Mater. Sci. Technol., 25 (2009) 499-507.
14. G. Kranthi, A. Satapathy, Computational Materials Science, 49 (2010) 609-614.
15. M. Kor, E. Abkhoshk, D. Tao, G.L. Chen, H. Modarres, Minerals Engineering, 23 (2010) 713-719.
16. L.A.Zadeh, Information and control, 8 (1965) 338-353.
17. Y.M. Ali, L.C. Zhang, Journal of Materials Processing Technology, 89-90 (1999) 561-568.
18. D. Chatterjee, G. Sutradhar, B. Oraon, Journal of Materials Processing Technology, 200 (2008) 212-220.
19. S. Ramanathan, R. Karthikeyan, M. Gupta, Journal of Materials Processing Technology, 183 (2007) 104-110.
20. S. Raßbach, W. Lehnert, Computational Materials Science, 16 (1999) 167-175.
21. O. Ünal, F. Demir, T. Uygunoglu, Building and Environment, 42 (2007) 3589-3595.
22. F. Yapici, A. Ozcifci, T. Akbulut, R. Bayir, Materials & Design, 30 (2009) 2269-2273.
23. H. Chen, Y. Liu, Y. Gao, S. Tao, H. Luo, Journal of the American Ceramic Society, 93 (2010) 1732-1740.

Appendix

The numerical simulation used in this study was validated with the comprehensive study of Chen et al which have both experimental and finite element simulation. Table 4 shows the validity and verification accuracy of finite element approach utilized in this work with by using results of mentioned research. After assuring about the affectivity and accuracy of this approach in numerical simulation, all abovementioned simulations of current manuscript was performed by same strategy.