



Coating thickness effect on stress distribution of coated cylinder head considering residual stress

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ABSTRACT

This paper presents the coating thickness effect on the stress distribution of a coated cylinder head. A typical thermal barrier coating was applied on a diesel engine cylinder head. Thus, the residual stress which occurred during the plasma thermal spraying was also considered. The coating system consisted of two layers; a metallic bond coat and a ceramic top coat. The bond coat thickness is considered as 50 to 250 μm and the top coat thickness was considered as 200 to 800 μm . The stress distribution was found by the finite element analysis using the ABAQUS software. Then, stress distributions were compared for various coating thicknesses. Finally, optimized values for each layer are suggested.

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1) Introduction

In automotive industries, aluminum-silicon-magnesium alloys have been widely used in engine components such as cylinder heads. This is owing to their proper mechanical, physical, and casting properties. One way to enhance diesel engines thermal efficiency is to apply a thermal barrier coating (TBC) system to the combustion chamber. Usually, TBC systems have a metallic bond coat (BC) layer and also a ceramic top coat (TC) layer which can be applied on components by the air plasma spraying (APS) method. These coating layers will cause a reduction in heat losses and therefore, the mean combustion temperature will increase. Then, fuel consumption and emissions such as hydrocarbons are expected to decrease [1-3].

Considering the effects of coating thicknesses and residual stresses (due to the plasma thermal spraying process) has been carried out by several researchers. Although investigating the stress distribution by the finite element (FE) analysis in coated cylinder heads has been performed rarely, on pistons and specimens (two dimensional modeling) has already been done vastly. Therefore, there is a lack of science in the field of studying stress distributions in coated cylinder heads, considering the residual stress.

Moridi *et al.* [1-3] studied the thickness effect on the stress distribution of coated specimens under thermo-mechanical loadings. They considered a real roughness of interfaces in a TBC system. Azadi *et al.* [4] presented a review of thermal barrier coating effects on the diesel engine performance and the components lifetime. In another article, Azadi *et al.* [5-6] optimized plasma thermal spray parameters by using a design of experiments. Their objective was the bending strength and also the thermal shock fatigue lifetime of coating systems in diesel engine applications. They obtained optimal values of the feed rate and the nozzle distance.

Scardi *et al.* [7] found the experimental residual stress on an aluminum disk with an APS yttria-partially-stabilized zirconia (PSZ) TBC system. Modeling of residual stresses in an APS zirconia/alumina TBC was performed by Widjaja *et al.* [8] by using the FE analysis. The effects of different cooling rates and the substrate preheating process on the residual stress distribution were also evaluated. They compared the FE results to the measured residual stress by the X-ray diffraction approach.

Cerit [9] analyzed a coated piston under thermo-mechanical loadings. He investigated effects of the coating thickness and width on temperature and stress distributions. It was observed that the normal stress on the coated surface would decrease with the coating thickness increase up to approximately 1 mm for which the stress value was minimized. Klusemann *et al.* [10] investigated the residual stress

in a thermal-sprayed tungsten carbide-cobalt coating, numerically. Their results of a detailed microstructure FE model were compared to a classical hole-drilling method. A FE simulation of the residual stress in a typical two-layer TBC system was performed by Wang *et al.* [11]. They used birth and death elements technique.

The residual stress was composed of two parts, i.e. the quenching stress and the thermal stress. The simulation results indicated that the two-layer TBC system had lower residual stress compared with that of the single-layer TBC system with the same thickness.

In this article, the FE simulation is used to calculate the stress distribution in a coated diesel engine cylinder head. Then, the residual stress according to the APS process is obtained to complete our previous work [12]. The BC and TC thickness effect is also investigated. FE Results including temperature and stress distributions are presented in figures.

2) Materials and simulations

In Figure 1, the FE model (with three-dimensional continuum elements) of the coated cylinder head is shown. The coated area is the combustion chamber which is shown in a lighter color. Other components are three valve ports, two valve guides, and four bolts.

The FE model consists of 30122 first-order 8-node, heat transfer and 3D stress, brick elements from which 8000 elements belong to TBC system. All nodes in coating layers are fixed to the nodes of the cylinder head with the aid of some interaction constraints such as tie. Reduced integration elements are used so as for decreasing the analysis run-time and, at the same time, provide more accurate stress predictions. The convergency of FE results is firstly checked and the size of element is properly refined.

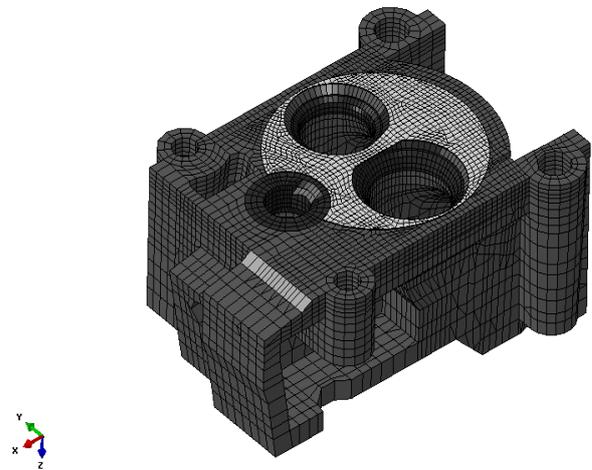


Figure 1: The FE model of the coated cylinder head

This FE model is subjected to cyclic temperature fluctuations ranging from a minimum value of 35°C

to a maximum value of 300°C. This thermal loading is applied for the un-coated cylinder head. In the coated cylinder head model, TC face temperature is considered as 350°C which is about 50°C hotter than the maximum temperature region of the valve bridge in uncoated head cylinder. This temperature rise is due to have better thermal efficiency with TBC systems [1-3]. Although this temperature rise is not constant through all over TC face in reality, just for the reason that the analysis is just focusing on the valve bridge region it can be considered as a simplification. Then, a thermal analysis is done to find the temperature distribution in all layers.

Mechanical loads are applied to the assembly in two analysis steps. In the first step, the three valve seats are press-fit into the corresponding cylinder head valve port using linear multi-point equation constraints and prescribed displacement loadings.

A static analysis procedure is used for this purpose. The cyclic thermal loads are applied in the second analysis step. It is assumed that the cylinder head is securely fixed to the engine block through the four bolt holes, so the nodes along the base of the four bolt holes are secured in all directions during the entire simulation. It should be mentioned that the number of cycles for applying the cyclic loads is considered as 100. The stress results are reported after these cycles.

The valve components are assumed to behave elastically. The two valve guides are made of steel, with the elastic modulus of 106 GPa and Poisson's ratio of 0.35. Two valve seats are made of steel, with the elastic modulus of 200 GPa and Poisson's ratio of 0.30 [13]. The body of the cylinder head is made of an aluminum alloy.

The two-layer visco-elastic and elasto-plastic model which is best suited for modeling the response of materials with significant time-dependent behavior is used for the cylinder head. Thermal, mechanical and viscous properties (parameters of the Norton's law) of the cylinder head are listed in Table 1 and Table 2. Plastic properties of the cylinder head are depicted in Table 3. Two coating layers are applied on the cylinder head.

All other material properties of the TBC system are reported in our previous work [1].

The thicknesses of BC and TC layers are considered as 50 to 250 μm and 200 to 800 μm , respectively. The BC layer is made of Ni-Cr-Al-Y and the TC layer is made of yttria stabilized zirconia (YSZ), $\text{ZrO}_2\text{-}8\%\text{Y}_2\text{O}_3$. For coating layers, elastic-plastic properties are considered. For calculating the residual stress (during the plasma thermal spraying process where the temperature is so high), viscous properties (the creep phenomenon) in coating layers are also considered [15].

For plastic properties of the TBC system, the yield stress is considered 270 MPa and 30 MPa for BC and TC layers, respectively [16].

Table 1: Material properties of the cylinder head [14]

Elastic modulus (GPa)	Poisson's ratio	Coefficient of thermal expansion ($1/^\circ\text{C}$)
70 at 20°C	0.33	2.26×10^{-5} at 20°C
65 at 150°C		2.26×10^{-5} at 175°C
65 at 200°C		2.51×10^{-5} at 225°C
62 at 250°C		2.51×10^{-5} at 400°C

Table 2: Viscous properties of the cylinder head [14]

A	n	m	f	T ($^\circ\text{C}$)
3.11×10^{-13}	7.4	0	0.2857	20
7.83×10^{-16}	7.4	0	0.2857	100
6.47×10^{-17}	7.8	0	0.3077	150
5.00×10^{-17}	7.8	0	0.3846	200
1.01×10^{-16}	7.4	0	0.5161	250
3.19×10^{-16}	7.8	0	0.5614	300

Table 3: Plastic properties of the cylinder head [14]

Yield stress (MPa)	Plastic strain (%)	T ($^\circ\text{C}$)
62.0	0.00	20
595.5	0.25	20
45.0	0.00	100
478.5	0.25	100
32.0	0.00	150
315.5	0.25	150
28.0	0.00	200
253.0	0.25	200
26.0	0.00	250
176.0	0.25	250
17.0	0.00	300
142.0	0.25	300

In order to find the residual stress, two approaches as fully coupled thermal-stress analysis or sequentially thermal-stress analysis could be done.

In fully coupled analysis which is defined in coupled temperature-displacement step, both thermal and stress results are reached at the same time. Besides, both effects of temperature field on stress distribution and stresses which cause plastic deformation on temperature distribution are considered simultaneously. However, in sequential analysis which is done in both heat transfer and static general steps respectively, just the effect of temperature field on stress distribution is noted.

Considering the fact that in this analysis plastic deformations are highly unlikely to be remarkable, fully coupled method can be interpreted as a prohibitively time-consuming and cumbersome alternative in this special case.

According to the thermal spraying process which applies coating layers on the cylinder head, a thermal cycle is applied on the FE model, before all mentioned loadings. This temperature history is shown in Figure 2. The temperature of the TC layer is reduced sharply from 2680°C [16] to room temperature. This cooling process up to 600 seconds will lead to the residual stress in the substrate and coating layers. It is worth mentioning that after 100 seconds the temperature of top coat face would reach to room temperature and the other 500 seconds time span is just to assure thermal stability of all layers. In other words, the transient heat transfer during cooling process is followed by a steady-state analysis. The convection coefficient, which plays the most crucial role on cooling gradient of TC face, is considered as 10 W/m²°K for the cooling step and it is just applied on the top surface of the cylinder head [16]. After calculating the residual stress, all mentioned thermo-mechanical loadings are applied to the coated cylinder head. The objective is to investigate the effect of residual stress consideration on stress distributions. It should be mentioned that viscous properties of coating layers and the substrate of the coated cylinder head, may cause a stress relaxation after 100 cycles of thermo-mechanical loadings.

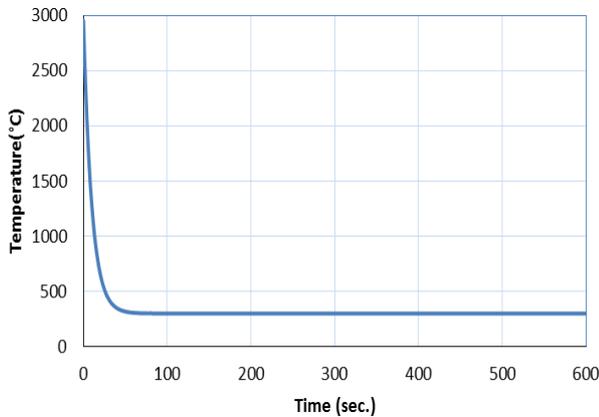


Figure 2: The temperature history for the thermal spraying process (the cooling step)

The sequentially coupled thermal-mechanical analysis is performed on the whole coated head cylinder based on both quenching stress (σ_q) and the thermal stress (σ_t), occur in the TBC system according to this cooling step, as following equations [16].

$$\sigma_q = \alpha_c E_c \Delta T \quad (1)$$

$$\sigma_t = \frac{E_c}{1 - \nu_c} (\alpha_s - \alpha_c) \Delta T \quad (2)$$

The first equation is due to the quenching process and the second one is due to the mismatch of the thermal expansion coefficient between the substrate

and coating layers. In mentioned equations, α_c , E_c , ν_c are the thermal expansion coefficient, the elastic modulus and poisson's ratio of coating layers, respectively. The other parameters α_s , ΔT are the thermal expansion coefficient of the substrate and the temperature difference.

3) Results and discussion

The valve bridge (between intake and exhaust valves) in the cylinder head has the highest temperatures. Thus, this area is the critical zone where the stress distribution is studied. The thickness of this area is also lower than other zones and therefore, the stress is maximized here. This is the other reason to investigate FE results at this area (the valve bridge). In coated cylinder head, mentioned happenings also occur.

As a first result, the residual stress (as the Von-Mises stress) due to the thermal spraying process is shown in Figure 3. It should be mentioned that in these results, the BC thickness is 150 μm and the TC thickness is 350 μm . As illustrated, when the thermal spraying process is considered, the stress in the substrate increases due to the residual stress. This stress enhancement is about 21 MPa in the substrate (near the interface).

In BC and TC layers, the creep phenomenon relaxes the stress at high temperatures. In other words, the effect of the residual stress in substrate is decreased due to stress relaxation phenomenon after thermo-mechanical loading conditions. It should be noted that the TBC system causes a temperature drop of about 100°C between coating layers and the substrate [1-3].

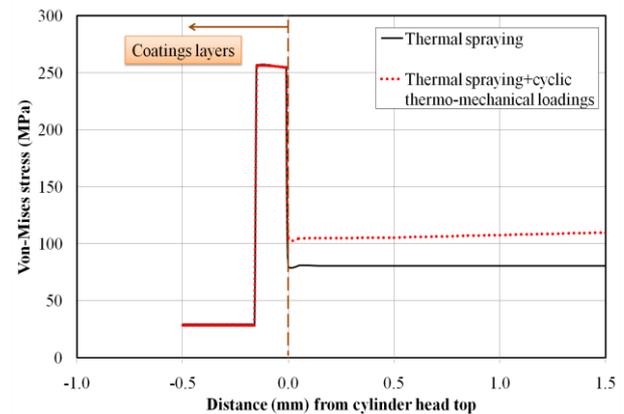


Figure 3: The Von-Mises stress through the thickness (at the valve bridge of the coated cylinder head)

This temperature distribution is also shown in Figure 4. Maximum temperature occurs on the face of the TC layer as 350°C. But in the substrate, the temperature is lower than that of the TBC system. This temperature difference is 80°C between the substrate and coating layers.

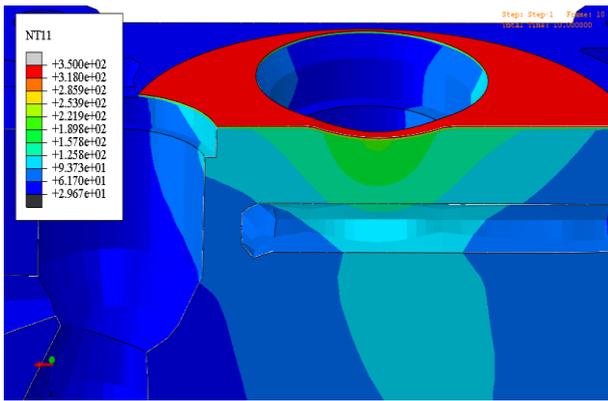


Figure 4: The temperature distribution through the thickness (at the valve bridge of the coated cylinder head) under thermal loadings

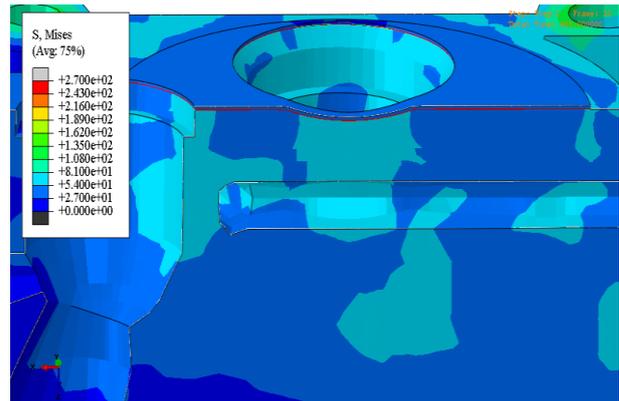


Figure 5: The Von-Mises stress distribution through the thickness (at the valve bridge of the coated cylinder head) under the thermal spraying process

Von-Mises stress distributions are shown in Figure 5 and Figure 6, for only the thermal spraying process and for the thermal spraying process plus cyclic thermo-mechanical loadings, respectively.

The maximum stress occurs at the BC layer. The value of the Von-Mises stress in the BC layer is near to its yield stress, 270 MPa. This can lead to the crack initiation. In such cases, the failure mechanism in TBC system is the separation of the BC layer and the substrate under thermal shock fatigue loadings. This is due to their material properties mismatch [1]. This mismatch is between the elastic modulus and the thermal expansion coefficient on the BC layer and the substrate.

Effects of the coating thickness are shown in Figure 7 to Figure 10, for the variation of the BC thickness and the TC thickness, respectively. These results include temperature and Von-Mises stress distributions. The TC thickness is constant as 350 μm , when the BC thickness changes and the BC thickness is constant as 150 μm , when the TC thickness changes.

By increasing the BC thickness, the temperature drop between the substrate and the BC layer is not affected. This temperature difference is about 80°C (compared to the uncoated substrate). But the Von-Mises stress decreases in the TC layer.

In general, the Von-Mises stress in the substrate decreases when the BC thickness increases. This reduction will become more remarkable by increasing the BC thickness.

In all BC thicknesses (from 50 to 250 μm), there are several points which stresses are near the plastic zone. When the BC thickness increases to 300 μm , then all area in the BC layer is in the elastic zone. If the optimization criterion is only considered as no plastic zones, then, 300 μm of the BC thickness can be considered as the optimized value.

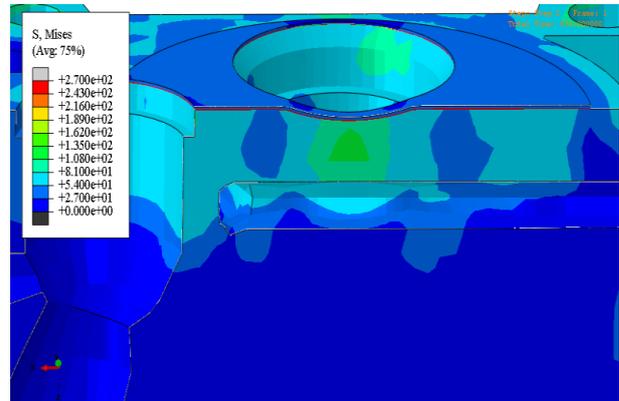


Figure 6: The Von-Mises stress distribution through the thickness (at the valve bridge of the coated cylinder head) under the thermal spraying process plus cyclic thermo-mechanical loadings

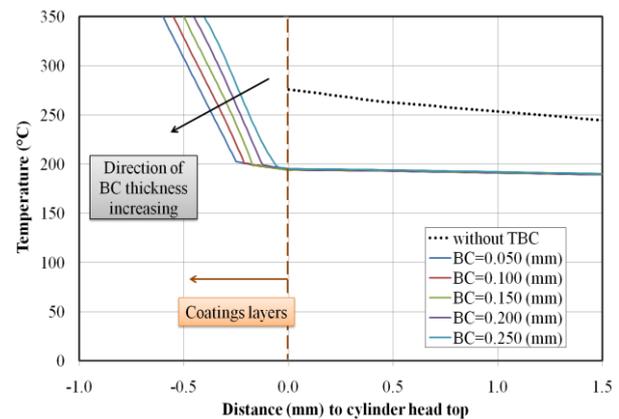


Figure 7: The temperature distribution through the thickness (at the valve bridge of the coated cylinder head) for various BC thicknesses

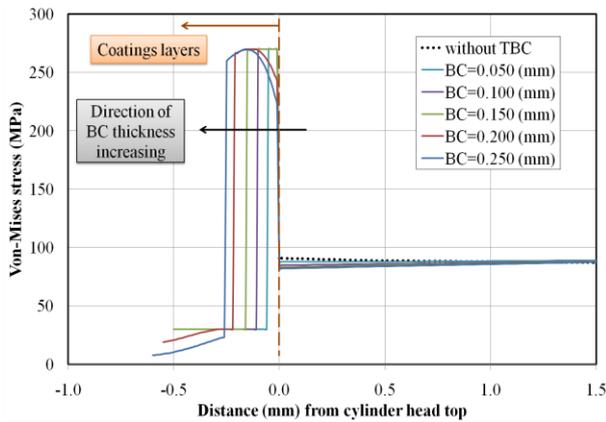


Figure 8: The Von-Mises stress distribution through the thickness (at the valve bridge of the coated cylinder head) for various BC thicknesses

For various TC thicknesses, the temperature drop between the substrate and coating layers enhances, when the TC thickness increases. The temperature difference is about 66°C when the TC thickness is 200 μm (the substrate-BC interface temperature of uncoated and coated head cylinders are 276.06 and 209.78, respectively). By increasing the TC thickness, this temperature difference increases but the rate of this enhancement decreases.

For the last TC thickness (800 μm) the temperature difference is about 96°C (the substrate-BC interface temperature of uncoated and coated head cylinders are 276.06°C and 179.99°C, respectively). By increasing the TC thickness, the Von-Mises stress in the substrate decreases from 6 to 11 MPa in comparison to the uncoated cylinder head. In lower TC thicknesses, all points of the TC layer are near the plastic zone. For 800 μm of the TC thickness, all points of the TC layer are in the elastic zone. This thickness can be considered as the optimized value, when the criterion is to have no plastic zones in coating layers.

It should be noted that for various TC thickness, all points in the BC layer are near the plastic zone as shown in Figure 8. Here, the BC thickness is 150 μm . Thus, the Von-Mises stress in the BC layer has no significant changes when the TC thickness increases. As a final result, if the optimization criterion is only considered as having no plastic zone in coating layers (to prevent the crack initiation), then 300 μm of the BC thickness and 800 μm of the TC thickness are optimized values. Therefore, the TBC thickness becomes 1.1 mm.

The optimized value for the TBC thickness (more than 1 mm) was reported by Cerit [9] for the piston application. This shows that the optimized value for the TBC thickness (as 1.1 mm) in the cylinder head application has a good agreement with the literature. One important note is that this optimization is only based on the stress distribution. For better optimization, fatigue tests for the TBC system and bond strength tests for the BC layer are required. As

shown in literatures [1-3], by increasing the TC thickness, the fatigue lifetime decreases. In these thermal shock fatigue tests, the substrate is separated from the BC layer as the main failure mechanism due to the mismatch of material properties, such as the elastic modulus and the thermal expansion coefficient [1].

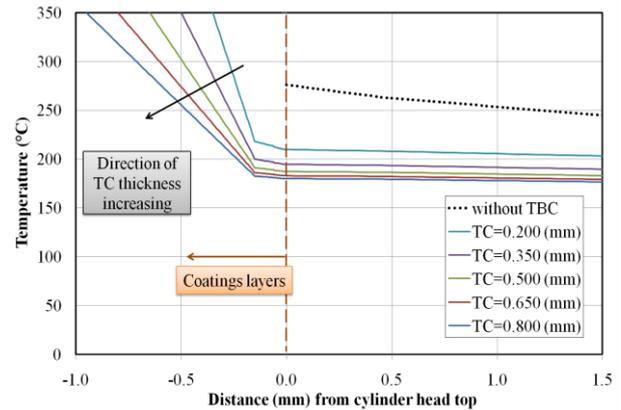


Figure 9: The temperature distribution through the thickness (at the valve bridge of the coated cylinder head) for various TC thicknesses

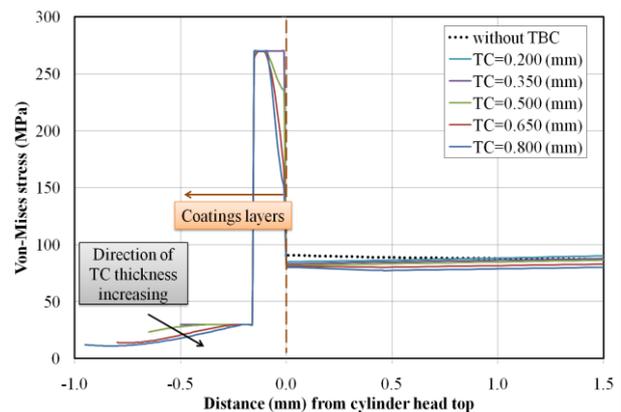


Figure 10: The Von-Mises stress distribution through the thickness (at the valve bridge of the coated cylinder head) for various TC thicknesses

As another important note, the interaction between the BC thickness and the TC thickness should be investigated to find the optimized value for no plastic zones. It means that higher TC thicknesses (than 350 μm) with higher BC thicknesses (than 150 μm) may lead to better behavior.

In this article, the BC thickness variation is investigated when the TC thickness is 350 μm and the TC thickness variation is investigated when the BC thickness is 150 μm . If effects of various BC and TC thicknesses are investigated, then the BC thickness of 250 μm and the TC thickness of 500 μm will be optimized values according to a proper temperature difference (between the substrate and coating layers) and also to have no plastic zones. Thus, the new optimized thickness value becomes 750 μm for the TBC system which is applies on a

diesel engine cylinder head. In this condition, contours of the temperature distribution and the Von-Mises stress are plotted in Figure 11 and Figure 12. Considering the valve bridge area, the temperature drop is calculated as 89°C (between uncoated and coated cylinder heads) and the Von-Mises stress reduces up to 10 MPa in comparison to the uncoated cylinder head. The maximum Von-Mises stress is 269 and 24 MPa, in the BC and TC layers, respectively. It should be noted that yield stresses are 270 and 30 MPa for the BC and TC layers, respectively.

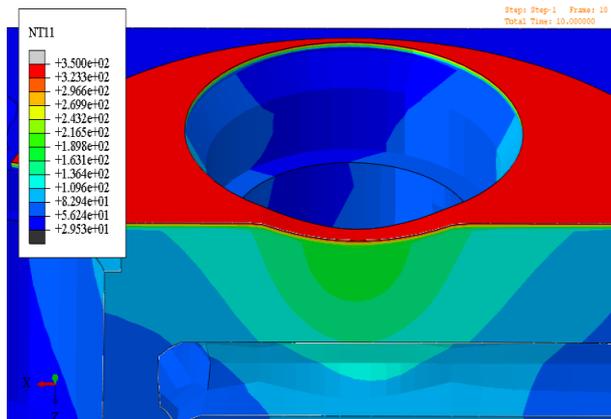


Figure 11: The temperature distribution through the thickness (at the valve bridge of the coated cylinder head) for optimized values (250+500 μm)

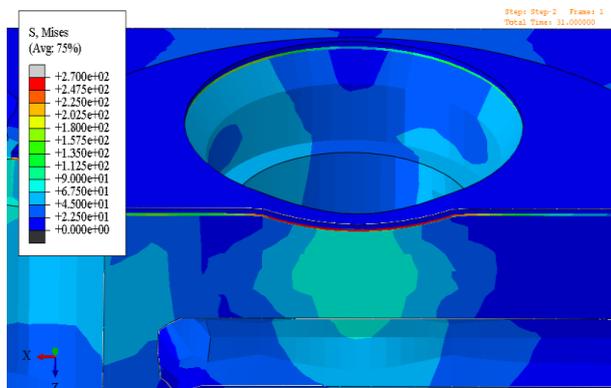


Figure 12: The Von-Mises stress distribution through the thickness (at the valve bridge of the coated cylinder head) for optimized values (250+500 μm)

4) Conclusion

The main objective of this research is to obtain temperature and stress distribution in a coated cylinder head by considering effects of the coating thickness and the residual stress according to thermal spraying process. FE results show that the stress increases in the substrate when the thermal spraying process is considered. The reason is the residual stress. The increase in substrate is not as much as predicted due to the viscous behavior of substrate which relaxes the stress under thermo-mechanical loading condition.

By increasing the BC thickness, the temperature difference between the substrate and coating layers has no changes, but by increasing the TC thickness (from 200 to 800 μm), the temperature difference increases from 66 to 96°C. The Von-Mises stress in the substrate decreases by increasing both the BC thickness and the TC thickness. However, these changes in the stress of the substrate are not significant. The reason can be due to multi-axial loadings and the complex geometry of the cylinder head. FE results demonstrate that the conservative value for the TBC thickness is 1.1 mm in the diesel engine cylinder head application when the objective is only to have no plastic zones. Having analyzed various BC and TC thicknesses by the FE method, the optimized thickness values can be considered as 250 and 500 μm for the BC and TC layers, respectively.

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چکیده

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بستار موتور دیزل

پوشش حائل حرارتی

این مقاله، به تاثیر ضخامت پوشش بر توزیع تنش بستار پوشش داده شده، می‌پردازد. یک پوشش حائل حرارتی خاص بر روی بستار موتوری دیزل قرار داده شده است. همچنین، تنش پسماند ناشی از فرآیند پاشش پلاسما، در نظر گرفته شده است. مجموعه پوشش از دو لایه تشکیل شده است: لایه فلزی اتصال دهنده زیرین و لایه سرامیکی فوقانی. شبیه‌سازی اجزاء محدود در نرم‌افزار آباکوس (ABAQUS) صورت پذیرفت. در این شبیه‌سازی، ضخامت لایه فلزی از ۵۰ تا ۲۵۰ میکرومتر و ضخامت لایه سرامیکی از ۲۰۰ تا ۸۰۰ میکرومتر در نظر گرفته شد. سپس، توزیع تنش بدست آمده در ضخامت‌های گوناگون، با یکدیگر مقایسه شد. در انتها، مقدار ضخامت بهینه برای هر لایه، پیشنهاد گردید.

تمامی حقوق برای انجمن علمی موتور ایران محفوظ است.