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# Study of the plasma deposition of $Al_2O_3$ powder on an internal combustion engine piston

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Due to high temperatures that can be found in the engine's combustion chamber some wear appears in the components. A proposed method for reducing the wear of the piston is plasma deposition of a ceramic layer of $Al_2O_3$. Thermal spraying is a method for obtaining parts that contain areas with special properties. For proper adhesion of the ceramic layer to the substrate an intermediate NiCr layer was used in the analysis. Choosing this type of powder was made according to the thermal wear resistance desired for the obtained ceramic layer. In thermal barrier coatings, high porosity is desirable because the thermal conductivity of the coating is low due to porosity. For a complete analysis of the coating both SEM and XRD analysis were performed on the samples subjected to high temperature. Also a finite element analysis of the piston with ceramic layer was done to determine the influence of the coating.

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*Keywords*: Atmospheric plasma spraying, $Al_2O_3$ powder, Scanning electron microscopy, Finite element analysis

## 1. Introduction

The research that is carried out currently in the field of internal combustion engines is pursuing technological innovations leading to lower manufacturing and maintenance costs and lower fuel consumption. Improved engine efficiency by applying design changes is rapidly developing in parallel with the application of ceramics and ceramic coatings on various parts or surfaces. To improve the engine performance, the energy obtained from the fuel combustion needs to be converted into mechanical energy at a high rate. By covering the combustion chamber of internal combustion engines with a ceramic material which exhibits a low conductive heat transfer coefficient it is possible to obtain an increase in the maximum thermal cycle temperature and pressure and simultaneously increase engine efficiency [1, 2, 3].

The ceramic coatings applied to the different surfaces that compose the combustion chamber of internal combustion engines have the purpose of reducing the amount of heat passing from inside the cylinder to the engine cooling system. A research topic analyzed in the past decades is the removal of the cooling system of the internal combustion engine and the development of ceramic coatings on various parts of the engine hot areas [4, 5]. In a conventional engine the removal of the cooling system would lead to the failure of the engine due to the mechanical and thermal limitations of the materials from which the parts are made and the limitations of the lubrication system.

In terms of emissions from the combustion process, the increase of the maximum thermal cycle temperature inside the combustion chamber that is enhanced with ceramic coatings can lead to a lower carbon monoxide emission and pollution [6, 7].

The combustion process that takes place inside the engine is the most important factor in terms of pollutant emissions, engine power output, fuel consumption, noise and vibration. In the diesel engines combustion process, the characteristics depend also upon the initiation of the combustion process [8, 9].

Considering the amount of heat lost through the cooling system we can infer that the usefulness of using materials with a low heat transfer coefficient and resistance to high temperatures can be important. These materials can form thermal barrier coatings for various components of the engine (low heat rejection engines LHR). Engines containing components with thermal barrier coatings can be considered as a step closer to adiabatic engines [10].

The value of the maximum thermal cycle temperature can reach 1100 ºC for turbocharged engines. By achieving these high flue gas temperatures, residual hydrocarbons and carbon monoxide present usually as emissions, are oxidized and become less polluting gases [11, 12].

This paper analysis the thermal behaviour of aluminium alloy samples with $Al_2O_3$ [13] coatings subjected to different working temperatures for periods of four hours. Another important factor that was analysed is the thermal and mechanical influence of the deposited coating on the internal combustion engine piston when subjected to gas pressure and thermal loading.

## 2. Experimental procedure

The considered samples were made of an aluminum-magnesium alloy usually used for the manufacturing of internal combustion engine pistons. Each sample had the dimensions of 30×50×2 mm. For a better adhesion between the base material and the top layer, a NiCr bonding intermediate layer was first deposited on the samples. Both the NiCr and $Al_2O_3$ coatings were deposited by atmospheric plasma spraying. The deposition parameters that were used on the plasma spraying installation are described in Table 1.

*Table 1. Deposition parameters*

| Powders | NiCr | $Al_2O_3$ |
|---|---|---|
| Spraying distance [mm] | 120 | 120 |
| Plasma gas intensity [A] | 600 | 600 |
| Arc voltage [V] | 62 | 65 |
| Argon flow [$m^3$/h] | 50 | 40 |
| Hydrogen flow [$m^3$/h] | 10 | 14 |

The samples were subjected to high temperatures in a furnace. The samples were heated at 400 ºC, 500 ºC and 600 ºC for a period of 4 hours and after that cooled naturally to room temperature. For each temperature a different sample was used. Both X-ray diffraction and scanning electron microscopy analyzes were carried out on the samples to show the influence of the thermal exposure on the phases and microstructure of the deposited layers.

For a better understanding of the behavior of a real piston with ceramic coating, a finite element analysis was done. The model consisted of two parts: the piston and the coating. The contact between them was considered as bonded with a pure penalty formulation. The analysis was performed using the Ansys 13 software.

## 3. Results for samples subjected to thermal loading

To better highlight the effects of the thermal exposure on the coating the first analysed sample is the one not subjected to temperature and the results of the SEM analyses are presented in Fig. 1. The deposited coating has a structure composed of consecutive grains which are usually called splats because of their geometry. The splat geometry is caused by the conversion of the high kinetic energy of the particles during the deposition process into shape changing energy when the particle reaches the surface [14]. During the deposition pores also form at the interface of successive splats. Because the layer is thick and is composed of splats deposited successively, cooling takes place at different rates inside the material and residual stress is accumulated following the process of thermal spraying. For this reason the ceramic layer structure presents cracks at the interface of consecutive splats and inside the splats. When the cracks propagate and meet obstacles, such as pores or other cracks, they tend to connect and form new pores.

In Fig. 1 b), which is done at a higher magnification, we can observe a separation between the columnar splat formations. The micro-cracks that formed during the cooling of the deposited coating led to the release of the accumulated internal stress.

Fig. 2 shows the results obtained from the XRD

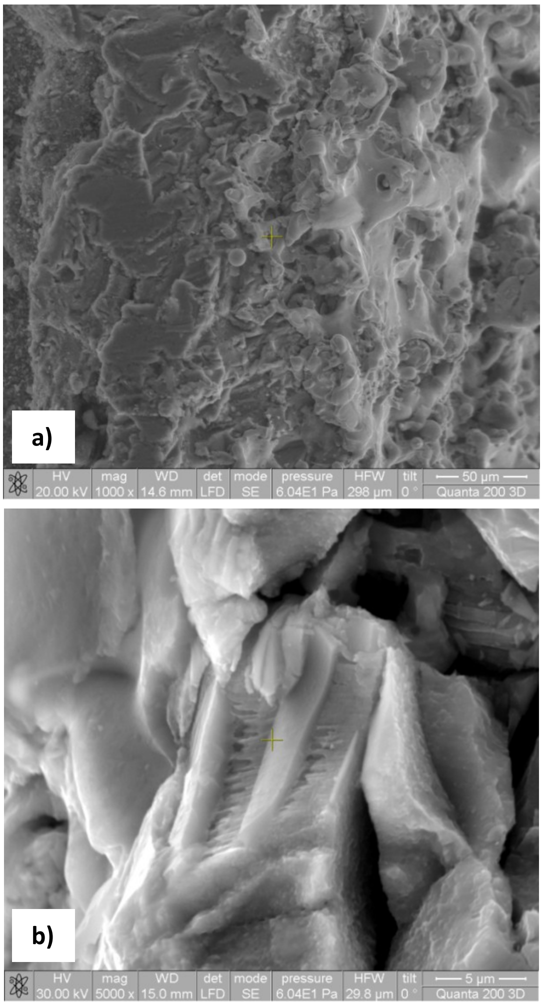


*Fig. 1. The SEM analyses on the sample with an $Al_2O_3$ coating not subjected to high temperature: a) coating at 1000×; b) coating at 5000×.*

analysis done on the sample not subjected to high temperature. The Al phase, crystallized in a cubic lattice, is characteristic for the base material and appears due to the porosity of the deposited coatings. The bond coating is formed by the $Al_{0.14}Ni_{0.86}$ phase crystallized in a cubic lattice. This phase also appears due to the porosity of the coating. The crystal lattice of the $Al_2O_3$ layer, following the plasma jet deposition, has the parameters $a$ = 4,98 Å, $b$ = 4,98 Å and $c$ = 4,98 Å and is rhombohedral.

The results obtained for the sample subjected to a temperature of 400 ºC for a period of 4 hours is presented in Fig. 3. Fig. 3 a) is done at a magnification of 1000× and shows an increase of the pores dimensions compared to the initial sample. The pores with the highest dimension appear at the interface between the deposited coatings and the base material. These pores are produced by the different thermal expansion of the materials which causes an increase of the existing pores dimensions and also additional crack propagation. The bond coating shows a higher compaction then the initial one. At a higher magnification it is revealed that the interfaces between consecutive splats increased in dimension which leads to a higher level of fragmentation of the top coating (Fig. 3 b).

The fragmentation is caused by the individual thermal expansion of each splat.

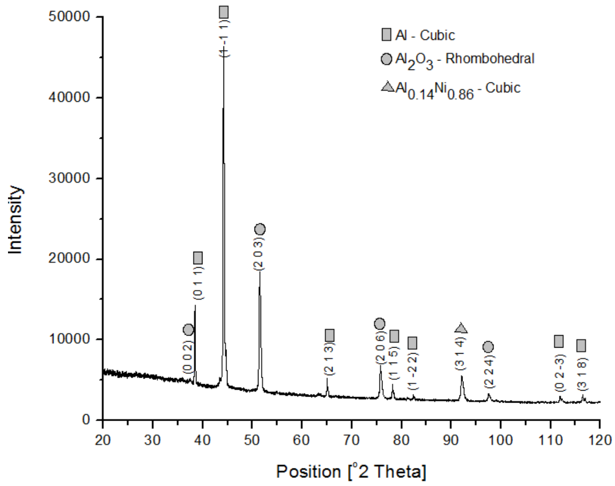


*Fig. 2. X-ray diffraction of the sample with $Al_2O_3$ coating not subjected to high temperature, scan range: 2θ = 20…120°.*

When heated, the splats increase their volume linearly which produces mechanical stress between neighbouring splats and additional crack propagation. After cooling the splats decrease their volume but the produced cracks remain.

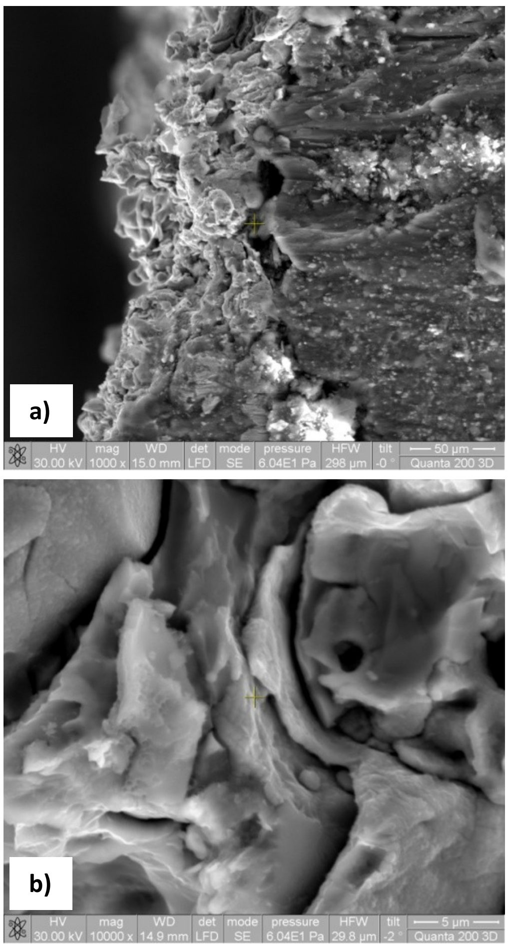


*Fig. 3. The SEM analyses on the sample with an $Al_2O_3$ coating subjected to a temperature of 400 ºC: a) coating at 1000×; b) coating at 5000×.*

The XRD analysis done on the sample subjected to a temperature of 400 ºC is presented in Fig. 4. The Al phase doesn't appear any more in this analysis fact which confirms the compaction of the bond coating. The $Al_2O_3$ phase that was initially crystallized in a rhombohedral lattice changed into an orthorhombic lattice.

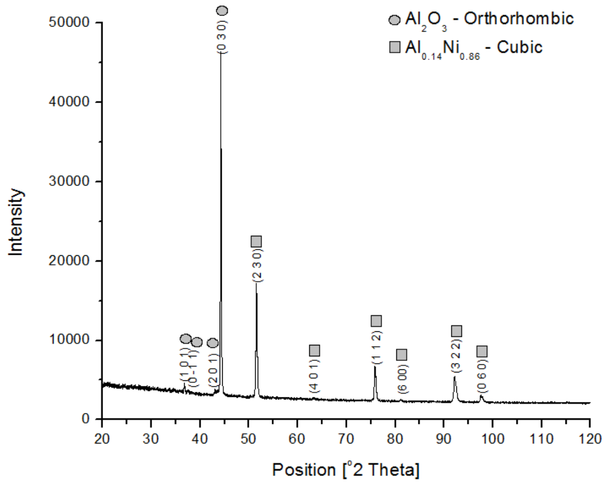


*Fig. 4. X-ray diffraction of the sample with $Al_2O_3$ coating subjected to a temperature of 400 ºC, scan range: 2θ = 20…120°.*

The SEM results for the sample subjected to a temperature of 500 ºC are presented in Fig. 5.

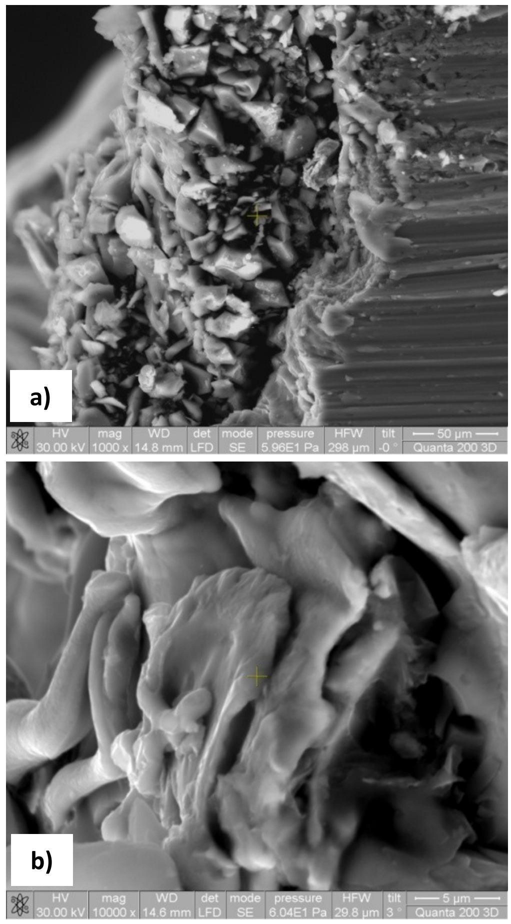


*Fig. 5. The SEM analyses on the sample with an $Al_2O_3$ coating subjected to a temperature of 500 ºC: a) coating at 1000×; b) coating at 5000×.*

The fragmentation of the top coating becomes evident at a magnification of 1000×. The interfaces between consecutive splats increased their size with a higher value. At the boundary between the base material and bond layer the pores increased their size but also cracks appeared which linked the formed pores. At a magnification of 10000× the deposited top coating shows a higher level of fragmentation due to the increase of pore dimensions and also due to crack propagation (Fig. 5 b).

The XRD analysis presented in Fig. 6 was done for the sample subjected to a temperature of 500 ºC. The compactness of the bond coating characterizes this sample also due to the absence of the Al cubic phase in the XRD pattern. $Al_2O_3$ phase also changes from the rhombohedral lattice of the initial coating to an orthorhombic lattice.

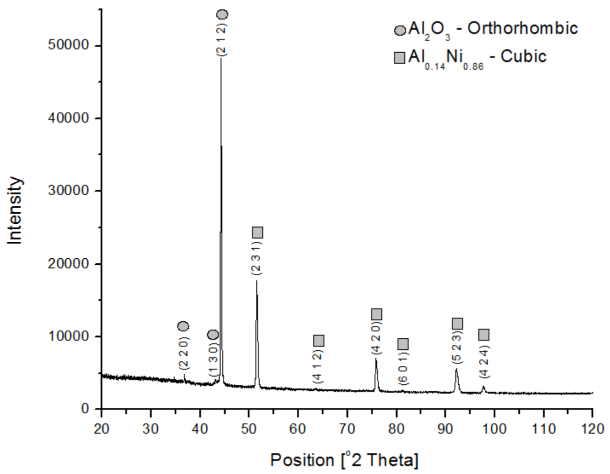


*Fig. 6. X-ray diffraction of the sample with $Al_2O_3$ coating subjected to a temperature of 500 ºC, scan range: 2θ = 20…120°.*

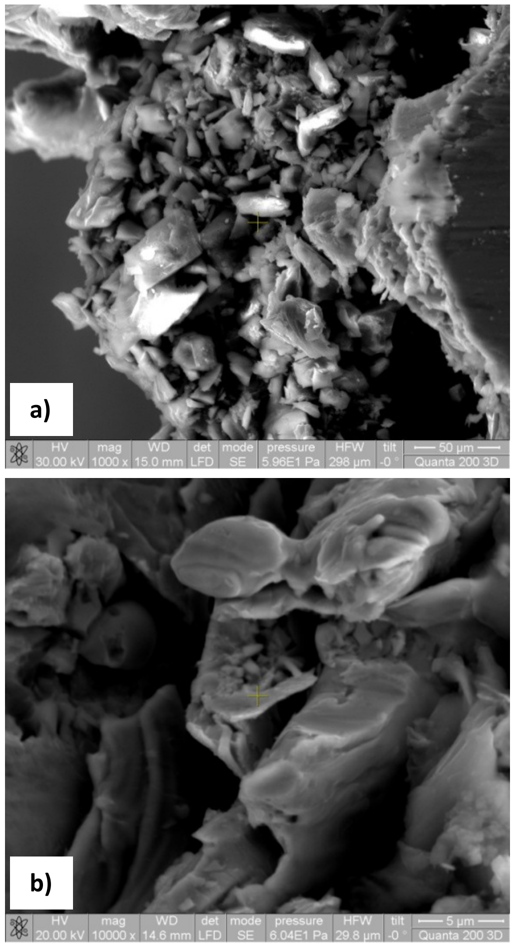


*Fig. 7. The SEM analyses on the sample with an $Al_2O_3$ coating subjected to a temperature of 600 ºC: a) coating at 1000×; b) coating at 5000×.*

For the samples subjected to a temperature of 600 ºC for 4 hours the SEM results are showed in Fig. 7. The fragmentation of the top coating is even more increased then for the previous samples and with a higher size of the interfaces between consecutive splats. The pores present between successive splats are dominant inside the layer. The pores that appear at the interface between the base material and deposited coatings are higher and the cracks fully connected the neighbouring splats. At a magnification of 10000× the increase of the pores between successive splats becomes more evident (Fig. 7 b). The fragmentation of the deposited coating increased even more for the sample subjected to temperature of 600 ºC.

From the constituent phase point of view, by increasing the temperature to 600 ºC no more significant changes occur in the sample. The Al cubic phase from the initial sample is not present and the $Al_2O_3$ rhombohedral phase changes to $Al_2O_3$ orthorhombic phase (Fig. 8).

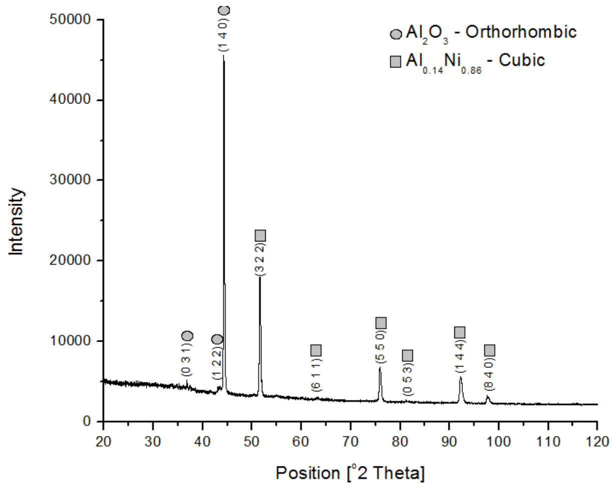


*Fig. 8. X-ray diffraction of the sample with $Al_2O_3$ coating subjected to a temperature of 600 ºC, scan range: 2θ = 20…120°.*

## 4. Results for the finite element analysis on the piston

The purpose of the finite element analysis was to obtain an assessment of the thermal and mechanical behaviour of an internal combustion engine piston. For the analysis, a 3D model of the piston with the coating placed only on the upper surface of the piston head was used. The mesh that resulted for the analysed piston is presented in Fig. 9 and consists of tetrahedral elements. The mesh used for the analysis is composed of 103,773 nodes with 65,302 elements for the piston and 21,588 nodes with 3030 elements for the coating.

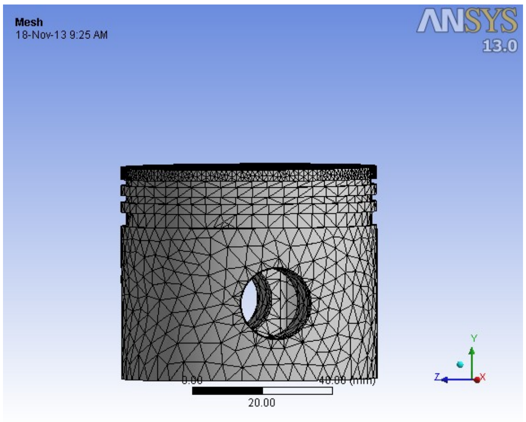


*Fig. 9. Mesh network of the piston with top coating.*

Two analyses were done to assess the performance of the piston. The first one considered only the mechanical loading of the piston as a result of the maximum thermal cycle pressure usually achieved in an internal combustion engine and the second analysis considered both the mechanical and thermal loading of the piston. The pressure loading considered in the analysis had a value of 4 bar and the thermal loading considered a maximum value of the flue gas of 700 ºC.

The results for the piston with coating and subjected to pressure are presented in Fig. 10.

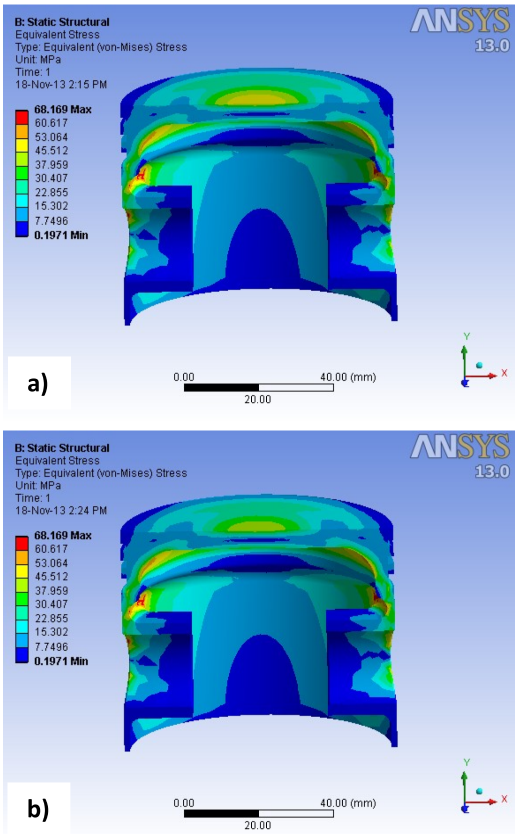


*Fig. 10. Equivalent stress distribution for the piston with an $Al_2O_3$ layer: a) with top layer; b) with hidden layer.*

The images show the equivalent stress distribution. The equivalent stress is calculated with the von Misses equivalence theorem which provides a correspondence between a complex state of stress consisting of normal and tangential stresses and a normal stress state which presents the same risk level. In the case of the piston with an $Al_2O_3$ top layer applied on the working surface, the maximum equivalent stress occurs in the connecting rod bore area of the piston pin and has a value of 68.17 MPa. In the deposited coating, the maximum equivalent stress has a value of 53.06 MPa (Fig. 10 a). In the piston head area the base material shows a maximum stress of 45.51 MPa (Fig. 10 b).

In Fig. 11 is presented the temperature distribution that occurs in the piston with a layer of $Al_2O_3$ deposited on the upper surface of its head. The flue gas temperature was considered 700 °C. The cooling system fluid was considered at a temperature of 110 ºC.

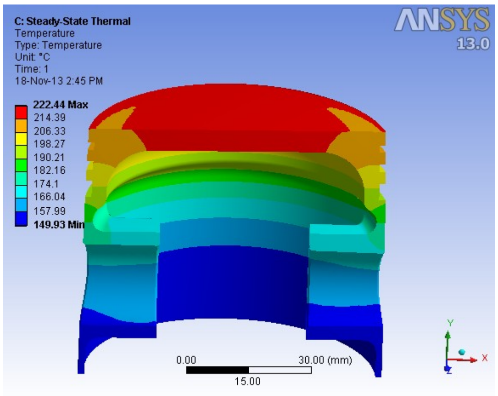


*Fig. 11. Thermal distribution in the piston with an $Al_2O_3$ top coating.*

The maximum temperature appears in the piston head area and has a value of 222.5 ºC. This is also the maximum temperature of the $Al_2O_3$ coating. The temperature of 222.5 ºC reaches the inner surface of the piston head.

The results for the thermo-mechanical coupled analysis are presented in Fig. 12. The maximum equivalent stress has a much higher value in the connecting rod bore area due to the thermal expansion of the aluminium base material. The stress that appears in the area of the piston head has a much lower value then in the previous case. This happens due to the higher stiffness in the piston head area. The higher stiffness is produced by the deposited coating. Maximum equivalent stress that occurs in the deposited coating has a value of 177.8 MPa (Fig. 12 a). In the base material (Fig. 12 b) the maximum equivalent stress has a value of 228.4 MPa and appears in the region connecting rod bore.

## 5. Discussion

The deposition of an $Al_2O_3$ coating on an aluminium-magnesium alloy base material can have limitations

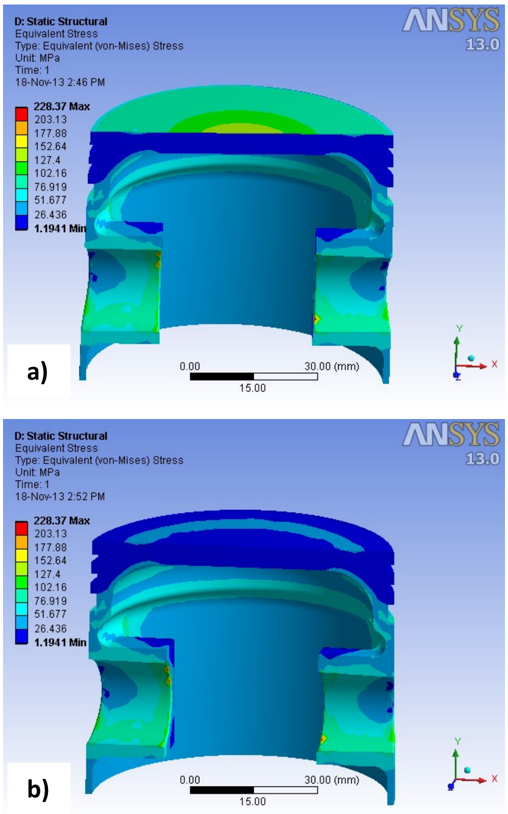


*Fig. 12. Equivalent stress distribution for the piston with an $Al_2O_3$ layer under thermo-mechanical coupled loading: a) with top layer; b) with hidden layer.*

according to the maximum working temperature of the part. Rising the working temperature can lead to high dimensions pores and cracks at the interface between the coating and base material. Also the top coating shows an increase in fragmentation with the increase of the working temperature. These factors can lead to the coating failure.

The mechanical and thermal behaviour of an internal combustion engine piston can be improved by applying a top ceramic coating. The improvement consists of an increase in the piston head stiffness which leads to lower strain and also protection of the base material from thermal and mechanical fatigue.

## 6. Conclusions

The atmospheric plasma spraying of an $Al_2O_3$ coating on an aluminium-magnesium alloy can be a practical option for improving internal combustion engine pistons behaviour if the maximum material temperature doesn't exceed 500 ºC. In this temperature range the coating can insure a good thermal protection and also enhances the stress behaviour of the part.

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