THERMO-MECHANICAL ANALYSIS OF SPRAYED LAYERS USING THE FINITE ELEMENT METHOD

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ABSTRACT

The present paper presents an analysis performed in order to determine the thermo-mechanical behavior at the layer-substrate interface in case of thermal spraying, by using the ANSYS R15.0 software. The analysis was made on high alloyed steel samples thermal sprayed on one side. For the 1st sample, the material used for the deposited layer was ZrO_2 stabilized with Y_2O_3 (ZrO_2+20% Y_2O_3) using the HVOF process. The 2nd sample was sprayed with stellite using the plasma spraying process. This analysis follows the idea of temperature distribution along with the other characteristics that define the thermal state in an object: the heat quantities released or absorbed, thermal gradient and thermal flow. In order to determine the causes of thermal expansions or contractions, the analysis is followed by a stress analysis. The obtained results show that the interface stresses are lower in the case of stellite coating, both steel and stellite having closer thermo-physical characteristics than steel and YSZ also including the intermediate layer.

KEYWORDS: reconditioning, sprayed layer, bond coat, stellite, thermal shock

1. Introduction

Metal spraying reconditioning is a method of remaking the nominal dimensions of the part by deposing additional material melted particles on the work piece surface. The purpose is to obtain improved properties of the deposited layers thanks to special materials which can be sprayed [1].

The chosen material, used for reconditioning, needs to have better mechanical features and the reconditioned part will be up to two or three times more resistant to wear, fatigue or corrosion, depending on the application [1].

The reconditioned parts, obtained through material deposition, are made of two distinct components, the basic material and the sprayed layer.

In terms of chemical composition, thermo-physical properties and the behavior to mechanical and thermal stresses, these two components usually have totally different expansion and contraction coefficients. This way, the risk of developing internal stresses which can compromise the entire structure appears [1].

The **HVOF** (High Velocity Oxygen Fuel) is a thermal spray process which utilizes a combination of oxygen with various fuel gases including hydrogen, propane, propylene, hydrogen and even kerosene (Figure 1). Fuel and oxygen mix and atomize within the combustion area under conditions that monitor the correct combustion mode and pressure [1, 2].

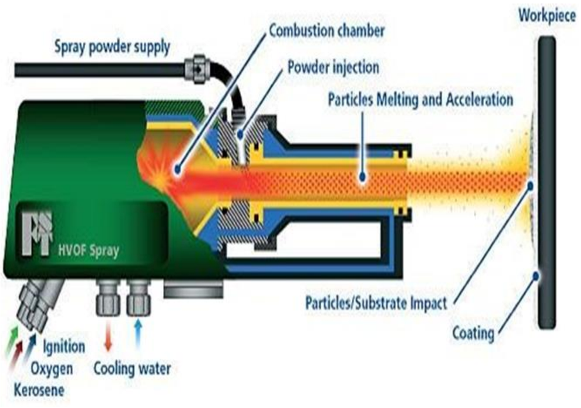

***Fig. 1.** Schematic of HVOF Combustion Chamber* [2]

The process creates a very high velocity which is used to propel the particles at supersonic speeds before impact onto the substrate.

One of the key benefits of this system’s high velocity is the extremely high coating density and low oxide content. The low oxides are due partly to the speed of the particles spending less time within the heat source and partly due to the lower flame temperature (around 3000 °C) of the heat source compared with alternative processes.

The **plasma spraying** process involves the latent heat of ionized inert gas being used to create the heat source, which melts the coating material and propels it to the work piece (Figure 2). The most common gas used to create the plasma is argon. Helium tends to expand the plasma and when used in combination with argon produces a “high velocity plasma” that exits the nozzle at about 488 m/sec. [1, 2].

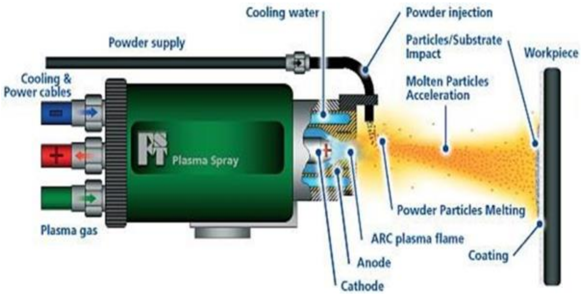

Fig. 2. *Plasma Spray Process* [2]

In commercial technology, plasmas are considered as hot streams of particles reaching temperatures higher than 10 000 °C. Today’s plasma spray guns are sufficiently robust to produce temperatures from 5000 °C to 16 000 °C for long time periods [1].

2. Experimental part

2.1. Data entry

In the case study presented below, the thermo-mechanical behavior at the layer-substrate interface in case of thermal spraying is highlighted.

The experiment started with the increase of the wear resistance of the steam turbine blades subjected to harsh conditions of high temperature and cavitation/erosion caused by the steam condensate. In order to perform the analysis, high alloyed steel samples X22CrMoV12-1 for turbine blades, thermal sprayed on one side were chosen.

The two X22CrMoV12-1 plates have the dimensions (XxYxZ) 100x60x5 millimeters. For sample no.1, the deposition was made in three steps: first was added a bond-coat of Sultzer Metco Amdry 997 powder of 0.01 mm thickness, secondly was deposed an intermediate layer of Zirconia stabilized pseudo-alloy ceria-yttrium, 0.01 mm thickness and thirdly the material used for the top coat was ZrO_2 stabilized with Y_2O_3 (ZrO_2+20% Y_2O_3) metal-sprayed using HVOF process, this layer being 0.3 mm thick (Figure 3).

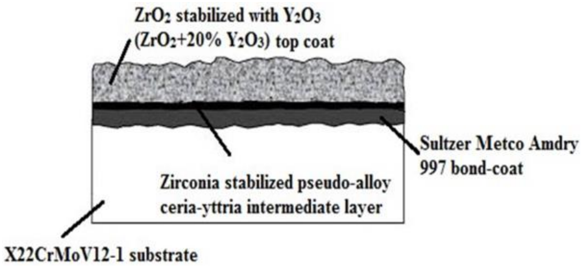

Fig. 3. *No. 1 specimen section*

Sample no. 2 (represented in Figure 4) was sprayed with Stellite 6 powder using the plasma spraying process. This layer is 0.3 mm thick.

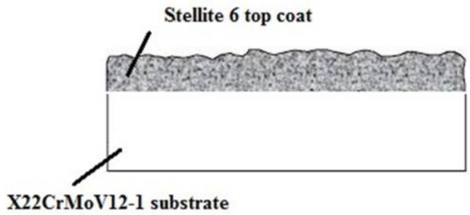

Fig. 4. *No. 3 specimen section*

2.2. ANSYS R15.0 data processing and results

Once the volumes of the entire studied structures defined, the characteristics and properties for each material were assigned and the next step - discretization of the structures – was defined like in Figure 5.

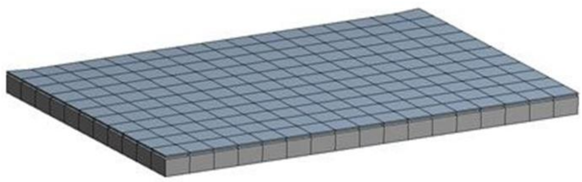

Fig. 5. *Structure discretization*

Figure 6 shows the block diagram of the simulation, containing the thermal and structural transient of the two analyzed specimens.

Fig. 6. *Block diagram of the simulation*

In choosing a material, to create a new one or to modify an existing material found in the library workbench, the module Engineering Data of ANSYS R15.0 was accessed (Figure 7) [5, 6].

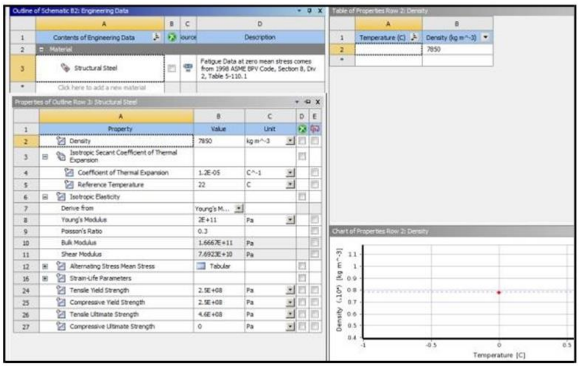

Fig. 7. *Engineering Data module*

The material characteristics of the high alloyed steel X22CrMoV12-1 taken into account for running the finite element analysis are presented in Table 1 [3, 4].

Table 1. *X22CrMoV12-1 characteristics*

	Properties	Values	Unit of measurement
X22CrMoV12-1	Density	7700	kg m^-3
	Thermal conductivity	47.9	W m^-1 K^-1
	Heat capacity	460	J kg^-1 K^-1
	Thermal expansion coefficient	12.1 e-006	K^-1
	Young’s Modulus	200 e+09	Pa
	Poisson’s ratio	0.3	-

In Table 2 are presented the material characteristics of ZrO_2 stabilized Y_2O_3 [3, 4].

Table 2. *ZrO_2 stabilized Y_2O_3 characteristics*

	Properties	Values	Unit of measurement
ZrO_2 stabilized Y_2O_3 (ZrO_2+20 % Y_2O_3)	Density	6600	kg m^-3
	Thermal conductivity	2.2	W m^-1 K^-1
	Heat capacity	540	J kg^-1 K^-1
	Thermal expansion coefficient	6 e-006	K^-1
	Young’s Modulus	160 e+09	Pa
	Poisson’s ratio	0.32	-

The material characteristics of Stellite 6 are presented in Table 3 [3, 4].

Table 3. *Characteristics of stellite 6*

	Properties	Values	Unit of measurement
Stellite 6	Density	7800	kg m^-3
	Thermal conductivity	55	W m^-1 K^-1
	Heat capacity	456	J kg^-1 K^-1
	Thermal expansion coefficient	6.6 e-006	K^-1
	Young’s Modulus	195 e+09	Pa
	Poisson’s ratio	0.32	-

The two structures are kept at an environmental temperature of 22 °C.

In Figure 8 below is presented the thermal shock testing diagram depending on time. This was scheduled in 3 steps, as explained below.

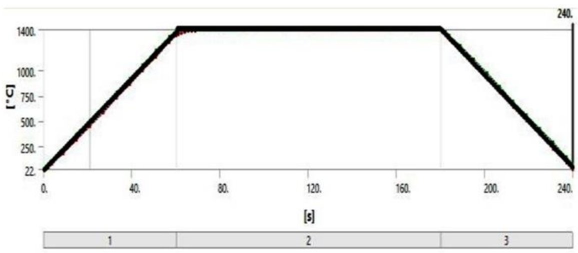

Fig. 8. *Temperature Graph depending on time*

In the first part of the experiment, each of them is submitted to a thermal shock, the heat source being oriented towards the sprayed layer (Figure 9). In 60 s the pieces are brought to 1400 °C, then maintained for 120 s at this constant temperature of 1400 °C.

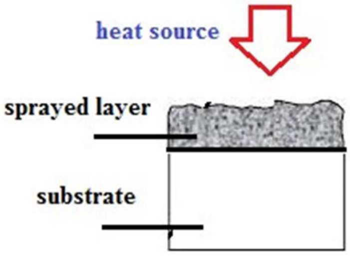

***Fig. 9.** Heat source principle scheme*

In the last part of the experiment a sudden cooling in air jet was applied to the structures, thus the parts being brought back at ambient temperatures of 22 °C within 60 seconds.

From the beginning of the cycle heat-cold in specially heating, we can observe the minimum and maximum tensions from the interface between the basic material and the deposited one.

The equivalent stresses for plate no. 1 sprayed with ceramic are in a range of 0.8-3200 MPa (Figure 10).

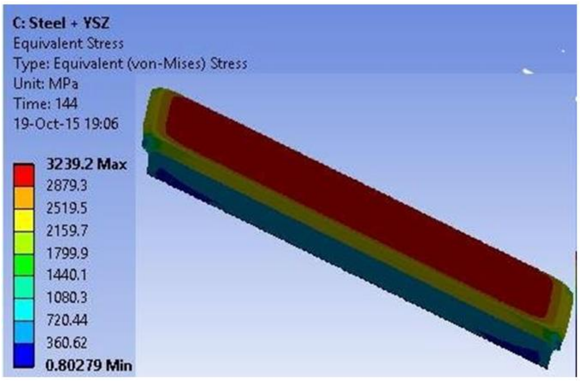

***Fig. 10.** Equivalent stresses (von-Mises) steel + YSZ*

On the other hand, the range of equivalent stresses in the stellite coated plate is 0-22.8 MPa (Figure 11).

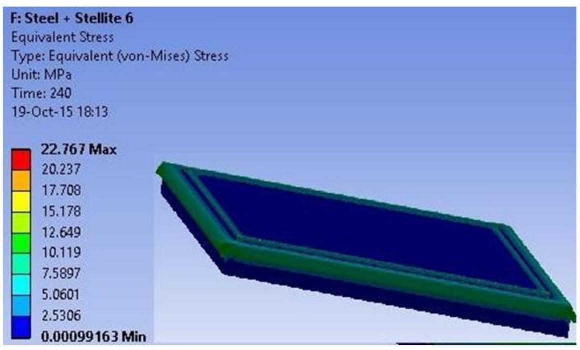

***Fig. 11.** Equivalent stresses (von-Mises) steel + stellite*

Regarding the characteristics that define the thermal state in object, we could observe that the total heat flux reaches a maximum value of 0.433 W/mm^2 in the steel-stellite structure (Figure 12).

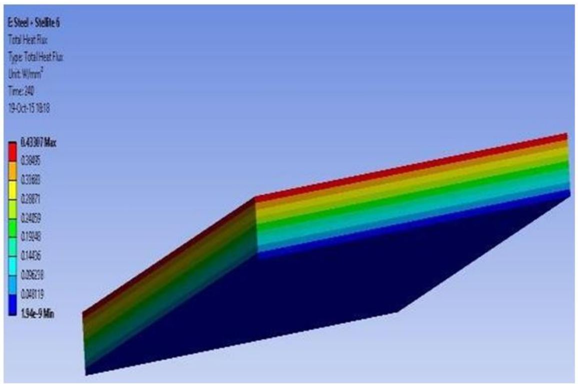

***Fig. 12.** Total heat flux steel + stellite*

An almost insignificant difference can be observed in the case of steel-ceramic specimen, where the maximum heat flux value is 0.433 W/mm^2 (Figure 13).

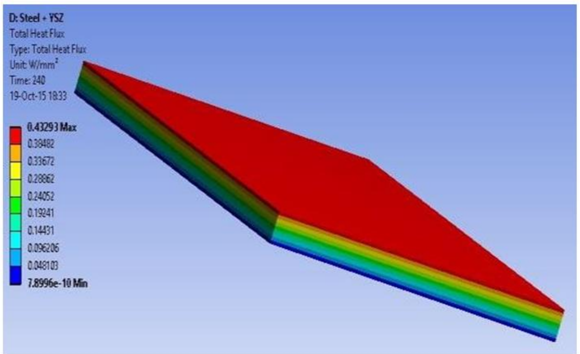

***Fig. 13.** Total heat flux steel + ceramic*

A graph of total heat flux in the steel-stellite structure depending on time was generated, as can be seen in Figure 14 below.

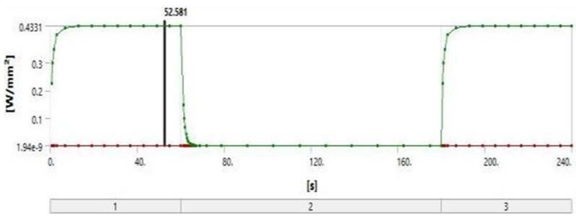

***Fig. 14.** Steel-stellite total heat flux depending on time*

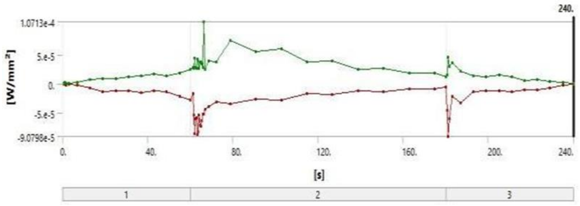

Fig. 15. *Steel-stellite directional heat flux in X*

At the end of the 3rd stage, after cooling the structures, the difference of temperature at the interface between the top coating and the basic material can be observed. If zirconia is used, 22 ºC were indicated at the surface, the intermediate layer went up to 79 ºC, then, at the level of the steel, the structure's temperature was 100 ºC (Figure 16).

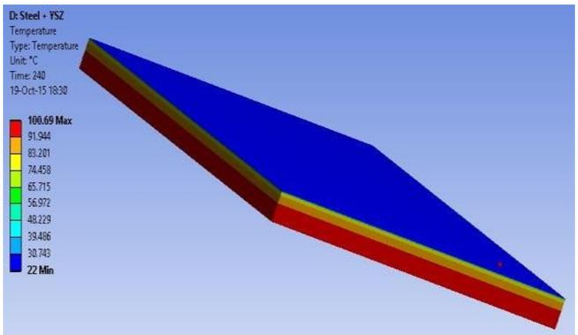

Fig. 16. *Steel-YSZ temperature after cooling*

At the steel-stellite interface, the structure reached a temperature value of 24 ºC. Then, at the base of the high alloyed steel plate, it gets up to 45 ºC (Figure 17).

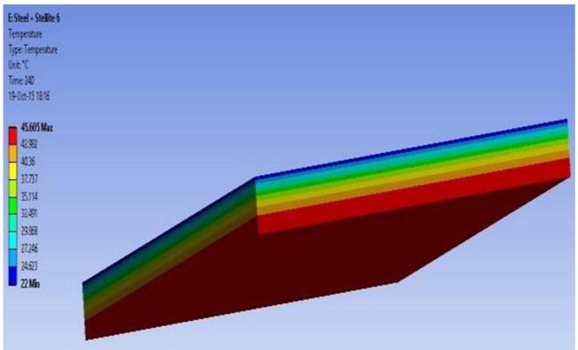

Fig. 17. *Steel-stellite temperature after cooling*

3. Conclusions

Conclusion (1). By the FEM analysis, applied through the ANSYS software, we could understand and interpret the thermo-mechanical phenomena that take place at the basic material – sprayed layer interface.

Conclusion (2). The obtained results show that the interface stresses are lower in case of stellite coating, both steel and stellite having closer thermo-physical characteristics than steel and YSZ also including the intermediate layer.

Conclusion (3). The low thermal conductivity of the ceramic layer does not allow for fast transmission of temperature. Ceramic has a smaller heat variation than steels. As time passes, the temperature curve flattens.

Conclusion (4). An optimization of the technological process of metal spraying, adapted to the requested working conditions in different situations of operating can be achieved through modifying the layer's thickness.

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