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Innovative solutions for roughness problems related to MCrAlY coatings manufacturing by HVOF II: Bond Coat/Top Coat Interface

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Abstract

MCrAlY (where M is Ni, Co or NiCo) coatings are used as single overlay coating or as bond coat for thermal barrier coating (TBC) systems. Vacuum plasma spray (VPS) MCrAlY coatings are considered state of the art today. Nevertheless high velocity oxygen fuel (HVOF) sprayed MCrAlY coating is gaining in popularity due to its quality and cost effectiveness. On the other hand HVOF process has some limits: It requires heavy sand blasting of the substrates to obtain an adequate base metal roughness for the good adhesion of the deposited MCrAlY coatings and this causes a high interface pollution. Moreover, HVOF process allows to obtain relatively low surface roughness of the MCrAlY coatings, which leads to a poor adhesion of the ceramic yttria partially stabilized zirconia (YPSZ) top coat. Studies performed by the authors tried to resolve these two problems by providing an adequate pollution free interface between substrate and coating and a rough surface of the HVOF coating in order to be used as bond coat for overlaying TBC coating.

This paper is the second part of two and addresses the developments of new MCrAlY HVOF deposition process, in order to obtain a rough MCrAlY coating to be used as bond coat for YPSZ top coat. Optical and electronic microscopies were used to evaluate the quality of the obtained coating, in comparison with the standard dense one. Air plasma spray (APS) was used to apply TBC systems on blades and vanes coated by the enhanced HVOF MCrAlY bond coat. TBC coated blade and vane sections successfully passed thermal fatigue tests following the procedure of an important original equipment manufacturer (OEM).

Key words: MCrAlY, HVOF, thermal barrier coating, interface, sand blasting

1. Introduction

The development of more efficient gas turbines for aircraft propulsion and power generation has always been related to the results of research in the concurrent fields of design and materials technology. Increases in temperature and therefore in efficiency led to a wide use of thermal spray coatings in order to improve the surface characteristics of the structural superalloys.

Namely the systems called TBCs (thermal barrier coatings) consist of air plasma sprayed top coat of (6–8 wt.%) Y_2O_3, partially stabilized ZrO_2 and MCrAlY bond coat (where M is Ni, Co or NiCo) deposited by different thermal spray processes.

Usually, the specifications of the main OEMs (original equipment manufacturers) require the deposition of MCrAlY alloys by low pressure plasma spray (LPPS) or vacuum plasma spray (VPS). Other methods such as air plasma spray (APS) and high velocity oxygen fuel (HVOF) may be desirable for their lower cost.

HVOF coating is today under evaluation as alternative for the LPPS/VPS process. The HVOF process shows some advantages such as the lower cost for the installation and maintenance of the plants and the similar coating quality [1–3].

On the other hand, at the state of the art, HVOF process, used for deposition of MCrAlY coatings, shows some disadvantages:

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– a final coating richer in oxides in comparison with LPPS/VPS MCrAlY coating,

– the necessity of heavy sand blasting of the substrates to guarantee a good coating adhesion, but this leads to high pollution of the interface between coating and substrate [4–6],

– a relatively low surface roughness of MCrAlY coatings deposited by HVOF, which makes it difficult to be used as bond coat for TBC, therefore having limitations to the exploitation of HVOF as extensive MCrAlY deposition process [5, 6].

The developments performed by the authors were aimed to overcome these problems and are reported in two papers, of which this is the second part, and it addresses the development of a new MCrAlY HVOF coating with enhanced roughness, to be used as bond coat for TBC coating.

The above mentioned disadvantage of HVOF process for the manufacturing of MCrAlY bond coat for TBC systems is the relatively low coating surface roughness, which hinders the possibility to act as bond coat for a TBC coating layer.

Several methods exist to overcome this problem, for example:

– to coat a bi-layer, the first dense, thick and non-rough by HVOF, the second thin, porous and rough using APS followed by a heat treatment [5],

– to coat a bi-layer, the first dense, thick and non-rough, the second thin, porous and rough using MCrAlY powder mixed with a plastic filler (polyester 5–15 % in wt.%) [6],

– to adjust the torch parameters in order to obtain higher roughness with the commercial available liquid fuelled torch: this leads to an increasing of the average roughness (to Ra of 9–11 μm) but does not allow to get a good morphology. The particles are rounded and the TBC attach on rounded edges, what is not ideal for a good adhesion.

The present study leads to the development of a process based on the modification of the HVOF parameters, as the torch characteristics and functional variables such as gases, flows, etc. The final MCrAlY coating is a bi-layer: the first layer is dense, thick and non-porous, the second is thin, porous and roughly deposited by a newly developed process. No interruption between the deposition of the two layers was necessary to obtain the desired coating.

Surface roughness of the MCrAlY coating has been obtained with Ra greater than 10 μm and has been applied on several blades and vanes to test the repeatability of the results on complex shape substrates.

2. Experimental

For the development of rough MCrAlY bond coat deposited by HVOF, in the first trials, pieces of mild steel welded onto a commercial blade were used as substrate material to optimize the proprietary deposition process. Final deposition tests were carried out using a commercial stage 2 blade made in Inconel 738 LC. The surface preparation was done by corundum blasting leading to a substrate roughness of $Ra = 3$–6 μm. The process used to deposit the dense and rough HVOF coating is not disclosed here due to industrial privacy rights. A specific proprietary powder (NiCrAlY) was used as requested by the proprietary OEM to coat the stage 2 blade. Commercial YPSZ ($ZrO_2/8Y_2O_3$) powder (827.7 H.C. Starck) was used for the deposition of ceramic top coat by Air Plasma Spray process.

The coated blade was sectioned in order to obtain metallographic mounts to be submitted to characterization by optical microscopy in order to determine the characteristics of the HVOF/TBC system. Two different kinds of metallographic preparation were used to reveal the microstructure of the metallic HVOF bond coat and ceramic APS top coat according to [1]. Furthermore, micrographic examination and microprobe analysis were performed by means of SEM microscope. The bond coat roughness was evaluated by the above mentioned stylus profilometer with a cut-off of 2.5 mm (with 12.5 mm of measurement length).

LPPS/VPS MCrAlY coatings are nowadays considered to be state of the art for the bond coat deposition. The results of the metallographic analysis as well as the roughness measurements obtained on the HVOF coated blade were compared with the ones obtained on a standard LPPS coated blade.

A mid-aerofoil segment was sectioned out from the coated stage 2 blade and submitted to the thermal shock (TCF) cycle according to the specified procedure.

Samples extracted from the treated blades and vanes were submitted to the following thermal shock (TCF) cycle, applied 1000 times:

– rapid heating of coated samples to about 1000 ℃,

– hold time at 1000 ℃ for 5 min,

– rapid cooling to room temperature,

– hold time at room temperature for 5 min.

The failure criterion was the spallation of the coating within 1000 TCF cycles according to the OEM specification with the exception of the edge zones [7, 8]. In fact, the first cracks are often observed at the extreme edges of the samples. It is due to the extreme heating and cooling conditions encountered at the edges [7, 8] but it is not correlated with the objective thermal fatigue resistance. The test piece was exposed to 1000 cycles with intermediate visual inspections after 1, 3, 5, 30, 100, 200, 300, 500, 700, 1000 cycles.

In order to apply to an actual component the complete HVOF coating developed during this study, a stage 2 vane was coated with the following cycle:

– Surface preparation performed by eXclean method (see the first paper of this study),

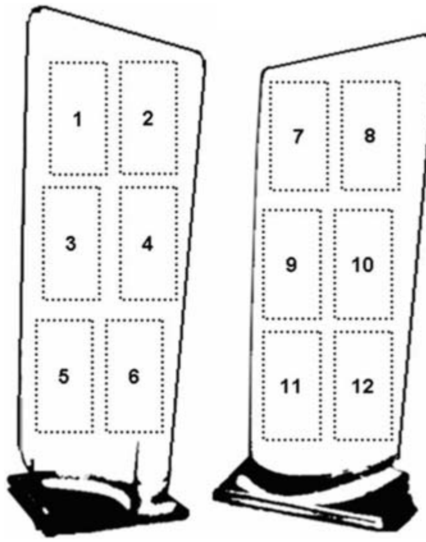

Fig. 1. Schematic representation of the HVOF and LPPS coated blade with areas indicated where roughness measurements were performed.

Table 1. Roughness measurements performed on the HVOF and LPPS coated blade with the relative standard deviation

Roughness measurements	NiCrAlY HVOF Coating *Ra* (μm)	NiCrAlY LPPS Coating *Ra* (μm)
Zone 1	13.95 ± 0.64	12.56 ± 0.50
Zone 2	13.52 ± 0.97	13.15 ± 0.79
Zone 3	14.65 ± 0.63	13.17 ± 0.58
Zone 4	11.77 ± 0.64	12.68 ± 0.56
Zone 5	12.51 ± 0.60	13.21 ± 0.64
Zone 6	12.48 ± 0.43	13.05 ± 0.73
Zone 7	13.60 ± 0.57	12.43 ± 0.19
Zone 8	13.56 ± 0.41	13.11 ± 0.34
Zone 9	14.63 ± 0.25	13.13 ± 0.27
Zone 10	11.65 ± 0.95	12.76 ± 0.32
Zone 11	12.51 ± 0.33	13.22 ± 0.81
Zone 12	12.84 ± 0.47	12.07 ± 0.88
Average roughness	13.14 ± 1.00	12.88 ± 0.37

– MCrAlY bond coat deposition by HVOF,
– Diffusion heat treatment,
– TBC coating (300 ± 100 μm of thickness).

Thermal shock (TCF) test has been executed on this component, too, in order to test the complete package object of the study and presented in this paper and in the first part.

3. Rough HVOF process set-up results

3.1. Characterization

The roughness measurements were performed on a rough HVOF MCrAlY bond coat in 12 different areas of the coated stage 2 blade as shown in the sketch of Fig. 1 (the coated blade was represented as a sketch in order to respect industrial privacy rights of the blade manufacturer). The collected values of roughness are summarized in Table 1, where values of roughness registered for an LPPS coated blade in the same areas are shown for comparison.

HVOF surface coating shows an average *Ra* value of 13.14 μm with a standard deviation of 1.00 μm, completely comparable with the one obtained by the LPPS deposited coating. The LPPS roughness resulted in a *Ra* of 12.88 μm with a standard deviation of 0.37 μm.

The metallographic analysis was performed in order to determine thickness and structure of the coatings. Figure 2 shows the cross section from the leading edge of the HVOF/TBC coated blade and Fig. 3 shows the cross section of the trailing edge of the same blade. These cross sections were polished to reveal the micro-

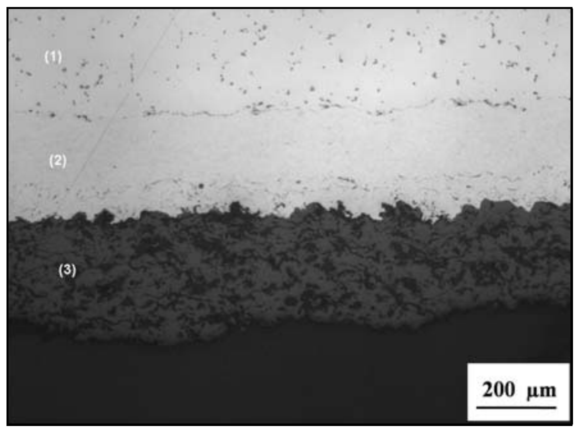

Fig. 2. Cross section from the leading edge of the HVOF/TBC coated blade (metallographic preparation for the analysis of the MCrAlY bond coat): (1) substrate, (2) HVOF bond coat and (3) YPSZ top coat.

structure of metallic bond coat layers. It is possible to observe that bond coat is formed by two layers: the first is dense and well adhering to the substrate, the outer layer is more porous and constitutes the rough surface where the ceramic coating adheres. The bond coat thickness ranges from 170 to 250 μm with porosity in a range of 0.3–0.5 % for the dense HVOF coating and a porosity of 2–5 % for the rough and porous HVOF coating as shown in Figs. 2, 3 and 5.

Figure 4 shows the cross section of the trailing edge of the APS TBC coated blade. This cross section was polished to reveal the microstructure of ceramic top

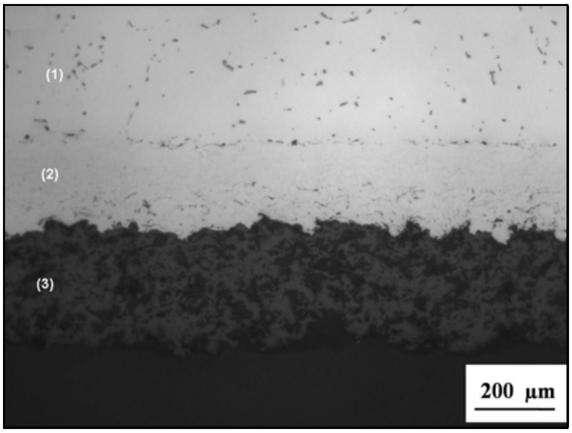

Fig. 3. Cross section from the trailing edge of the HVOF/TBC coated blade (metallographic preparation for the analysis of the MCrAlY bond coat): (1) substrate, (2) HVOF bond coat and (3) YPSZ top coat.

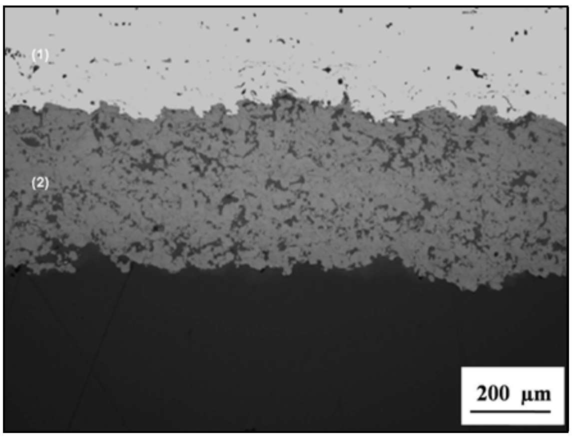

Fig. 4. Cross section of the pressure side of the APS/TC coated blade (metallographic preparation for the analysis of the TBC ceramic coating): (1) HVOF bond coat, (2) YPSZ top coat.

coat layer. The top coat shows a thickness that ranges from 280 to 370 μm and a porosity level in the range 12–17 % in agreement with the OEM specification. The microstructure of the top coat was homogeneous. The same porosity level of YPSZ ceramic top coat is requested on LPPS bond coat coated components.

Finally the chemical composition of both the NiCrAlY HVOF layers was analysed by SEM/EDAX system to determine if the different deposition process affected the chemical composition of the bond coat. Figure 5 shows the Back Scattered Electron Image of the analysed zones of the HVOF NiCrAlY bond coat.

The EDAX spectra of the dense HVOF NiCrAlY layer and of the rough HVOF NiCrAlY layer are shown in Figs. 6 and 7, respectively. The spectra resulted to be very similar. It is possible to see the typical EDS K lines related to nickel, chromium and aluminium.

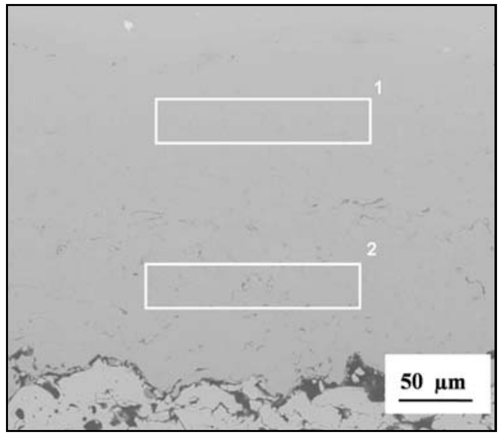

Fig. 5. Back Scattered Electron image of the HVOF NiCrAlY bond coat. The white rectangles indicate where microanalyses were performed: (1) dense bond coat and (2) rough bond coat.

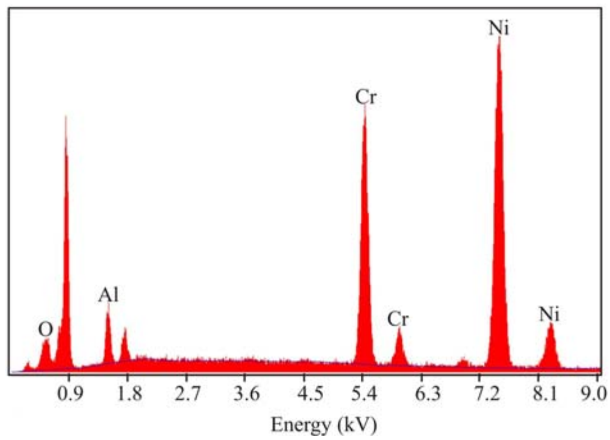

Fig. 6. EDAX spectrum of the zone 1 of HVOF NiCrAlY bond coat as indicated in Fig. 5.

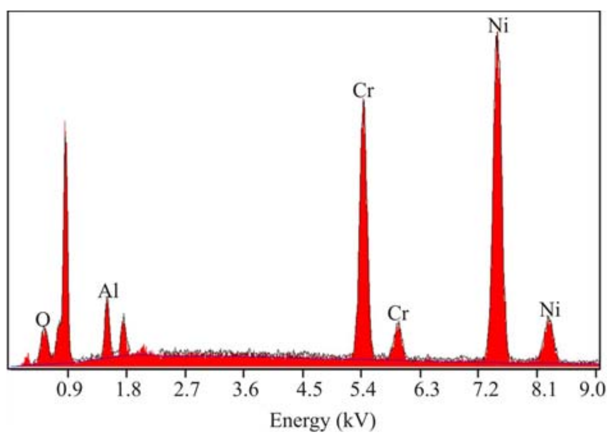

Fig. 7. EDAX spectrum of the zone 2 of HVOF NiCrAlY bond coat as indicated in Fig. 5.

Table 2. Ratio between the concentrations of Ni, Cr and Al for both of the HVOF coated layers

	Ni	Cr	Al
Dense HVOF layer/Rough HVOF layer	1.01	0.98	0.97

The analysis of the data suggests the presence of a small amount of oxygen in both the layers. It is not possible to quantify the amount of oxygen in the coated layers by EDS technique so the ratio between the concentrations of Ni, Cr and Al for the HVOF coated layers [9] were evaluated.

The results are summarized in Table 2. Taking into account the errors in the EDS analytical method, the concentration of the main elements (Ni, Cr and Al) of the bond coat is the same in both of the HVOF coated layers.

3.2. Thermal fatigue resistance

TCF test has been performed running 1000 cycles (which is the requested number to consider the test passed according to OEM specification). No signs of delamination were detected on the surface of the blade section on both sides of the blades.

All the parts of the blades were not damaged and also the leading edge showed a good TCF resistance. The results obtained are comparable with parts coated with a TBC system where the bond coat was deposited by LPPS [10].

It can be stated that the developed HVOF process achieved a good bond coat with performance similar to a LPPS deposited MCrAlY bond coat. The developed process was scaled up and implemented in production on a set of the same stage 2 components.

3.3. Validation of surface preparation method and rough MCrAlY coating

As mentioned, in order to apply to an actual component the complete HVOF coating developed during this study and test it, a stage 2 vane was coated by HVOF and TBC (300 ± 100 μm of thickness) after surface preparation obtained with the eXClean method (see the first paper of this study).

TCF test has been performed running 1000 cycles (which is the requested number to consider the test passed according to OEM specification). No signs of delamination were detected on the surface on both sides of the vane. All the parts of the blades were not damaged and also the leading edge showed a good TCF resistance. The results obtained are comparable with parts coated with a TBC system, where the bond coat was deposited by LPPS and the preparation is standard [10].

4. Conclusion

The study presented in this paper addressed the development of a new surface preparation process and of an HVOF process in order to deposit MCrAlY coating to be used as bond coat for TBC.

HVOF deposition process has been developed to obtain a rough MCrAlY coating to be used as bond coat for yttria partially stabilized zirconia (YPSZ) top coat. The process was applied to a stage 2 blade and tested by thermal cycling fatigue (TCF) test according to the specification of an important OEM. Roughness measurements for the developed HVOF process gave *Ra* value in a range of 11–14 μm, comparable with LPPS deposited MCrAlY bond coat. By metallographic investigation, it could be shown that the bond coat was formed by two layers: the first layer is dense and well adhering to the substrate, the outer layer is more porous and constitutes the rough surface where the ceramic coating adheres. EDAX analysis shows that the chemical composition of both layers is the same. TBC coating shows a homogeneous microstructure in all the parts of the coated blade in agreement with the OEM specification. TCF test performed according to the specification of blade manufacturer was passed successfully.

Moreover, a stage 2 vane was prepared and coated with eXclena method (see first paper of this study) and with the new rough HVOF process. TBC has been applied and the component passed successfully the TCF test.

Performance wise, the developed HVOF process is comparable with the LPPS, when acting as bond coat for a TBC, as demonstrated by the TCF test.

Currently the improved HVOF process has obtained the qualification of the most important OEM and has been applied in production to several components both blades and vanes.

The combination of eXclean surface preparation methodology (see first paper of this study) and the developed HVOF deposition parameters to obtain rough MCrAlY bond coat permit to make TBC systems with bond coat characteristics very similar to VPS/LPPS MCrAlY bond coat and with comparable thermal fatigue resistance.

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References

[1] DAVIS, J. R. et al.: Handbook of Thermal Spray Technology. Materials Park, OH, ASM International 2005.

[2] SCRIVANI, A.—BARDI, U.—CARAFIELLO, L.—LAVACCHI, A.—NICCOLAI, F.—RIZZI, G.: Journal of Thermal Spray Technology, *12*, 2003, p. 504.
[3] SCRIVANI, A.—RIZZI G.: In: Proceedings of TMS 2007. Annual Meeting & Exhibition. Edited by TMS. Warrendale, USA, p. 61, ISBN: 978-0-87339-670-7.
[4] Abdus Suttar Khan, Mohamed Nazmy: MCrAlY bond coating and method of depositing said MCrAlY bond coating. United States Patent 7264887.
[5] Warren Arthur Nelson, Jon Conrad Schaeffer, Sharon Trombly Swede, David Vincent Bucci, Joseph Debarro, Terry Howard Strout, Tyrone Robert Mortensen: Bi-layer HVOF coating with controlled porosity for use in thermal barrier coatings. United States Patent 20050260434.
[6] BACK, F.-W.—MOHWARLD, K.—ENGL, L.—DUDA, T.: In: Proceeding of the International Thermal Spray Conference 2006. Eds.: Marple, B. R., Hyland, M. M., Lau, Y.-Ch., Li, Ch.-J., Lima, R. S. Materials Park, USA, ASM International 2008, p. 1.
[7] SCRIVANI, A.—RIZZI, G.—BERNDT, C. C.: Materials Science and Engineering, A, *476*, 2008, p. 1.
[8] SCRIVANI, A.—RIZZI, G.—BARDI, U.—GIOLLI, C.—MUNIZ, M. M.—CIATTINI, S.—FOSSATI, A.—BORGIOLI, F.: Journal of Thermal Spray Technology, *16*, 2007, p. 816. doi:10.1007/s11666-007-9128-2
[9] GRIEKEN, R.—MARKOWICZ, A.: Handbook of X-Ray Spectrometry. CRC Press 2001, ISBN: 9780824706005.
[10] SCRIVANI, A.—BARDI, U.—NICCOLAI, F.—RIZZI, G.—GROPPETTI, R.: In: Proceedings of ICCE/8, 8-th International Conference Composites Engineering 2001. Ed.: Hui, D. University of New Orlando, USA, ICCE and CE 2001.