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STUDY OF THE VIABILITY OF DEFECTS EVALUATION IN TBC COATINGS BY EDDY CURRENT NON DESTRUCTIVE TESTING

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Abstract.
Thermal barrier coatings (TBC) are widely used in components subject to oxidizing atmospheres and high temperature operations. Such components normally showed a two layer coating, a metallic coating against oxidation and a ceramic coating with intend to reduce the temperature of the component. In this work the samples were manufactured with one layer composed by a NiCrAlY bond coat and a second layer composed of a ceramic Yttria Stabilized Zirconia are deposited on an Inconel 718 substrate. In this case the eddy current method, with intend to examine these coatings has been used. This paper presents the study of the viability of this application in coating system with some defects. These defects were prepared with intention to simulate some defects like: cooling holes, substrate failure and ceramic coating failure. This study, with eddy current non-destructive testing, indicated that it is possible the evaluation of the coatings with the presence of defects and cooling holes.

Keywords: *TBC, Eddy currents, non-destructive testing*

1. INTRODUCTION

The use of non-destructive inspection method with eddy current have been used to monitor the manufacturing process of the components and their life cycling. Components used in hot sections of some equipments, like steam turbines, aeronautical turbines and industrial gas turbines, are exposure at high temperature and high oxidizing conditions (Bose, 2007). The inspection of these components with eddy current method have some important advantages, like: portable equipment, no surface preparation and quick results. However, this technique shows some influences by the operator experience, for example, influence the sensitivity of the responses and the interpretation of the results. For a better analysis of the results, it is necessary to know, how some defects affects the eddy current signals. Eddy current analysis on the high temperature components are subject of recent works (Smith, et al., 2015).

Eddy current testing is based on the electromagnetic induction, when a probe, containing a wire coil, with alternating current flows generates an oscillating magnetic field. If the magnetic field is brought close to a conductive material, a circular flow of electrons known as an eddy current will be created. That eddy current generates its own magnetic field, which will interact with the magnetic field originated from the probe, Fig. 1. With this interaction a non-conductive coating thickness and some defects like near-surface cracking will interrupt or alter the amplitude and pattern of the eddy current and the resulting magnetic field can be evaluated by comparison (Hellier, 2003; Nelligan and Calderwood, 2015).

Eddy current testing can be used in a wide variety of applications. Some of the most common are : Weld Inspection - for a surface and subsurface testing; Heat Treatment Inspection - the measurement of conductivity can be used to identify some heat treatments in different alloys; Surface Inspection - surface cracks in machined parts can be readily identified with eddy current; Corrosion Detection - detect and quantify corrosion on the inside of thin metal such as aluminum aircraft skin; Bolt Hole Inspection - cracking inside bolt holes can be detected using bolt hole probes. Tubing inspection, inspection of tubing at the manufacturing stage and field inspection of tubing like heat exchangers can be done with eddy current technique (Nelligan, Calderwood, 2015).

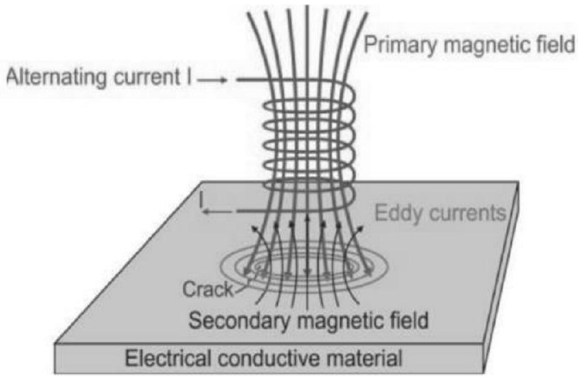

Figure 1- Eddy Current response near the surface of the metallic substrate (adapted from Smith, et al., 2015).

Typically, bond coat and top coat are deposited on the component forming the TBC, thermal barrier coating, which provide a chemical and thermal protection, respectively, reducing the substrate metal oxidation and decreasing the operating temperature of the same (Meherwan, 2006; Bose, 2007).

In this work the following situations were analyzed by eddy current; influence of bond coat on the conductivity of Inconel 718 samples, inspection of surface with cooling holes that are also used for base metal cooling in real components. Some defects, like cracks and coating detachment, are simulated on the samples with intend to observe the eddy current response on these defects.

2. EXPERIMENTAL PROCEDURE

2.1 Sample Preparation

Rounded samples are confectioned with Inconel 718 superalloy, with NiCrAlY bond coating deposited by HVOF, High Velocity Oxy-Fuel Process, with a Sulzer Metco Diamond Jet HVOF DJ2700 equipment, and finally a ceramic coating YSZ was deposited by APS Air Plasma Spraying Process using a Sulzer Metco APS 9MB equipment, Table 1.

Table 1- Bond Coating and Top Coating Materials.

	Powder Manufacturing	Chemical Composition					
		Ni	Cr	Al	Y	Zr	Hf
Bond Coating	Gas Atomized Powder	Res.	22,0	10,0	1,0	-	-
Top Coating	Agglomerated and Sintered	-	-	-	7,5 (Y_2O_3)	Res.	1,0 (HfO_2)

A total of eight samples were prepared, two samples were used to characterize the influence of bond coat on the eddy current testing, with no ceramic coating application. Two were used to analyze the influence of the cooling hole on the eddy current evaluation of the coatings. Two samples were used to simulate the influence of the substrate crack on the coating analysis, and two samples were used to observe of ceramic coating spalling influence on the eddy current behavior.

To simulate the cooling holes, the samples were drilled, with a diameter of 1.5mm and 3mm depth, before the deposition of the TBC layers. After deposition, to avoid a direct projection of the sprayed particles on the holes, a resin masking were used, as used in real components, Fig. 2.

Figure 2 (a) illustrates the samples with two different resin mask. After the application of the resin, they were exposed to an ultraviolet light to cure the resins. After HVOF coating deposition, a resin masking were applied again, Fig. 2 (b).

Figure 2 (c) shows the sample after deposition of the ceramic layer, where the resin was removed without damaging the coating. These samples were analyzed with eddy current equipment with intend to verified the influence of the cooling holes on the thicknesses measurement and electrical characterization of the samples. With the objective to evaluate the thickness using optical microscopy technique, these samples were and prepared with grinding and polishing for analysis by an optical microscope, shown in Fig.2 (d).

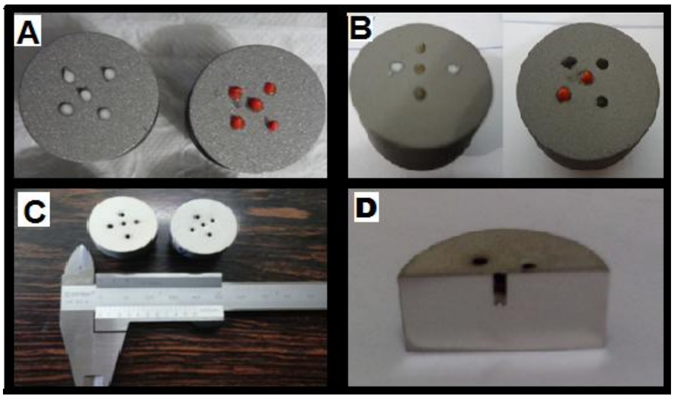

Figure 2- (a) Samples with masking resin and blasted; (b) Samples with replacement of masking resin; (c) Samples with set of TBC's deposited; (d) Sample prepared for micrograph.

The defects simulating cracks in the substrate were made by cutting the base metal as shown in Fig. 3. In the sample shown in Fig.3 (a) the cutting was made with manual saw disc system. In the sample illustrated in Fig.3 (b), the defect was done with a precision saw cutting machine, making a channel with 1 mm of thickness, the deposition of layers of bond and top coat were made after these cuts.

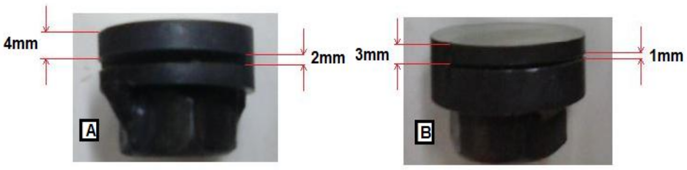

Figure 3 - Cuts inserted in the side of samples

To simulate the occurrence of detachment between the bond coat and top coat, samples were prepared with HVOF coating and these bond coats were grinded to reduce the roughness and reduce the ceramic coating adhesion, Fig. 4.

Figure 4- Samples with bond coat sanded.

After grinding the bond coat, the YSZ was deposited by APS plasma spray. After the deposition it was found an insufficient adhesion between the bond coat and the ceramic layer, simulating a top coat detachment, as can be seen in Fig. 5.

Figure 5 – Samples with detachment.

2.2 Eddy Current Testing Methodology

Eddy current analysis was made with a Olympus NORTEC 500D® equipment, the probe used was the Nortec PowerLink SL, using 25 and 50KHz of frequency. The eddy current testing was also performed in order to obtain thickness measurements of the TBC coating with a 480KHz SN NORTEC conductivity probe. Each sample was tested five times with the Eddy Current equipment, and the results were compared with the thickness measured by optical microscopy, (ASTM E364; ASTM E 1004).

The probe of 480KHZ was calibrated using the reference materials with electrical conductivity in accordance with International Annealed Cupper Standard (IACS), the samples used were 1.08% IACS (Titanium 6Al4V) and 29.84% IACS (T351 Aluminium-Al2024 / 3) and 100.63%IACS (Copper) (IOWA, 2002).

3. RESULTS AND DISCUSSIONS

3.1 Study of the Influence of Bond Coat on Inconel 718 Samples

The objective of this section is to analyze the influence of bond coat on the coating thickness measurement and Inconel 718 substrate conductivity. This analysis have the intention to separate the influence of bond coat, and top coat, on the results obtained with this non-destructive testing.

Initially, the samples of Inconel 718 substrate were analyzed regarding the electrical conductivity in % of the IACS and also the impedance plane of the substrate, with and without bond coat. According to Adolpho Soares (2009), electrical characterization of the material sample should be preferably made by electrical conductivity, particularly using the IACS measurement system. The results obtained with these samples are illustrated in Fig. 6. This Figure indicates that the NiCrAlY bond coat have a lower electrical conductivity than the substrate sample. Thus, the presence of this alloy as a coating, results in a decrease on the conductivity of the system composed by the Inconel substrate and bond coating, compared to the substrate alone, as observed in Fig. 6.

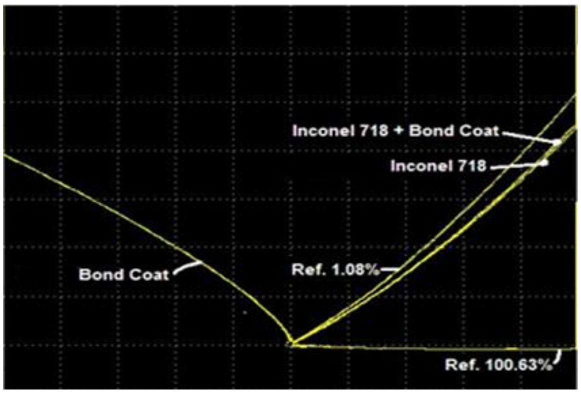

Figure 6 - Impedances Plan of bond coat and Inconel 718

Figure 7 (a) shows the impedance plan analysis by comparing the sample of Inconel 718 with the reference materials 100.63% and 1.08% IACS. Since Fig. 7 (b) illustrates the impedance plan Inconel 718 with and without bond coat.

The impedance curves indicate that the bond coat layer decrease the electrical conductivity of the sample, as can be seen in Fig. 7 (a) and (b). To observe this change it is necessary to improve the resolution of the analysis, the frequency used in this analysis was 50KHz, and the gain used was 90dB. It is recommended to perform at least five repetitions of in each same area, moving the probe up to the surface with constant speed and always on the same point of the piece, observing any deviation of the trajectory. After the trajectory was well defined the screen image should be saved.

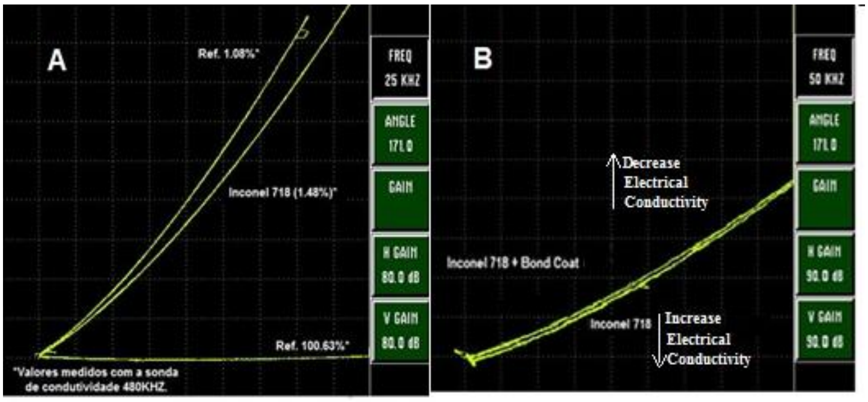

Figure 7- (a) Impedance plane of 1,08% reference and Inconel 718 substrate (b) Impedance plane of Inconel 718 with and without bond coating.

When performing analysis of the sample with bond coat deposited on Inconel 718, with the conductivity probe 480KHZ, Fig. 8, it was found that the probe was reading the bond coat thickness, 106 μm in these samples. It was observed that these measurements are in accordance with the optical microscopy analysis.

Figure 8 - Conductivity and thickness (lift-off) reading in the sample with bond coat deposited on Inconel 718.

The metallic coating measurement was possible due to changes on the electrical conductivity between the bond coat and the superalloy substrate. The results are confirmed by the impedance plan changes, shown in Fig. 7(b), which shows the conductivity of the sample deposited slightly smaller than the superalloy substrate.

In order to analyze the bond coat influence on the base metal with eddy current test, it can be concluded that the eddy current method can measure the thickness of the bond coat, because of the metallic bond coating layer have different electrical conductivity, compared with the Inconel 718 base metal.

According Adolpho Soares (2009), the probe of non-conductive layer thicknesses can read the thickness of a conductive layer deposited on a conductive metal, since their electrical conductivities are different. The author also reports that the presence of a conductive layer on a conductive material, change the conductivity of the system, and if there is variation on the bond coat or top coat thickness, the conductivity will also vary, causing the change on the signal test and making the thickness measurement possible.

3.2 Analyse of the Samples with Cooling Drilled Holes

Some components subjected to high temperature have cooling holes that are used to reduce the temperature of the component. In this case some different samples were made to simulate this situation, where the analysis with the eddy current test was used on NiCrAlY with Ceramic Coatings on substrates with drilled holes.

The thickness measurement using the 480KHz probe in samples with TBC and holes were efficient, because it was compared to the measurements obtained by micrograph analysis. Table 1 shows a small difference between thicknesses obtained by the destructive method with the non-destructive method .

Table 1- Thicknesses of TBC acquired with eddy currents and micrograph.

	Thicknesses (mm)	
Samples	Eddy Current	Micrograph (Top + Bond Coat)
1	0,310	0,311
2	0,419	0,415

The analyzis of the phase angle was done comparing samples with and without holes. The results indicate a small reduction in electrical conductivity due to the presence of holes. Fig. 9 indicates that for the two samples there was a similar decrease on the conductivity, as evidenced by an increase in phase angle, relative to a reference conductivity of 100.63%.

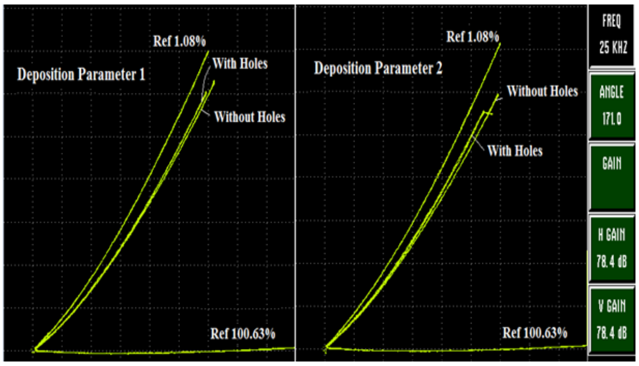

Figure 9 - Analysis of the phase angle of the samples with and without holes.

The results demonstrate that the eddy currents technique can give reliable information even on regions of the components with cooling holes. The probe of 480KHz, can make measurements of the thickness even in the presence of holes in the coating. However, the impedance plan analysis indicated a decrease in conductivity, showed by the increase of phase angle curve in relation to 100.63% ICAS reference. This could be the presence of air pockets (holes), on the eddy currents magnetic field flow. So, this behavior needs to be considered in the analysis of the components, comparing the conductivity of surfaces with the same geometry characteristic (Viswanathan, 2006).

3.3 Eddy Current Analysis of Simulated Failure Samples

The objective of this section is to evaluate if the phase angle analysis would be able to detect failures localized on the substrate. In this study the probe Nortec PowerLink SL / 300Hz-10kHz was adopted. Figure 10 illustrates the electrical behavior of the samples, comparing samples with and without defect on the substrate.

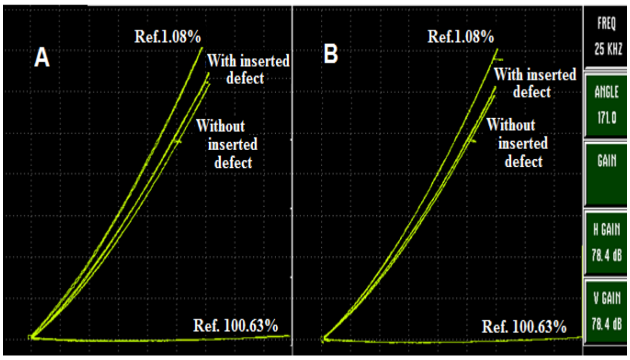

Figure 10 - Impedance plan - comparing samples with and without defect inserted.

Figure 10 indicates that the samples with a cutting defect showed a decrease on electrical conductivity, evidenced by the increase on angle relative to the reference of 100.63%. These results are very similar that observed on Fig. 9, demonstrating the importance of the use of reference sample.

The difference in separation of the curves 10(A) and 10(B) is due to the flaw distance relative to the top face of the sample, were in the 6(A) the distance was 4mm and in the 6(B) the distance was 3mm. This simulation indicate that the eddy current equipment was able to detect a failure on the base metal, with a probe SL / 300Hz-10kHz using frequency of 25KHz.

3.4 Analysis of Samples Simulating the Spalling of the Ceramic Coating

The electrical characterization of the samples with ceramic coating spalling was performed with the probe Nortec PowerLink SL/300Hz-10kHz. As evidenced in this study, the influence of bond coat on the eddy current test was already observed, due to lower electrical conductivity of NiCrAlY coating, compared with the Inconel 718 substrate. Thus, when a small region of the bond coat was grinded the conductivity increase, comparing to the sample Inconel 718 + TBC without defect, Fig. 11.

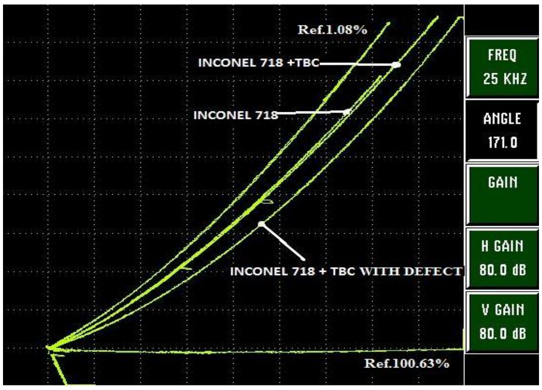

Figure 11- Analysis of the phase angle.

Figure 11 shows the impedance analysis, indicating that the electrical conductivity of samples with top coat spalling, due to the bond coat sanding in the area under, was greater than the sample without this defect, this is due to removal of a part of the bond coat, when Bon Coat was deposited on Inconel 718 takes a small decrease electrical conductivity, as shown in Fig.6. These samples did not suffer oxidation cycles, the difference in electrical conductivity, which results in a phase angle change is linked to the thickness of the bond coat on the sample (Khan, 2008, Cai, 2014, Estarki, 2014).

This test may be used to evaluate the quality of the deposited coating, comparing a reference sample with others samples with the objective to observe the coatings properties. However, it should be noted that due to the sensitivity of the technique, some factors as temperature, presence of magnetic fields near the tested sample and operating can interfere with the results, and they should be carefully analyzed and controlled.

4. CONCLUSIONS

The eddy current test was able to measure the thickness of bond coat on the substrate Inconel 718 as well as the electrical conductivity of the samples. It was also observed that the analysis of thickness and conductivity with eddy current technique can be performed even in samples containing cooling holes. It was also verified that these holes promoted a slight reduction in electrical conductivity of the samples.

This study indicated that the presence of defects in the substrate can be detected with the use of eddy current. The simulation of the ceramic coating detachment was also observed by eddy current testing.

However, eddy current is a qualitative analysis, and a reference sample must be considered for this analysis. Comparing the phase angles and thicknesses of the coating for the same component, for example, the monitoring by eddy current of the component, during the operation, can be useful to observe defects and coatings fail during their service life.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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