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Characterization of mechanical and surface finishing properties of metallic coating obtained by arc electric thermal spray

Caracterização das propriedades mecânicas e de superfície de revestimento de revestimento metálico obtido por pulverização térmica elétrica arc

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ABSTRACT
The Brazilian thermoelectric plants that use coal as a thermal source use pulverized combustion technology. The aim of this work was to characterize some properties of a metallic coating obtained by arc electric thermal spray in order to protect boiler's surface against ash's aggressive action from coal burning. The evaluated parameters considerably influence the characteristics of the coating's lifes service. An iron chromium base alloy, reference herein as Alloy B, was used in this study. A chemical analysis of the coating, Alloy B, was performed in order to compare if there were any difference between the chemical composition of the wires used and what was incorporated into the coating by the thermal spray process. Therefore, Energy Dispersive Spectroscopy technique (EDS), Quantax software and PyMCA program were used. The chemical analisys results of the coating was quite similar to the given composition of the wires. To verify the coating hardness, Vickers (HV) microhardness measurements were performed on the coating region, on the substrate and on the boundary region of the coating between substrasts. Vickers microhardness measurements were obtained by PANTEC MV-1000A microdurometer. As substrate an 8 mm thick steel sheet with a chemical composition and thickness similar to the steels used in the water wall pipes of Brazilian boilers were used. The coating hardness (730 HV) was on the order of four times greater than the substrate's hardness (179 HV) to be protected. This property was homogeneous for the coated layer showing that hardness values indicates that good adhesion of coating's cast particles occurred, and the spray distance proved to be effective. The roughness was obtained through measurements made

on images generated by Optical Microscopy (OM). Measurements of the variation in heights between peaks and coating depressions were obtained on the generated images. These measurements generated an average value Ra = 27.5 μm. Roughness measurements obtained by conventional technique (Digital Surface Profile Gauge) were performed too and showed that the method of measurements on the OM images was not effective to evaluate the high coating roughness generated by the arc electric thermal spray method, in this case, 248 µm.

Keywords: Arc electric thermal spray, Thermoelectric plants, metallic coating, boiler, ash erosion.

RESUMO

As usinas termelétricas brasileiras que usam carvão como fonte térmica usam tecnologia de combustão pulverizada. O objetivo deste trabalho foi caracterizar algumas propriedades de um revestimento metálico obtido por spray térmico elétrico a arco, a fim de proteger a superfície da caldeira contra a ação agressiva das cinzas da queima de carvão. Os parâmetros avaliados influenciam consideravelmente as características do serviço de vida útil do revestimento. Uma liga à base de ferro e cromo, aqui referida como Liga B, foi usada neste estudo. Uma análise química do revestimento, Alloy B, foi realizada para comparar se havia alguma diferença entre a composição química dos fios utilizados e o que foi incorporado ao revestimento pelo processo de pulverização térmica. Portanto, foram utilizadas a técnica de Espectroscopia Dispersiva de Energia (EDS), o software Quantax e o programa PyMCA. Os resultados da análise química do revestimento foram bastante semelhantes à composição dada dos fios. Para verificar a dureza do revestimento, foram realizadas medições de microdureza Vickers (HV) na região do revestimento, no substrato e na região limite do revestimento entre os substratos. As medidas de microdureza Vickers foram obtidas pelo microdurômetro PANTEC MV-1000A. Como substrato, foi utilizada uma chapa de aço de 8 mm de espessura, com composição química e espessura semelhante à dos aços utilizados nas tubulações de água das caldeiras brasileiras. A dureza do revestimento (730 HV) foi da ordem de quatro vezes maior que a dureza do substrato (179 HV) a ser protegida. Essa propriedade era homogênea para a camada revestida, mostrando que os valores de dureza indicam que ocorreu uma boa adesão das partículas fundidas do revestimento e a distância de pulverização provou ser eficaz. A rugosidade foi obtida através de medições feitas em imagens geradas por Microscopia Óptica (OM). Medidas das variações de altura entre picos e depressões de revestimento foram obtidas nas imagens geradas. Essas medições geraram um valor médio Ra = 27,5 μm. Também foram realizadas medições de rugosidade obtidas pela técnica convencional (Digital Surface Profile Gauge) e mostraram que o método de medição nas imagens OM não foi eficaz para avaliar a alta rugosidade do revestimento gerada pelo método de pulverização térmica por arco elétrico, neste caso, 248 µm .

Palavras-chave: Spray térmico elétrico a arco, usinas termelétricas, revestimento metálico, caldeira, erosão de cinzas.

1 INTRODUCTION

The national production of electric energy is mostly from the hydroelectric and thermoelectric sector (Abradee, 2019). Brazilian thermoelectric plants that use coal as a thermal source use pulverized combustion technology. Considering the high percentage of fly ashes present in Brazilian coal, the metallic parts of the interior of the boiler, and especially the pipes inside the boiler, suffer accentuated wear depending on the composition and amount of ash that can lead to losses for profit to the operator (Viswanathan, 1993).

Gomes (2018) has characterized light ashes generated by the burning of pulverized coal used as a power source for a power plant boiler thermal power station in southern Brazil. In his study he concluded that the wear impact of the ash particles can be more intense than other mechanisms of boiler component wear, such as the corrosion mechanism, since the environment was alkaline and sulfur free.

In this sense it is essential to delay the deterioration process of the steel tubes surface. There are several processes that can be used industrially to increase surface properties by delaying the pipes deterioration and devices inside the boilers, obtaining greater hardness, improving the wear resistance, corrosion, high temperatures resistance, maintaining the electrical or thermal conductivity between other requirements (Szymanski, et al, 2015). Among the processes, we can mention thermal spraying, in which a substance or a combination of them fuse (in their conventional options) through the use of some kind of energy (combustion, arc eletric, plasma, among the most common) and then this substance is projected toward a previously prepared surface with a suitable roughness, which will help to get a better grip of the designed material (Davis, 2004). The sprayed material is intended to provide the base metal with the desired property to combat or delay the deterioration process of the surface thereof.

The aim of this work was to characterize some properties of a metallic coating obtained by Arc electric thermal spray in order to protect the surface of the boiler piping of thermoelectric power plants against the aggressive action of the ash from coal burning.

A chemical analysis of the coating, referenced here as Alloy B, was performed in order to compare and check if there were any difference between the chemical composition of the wires informed by the manufacturer and used in the thermal sprayed process and what was effective incorporated into the coating by the thermal spray process itself.

Therefore, EDS analysis, Quantax software and PyMCA program were used. At this point of the research, Hardness Vickers (HV) and medium roughness (Ra) measurements of the surface of the coating were evaluated too.

The evaluated parameters measured considerably influence the characteristics of the coating life in service as mentionated by Cossenza (2018), Godwin et. al., (2017) and Murugan et. al., (2014).

2 MATERIALS AND METHODS

In this experiment, an 8 mm thick steel sheet donated by Arcellor Mittal (http://brasil.arcelormittal.com.br/) with a chemical composition and thickness similar to the steels used in the water wall pipes of Brazilian boilers (0.2 Wt% C) was used.

As a coating to be studied, a metal alloy, referenced herein as Alloy B, was used. Table 1 shows the chemical composition of the alloy used given by the manufacturer.

Table 1: Alloy's B composition

Chemical Composition	
Element	**Weight (%)**
Silicone	1,6
Chrome	29
Manganese	1,65
Boron	3,75
Iron	Balanced

The TAFA - 8835 thermal spray equipment was used at a pressure of 60 Psi, Amperage – 100 A, Voltage – 28-30 V and compressed air to propel the particles to the substrate. Spraying was performed perpendicularly in Horizontal and Vertical passes on the surface of the previously prepared sample (Sa $2^{1/2}$ abrasive blast-cleaning according ISO 8501-1 and ISO 8504-2). Table 2 shows the parameters of Thermal Spray used for spray the coating. The parameters listed below were given by the project partner company who sprayedthe samples.

Table 2: Spray parameters

Coating spray parameters	
Deposition rate	3,64 kg/h/100 A
Wire consuption	1,2 kg/m²/ 100 µm
Position spray pattern	3" (76,2 mm)
Length of wire per inch	1/16"
Spray distance	80 -120 mm
Final sample thickness	8,68 - 8,78 mm
Gun position	90° ± 5

After spraying the final thickness of the sample was approximately 8.7mm.

The EDS feature is used to identify and map (Braga, et al, 2019; Braga, et al, 2020) the chemical elements distribution and obtain the chemical elements characteristic energy spectra present in the regions of analysis. In this way, analysis of the chemical elements that compose the studied coating was performed by EDS. The phases generated by the coating, as well as the networks of oxides and inclusions formed were characterized by obtaining images of the sample coating region. The microscope with EDS detector was operating with BSE detector (backscattered electrons) at 15 kV, low vacuum and working distance of 7.7 mm. The EDS results were obtained by scans lasting 10 minutes each and analyzed by Brucker's Quantax program.

To identify the presence of manganese, the PyMCA program was used because only through the analysis of EDS through the Quantax program it was not possible to certify the existence or not of manganese, since the element is present in low alloy concentration and its primary peak overlaps the secondary one of chromium, and secondary to the iron primary, elements present in higher quantities and by PyMCA program, it can be built a multi-element calibration to determinate an specific element well-characterized in terms of precision extracting the spectra of arbitrary regions on the maps (Heginbotham and Solé, 2017; Felix, et al, 2018; Freitas, et al, 2019).

Hardness measurements were performed in three different regions of the surface of the coating and in three substrate regions of a sample previously submitted to metallographic preparation, in a total of 6 grids of 30 points each as we can see in Figure 1.

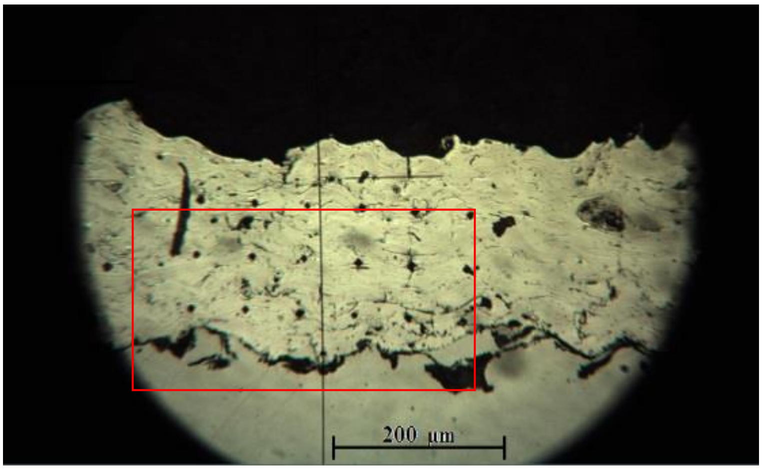


Figure 1: Hardness grid scheme (highlighted area).

Roughness measurements were performed on various coating regions, as we can see in Figure 2, obtained by Optical Microscopy (OM). It was used 10 OM images and performed 20 measurements of the variation in heights between peaks and coating depressions from horizontal line reference each, in a total of 200 measurements.

A convencional technique to evaluate roughness measurements (Digital Surface Profile Gauge) were performed too. To this case, the roughness measurements were obtained by a roughness gauge: Digital Surface Profile Gauge | Elcometer 223 - Elcometer USA. A total of 100 measurements were performed in a 10 x 15 cm coated sample.

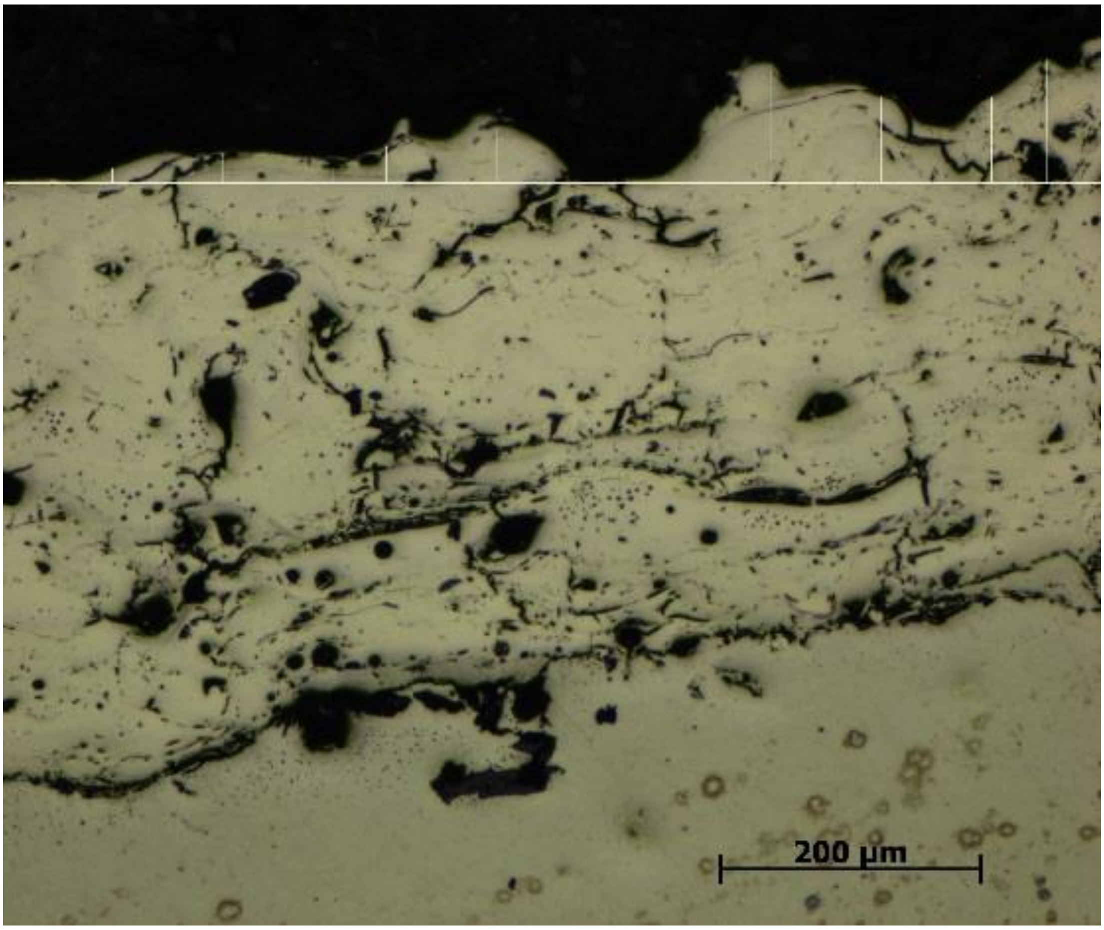


Figure 2: Roughness measurements scheme.

3 RESULTS AND DISCUSSION

To perform the chemical analysis of the alloy, several areas of interest were selected as presented in the highlighted area of Figure 3.

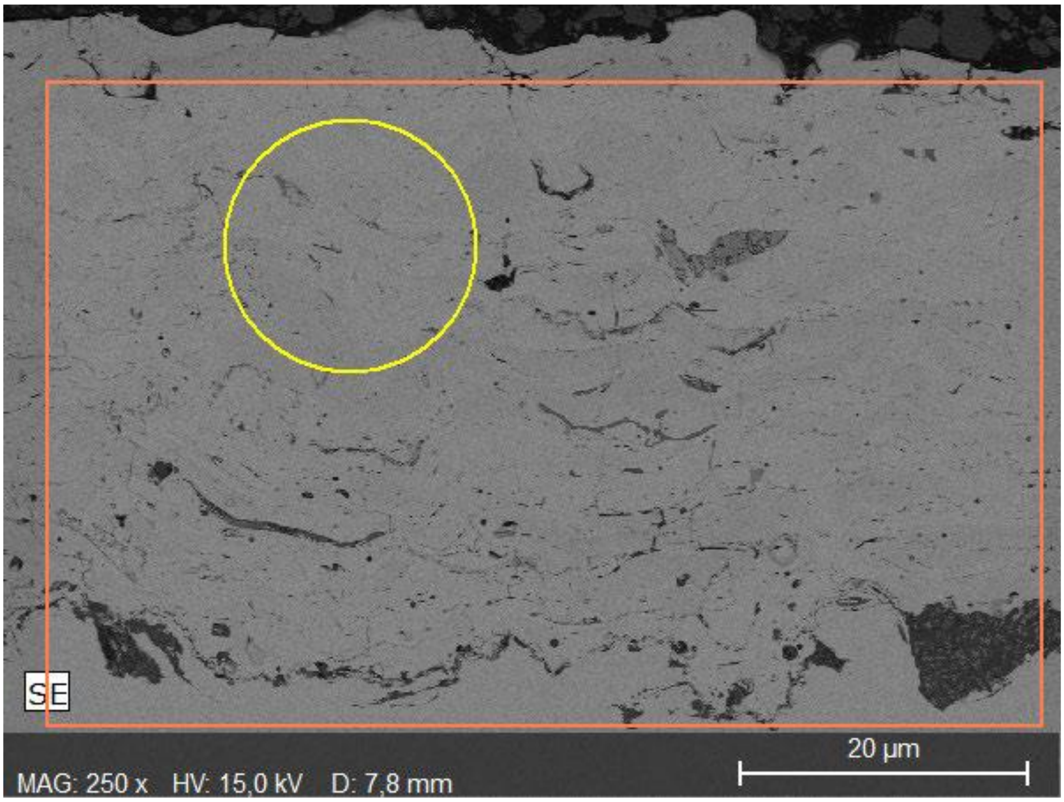


Figure 3: Example of selected EDS analysis circle area.

The results obtained by the chemical analysis performed by EDS / Quantax on the coating are as shown in Table 3.

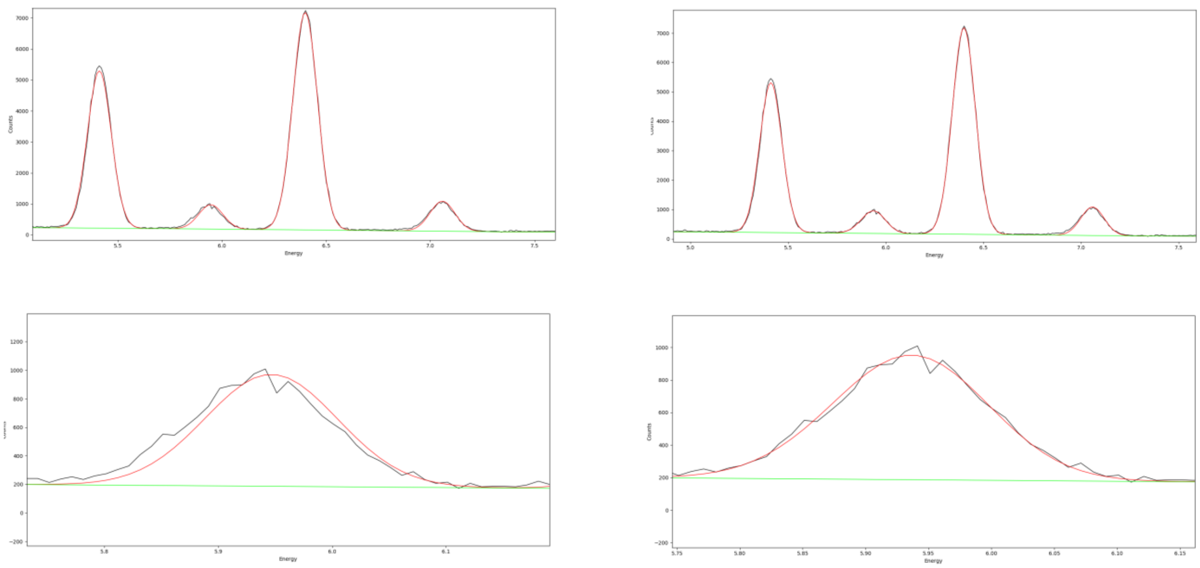
Table 3: Chemical analysis of coating results by EDS *versus* wire chemical elements (informed by the manufacturer)

Chemical element	Concentration% weight EDS	Concentration% weight Manufacturer
Iron	68,17	64
Chrome	29,69	29
Silicon	1,02	1,6
Manganese	-	1,65
Boron	-	3,75

Comparing the results it was verified that silicon, chromium and iron are in quite similar quantities. In relation to the boron, the EDS did not identify percentage of concentration because boron is a very light element (Nasrazadani and Hassani, 2016).

Although the results of chemical analysis by EDS are semi quantitative, that is, they do not show the exact values present but a ranking of elements, the obtained results showed that the chemical elements present in the wire used for thermal spraying were totally incorporated in the obtained coating layer.

The manganese presence determination occurred after PyMCA program analysis. Figure 4 shows the curves obtained, two without Mn (a) and others two with Mn (b). Analysing the second peak of Cr, which is enlarged in the images below, it can be observed that without Mn (Figure 4 – a) the theoretical red curve is shifted to the right relative to black experimental curve. This fact is corrected when adding Mn to the analysis (Figure 4 –b). This is because the energy in KeV of the secondary peak of Cr is slightly higher than the primary peak of Mn (Secondary Cr: 5,947 *versus* 5,900 from Mn).



(a) (b)

Figure 4: Manganese analysis; a) Without Mn; b) With Mn

An aluminum concentration was observed in the interface region between the coating and the substrate due to aluminum remnants originated from the abrasive blasting process, as in the highlighted regions in Figure 5. When the aluminum oxide is located in the middle of the region, however when the presence of aluminum alone is verified the region has spherical geometry (Guapyassu, 2019).

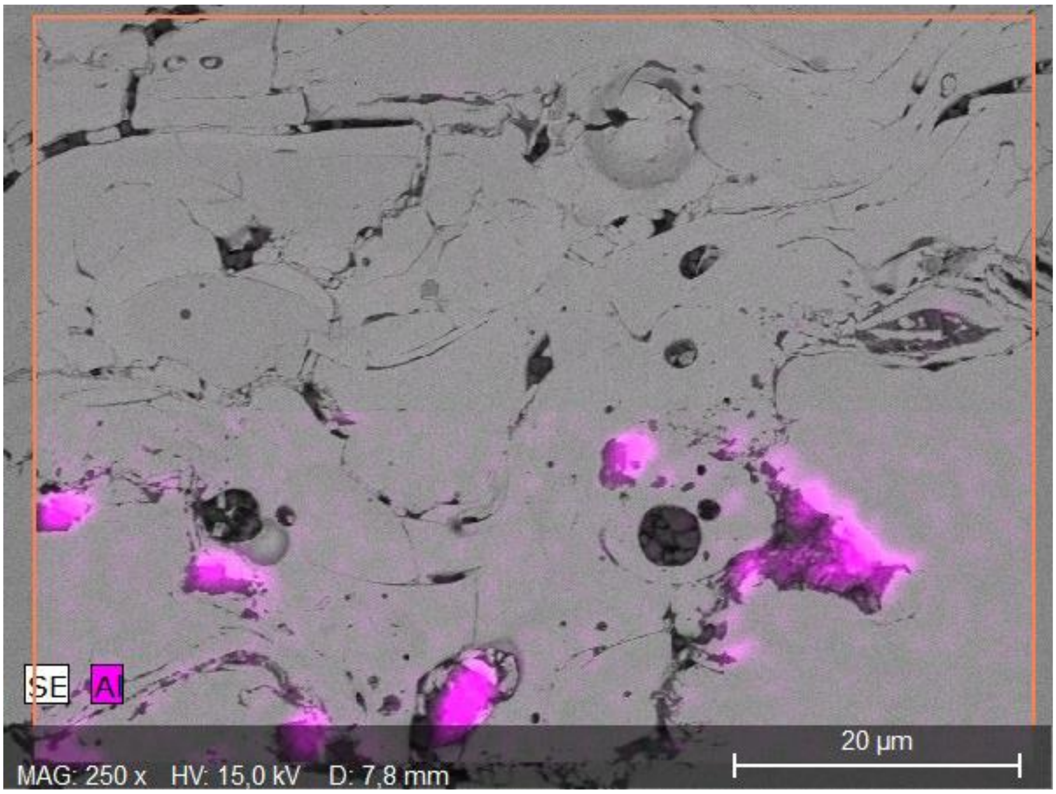


Figure 5: Aluminum presence analysis in the coating.

Table 4 presents the results of the hardness tests. It was observed that the hardness of the coating was on the order of four times greater than the hardness of the substrate to be protected. This property was homogeneous for the coated layer.

Table 4: hardness test results

	Grid 1 (HV)	Grid 2 (HV)	Grid 3 (HV)	Average (HV)
Coating	753,29	754,71	683,61	730,54
Coating and substrate edge	217,70	223,60	212,06	217,79
Substrate				179,26

The homogeneity of the hardness values indicates that good adhesion of the cast particles of the coating occurred and that the spray distance proved to be effective for the intended purpose, since this parameter is a determinant factor for a desired hardness increase (Ihsan and Yetgin, 2013).

As can be observed, in the interface region between the substrate and the coating layer the hardness measurements showed higher values, which was expected due to the work hardening caused by the substrate blast-cleaning process before being coated (Multigner, et al., 2009).

Table 5 presents the results of average roughness (Ra) of the sprayed surface for the two methods used.

Table 5: surface roughness obtained by the arc electric thermal spray method

	Ra (µm)
Measured in OM images	27,49
Rugosimeter	247,84

The result of the roughness test by means in MO images was very dissimilar to the result obtained by means of the rugosimeter. This may be related to the fact that the measures in MO images technique did not consider the effect of curvature on a macroscopic scale of the surface of the material, but only the relative microscopic scale. This results were not coherent, unlike the values obtained by the rugosimeter measurements that were close to the values normally generated by the arc eletric thermal sprayed technique (Adamiak, 2018).

4 CONCLUSION

Considering all the techniques presented and used in this study, it can be concluded that:

- The coating parameters allowed a deposit homogeneously on the surface of the sample;
- Roughness measurements performed on OM images differed significantly from the measurements obtained with the rugosimeter, the latter being the method that still remains the most reliable;
- It was observed a great similarity in the results between the comparison of the chemical composition of the wires used in the thermal sprayed process informed by the manufacturer and those found after analysis wich means that the wire chemical composition was incorporated into the coating by the thermal spray process;

- Through the analysis by the PyMCA program it was possible to verify the presence of manganese. Therefore, SEM, EDS analysis and PyMCA analysis were satisfactory because they fulfilled their respective purposes of observing the microscopic characteristics and to identify the distribution of the chemical elements present in the sample.

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