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ABRASION RESISTANCE OF NICKEL ALUMINIDE COATINGS DEPOSITED BY HVOF AND PTA PROCESSES*

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Abstract
This study aims to compare the wear resistance assessed in rubber wheel abrasion test of nickel aluminide coatings deposited by for Plasma Transferred Arc (PTA) and High Velocity Oxigen Fuel (HVOF) manufacturing, using the same raw material. A nickel aluminide powder was atomized and deposited on 316L steel plate substrate. After deposition, some specimens were submitted to a heat treating (1200 °C for 24 h followed by 760°C for 24 h). The coatings deposited using PTA developed different microstructures due to the incorporation of substrate elements, its performance was better than the HVOF coatings, although their Vickers hardness was similar. After heat treating, a significant variation in hardness and wear resistance was observed. For PTA specimens, there were decrease in hardness of 35%, while for HVOF ones this drop was approximately 20%. Nonetheless, the effect of thermal exposure in wear resistance was quite different: an increase of 21% was observed for HVOF coatings, while a reduction of 20% occurred in PTA ones. Microstructures modifications in PTA coatings were significant for their wear resistance. On the other hand, the reduction of porosity and sintering were responsible for a better performance of heat-treated HVOF coatings.
Keywords: Rubber wheel abrasion; HVOF; PTA; Nickel aluminide coatings.

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1 INTRODUCTION

High-velocity oxygen fuel (HVOF) and plasma transferred arc (PTA) processes are among the most used techniques to deposit Ni-based alloys to prevent wear [1]. However, the comparison between them with respect to the wear performance is not so common for these families of coatings.
Kim et al [2] tested the Armacor M alloy (a Fe-Cr-B based coating) against two-body abrasion processed by both HVOF and PTA. Although Armacor M coatings have the same hardness, the latter shows better wear resistance because of the size and orientation of its boride phases. Unfortunately, a series of annealing treatments applied to the thermally sprayed coatings were not tested with respect to the abrasive wear resistance, probably because these authors verified a decrease in their hardness [3].
Hill et al [4] also studied iron-based alloys produced by HVOF and PTA processes, including a post-treatment of quenching and tempering. Once more, the resulting microstructure obtained with PTA offered a highest wear resistance. But it was worthwhile that the heat treatment, especially for the thermally sprayed coatings, increased the wear resistance due to a higher hardness and distinct carbide precipitations.
Ni-based alloys were investigated by Hart et al [5]. They showed for Ni-Cr-B-Si + WC compositions a better performance when coatings were processed by PTA. In this case, some industrial applications were very well described, but no detailed reasons for their findings were presented.
Kulu et al [6] studied the wear performance of Fe- and Ni-based coatings deposited by HVOF and PTA processes. The best resistance was found for those coatings with Fe-rich matrix using PTA, but their alloy design did not consider the possibility to form intermetallic phases.
Considering intermetallic phases, new Ni-base alloys have been developed, aiming the increase of wear and corrosion resistance, with the expectation to guarantee the same performance at high-temperatures [7]. This family is composed by an intermetallic matrix with dispersed carbides. Following this trend, nickel aluminides were employed as raw material for HVOF-sprayed [8] and PTA-welded coatings [9].
The abrasive wear resistance of HVOF-sprayed coatings can be improved after heat treatments [10]. On the other hand, when nickel aluminides coatings deposited by PTA are subject to heat treatments their microstructural stability can be decisive to perform reasonably [11].
In a previous publication [8] the abrasive wear resistance of HVOF nickel aluminide coating was compared to the cast condition with the same initial composition. However, the cast material was tested only after it have been heat treated and an additional comparison could have been made, supposing the improvement on properties of a HVOF-sprayed coating after the same thermal cycle.
Considering the possible contributions in the field of surface engineering, the current investigation aims to compare the abrasive wear resistance of HVOF and PTA coatings processed with the same raw material (a Ni-based alloy), and the effect of a specific heat treating in their resistances.

2 MATERIAL AND METHODS

Nickel aluminides coatings were deposited using two different processes, high-velocity oxygen fuel (HVOF) and plasma transferred arc (PTA). For both cases,

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substrates of 316L stainless steel were used. In the same way, the raw material, an atomized powder with the nominal composition of Ni–0.86C—12.10Cr–8.7Al–0.05%B, was used in the studied processes. The powder mixtures were homogenized for 1 hour at 80 rpm in a Y mixer and dried at 100 °C for 48 hours before depositions.
The processing parameters selected for HVOF deposition was based on the previous study [8], which performed better against abrasive wear. The main variables are the propane flow (65.3 L/min), the oxygen flow (177.1 L/min), resulting in an O2/C3H8 ratio of 3.6. Other parameters were: Coatings were deposited using a METCO Diamond Jet HVOF gun with DJ 2701 air gap at a spray distance of 200 mm, powder spray rate of 60 g/min and air compressed flow rate of 304 L/min.
PTA-welded coatings were manufactured for wear tests with 160 A. The other parameters of PTA were: powder feeding rate 500 g/min, welding speed 100 mm/min, distance torch-specimen 10 mm, plasma gas flow 2 L/min, protective gas flux 15 L/min, feeding gas flux 2 L/min.
Argon of 99.995% purity is used as the plasma, protection and transport gas. The quality of surfaces was analyzed by visual inspection for the presence of cracks. The dilution level was determined at the cross-sections of the coatings based on the iron content, using semi-quantitative Energy Dispersion Spectroscopy (EDS) analysis of the iron profile, applying the equation $\Delta\%Fe= (\%Fe_{final}/\%Fe_{initial})$ / (%Fe of substrate); where $\%Fe_{initial}$ was taken as zero.
To cover the total area of specimen submitted to the wear test, three to four beads were made. An analysis of dilution level was performed in a specimen based on the differences of iron content. The measured dilution level in this case is 23%, meaning that the elements of substrate were incorporated into coating. This dilution level is smaller than that observed for the same coating composition processed using elemental powders [9], and some reasons for this discrepancy were discussed in [12].
The transverse cross sections of the PTA coatings were prepared using standard metallographic procedures. Specimens were electrolitically etched in an oxalic acid solution and the microstructure was investigated using scanning electron microscopy (SEM).
After deposition, some specimens were heat treated, heating at 1200 °C for 24 h followed by 760 °C for 24 h, using argon as protective gas. After both heating, the specimens were cooled in mild air up to room temperature. This heat treatment was described in the literature for as-cast nickel aluminide alloy [13].
Hardness of coatings was evaluated using Vickers indentation, performed using a load of 300 g (an average of 10 indentations per specimen), at the cross-sectioned areas. The semi-quantitative chemical analyses were carried out by energy dispersive spectroscopy (EDS) using scanning electron microscope (SEM).
Wear tests were conducted in the rubber wheel abrasion test (RWAT), following the procedure E described by ASTM G65 standard [14]. Sand particles of quartz were used as abrasive material, with an average particle size of 0.3 mm.
Before wear tests, the specimens were ground, in order to achieve suitable flatness and surface roughness for specimens, attending the specifications of the ASTM wear testing standard. However, this operation was not repeated after heat treatment. Worn surfaces were revealed in SEM, to describe the micro-mechanisms of abrasive wear.

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3 RESULTS AND DISCUSSION

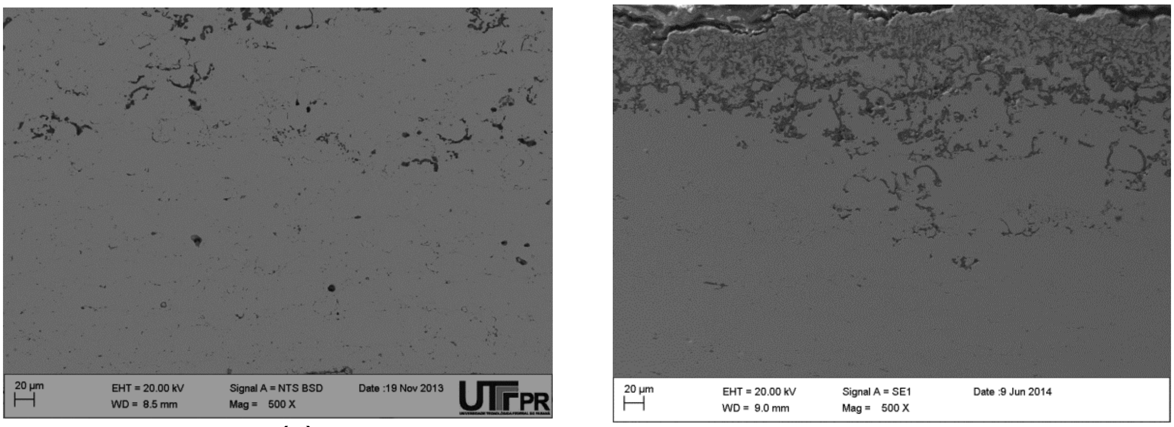
3.1. Characterization of coatings

Table 1 shows the Vickers hardness of tested coatings. As-deposited coatings presented significant difference with respect to the process. Farina et al. [13] found for an as-cast nickel aluminide a hardness of 338 HV.

Table 1. Hardness values of HVOF and PTA coatings (HV0.3)

	As-deposited	Heat treated
HVOF	470 ± 50	380 ± 30
PTA	297 ± 7	270 ± 20

After heat treating a significant decrease in hardness of sprayed-HVOF coating was observed. This result is contrary of that observed by Farina et al. [13], who found for a cast nickel aluminide 530 HV, after the same heat treating cycle. These researches attributed this result to the precipitation of carbides.
In the case of HVOF, even controlling the atmosphere during heat treatment, the oxidation of coatings was not avoided completely. Cross-sectional images of HVOF-sprayed coatings are presented in Figure 1. It shows a significant presence of oxides within the upper region of treated coating. EDS analysis confirm aluminum as the main element within oxides regions. The measurement of hardness was made avoiding the oxides regions. Thus, the reduction in hardness after heat treatment can be explained by the diffusion of elements, especially the aluminum. This process can reduce the amount of intermetallic phases, creating soft regions of solid solution.



(a) (b)

Figure 1. Cross-sectional images of HVOF coatings: a) as-deposited, and b) heat treated. Note the presence of oxides in the upper region of image.

In the case of PTA, Figure 2a shows the presence of carbides at the grain boundaries, as shown in Figure 1a, in the as-deposited condition.

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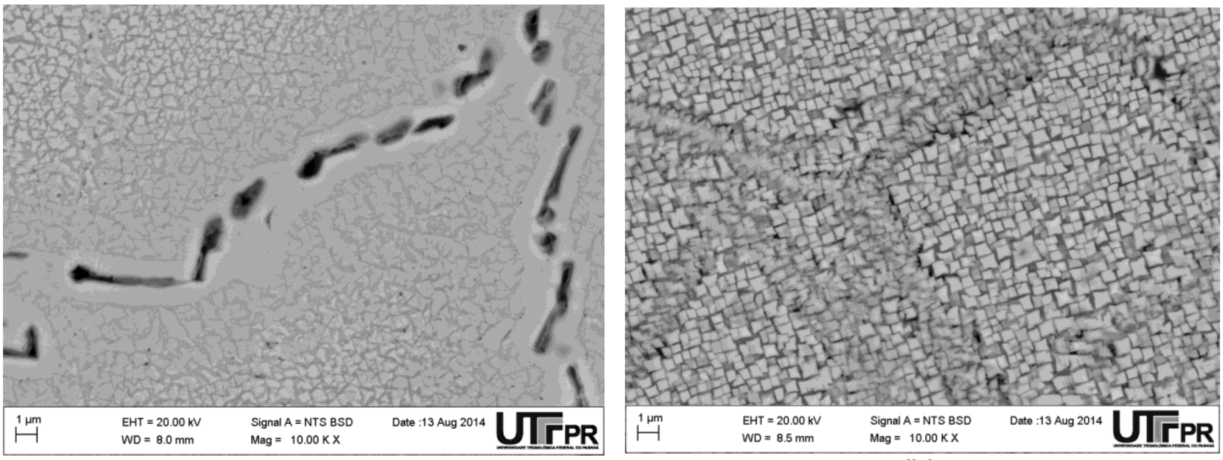

(a) (b)

Figure 2. Detail of microstructure of PTA coatings: a) as-deposited (note the presence of carbides), and b) heat treated.

After heat treatment, the carbides were not more revealed, due to their probable dissolution (Fig. 2b). This result is in agreement with the observed decrease in hardness (Table 1), but in opposite with the findings described by [13]. The presence of iron can affect the kinetics of precipitation, and a metallurgical analysis is relatively complex, as demonstrated in [11]. Considering the relatively low volume fraction of carbides, and the maintenance of intermetallic matrix, the low reduction in hardness after heat treatment is in agreement with the descriptions of coatings microstructures.

3.2. Wear Performance

Table 2 shows the mass loss determined in RWAT for PTA and HVOF coatings.

Table 2. Mass loss values for HVOF and PTA coatings determined in RWAT [g/N.min]

	As-deposited	Heat treated
HVOF	0.0011 ± 0.00002	0.00083 ± 0.00003
PTA	0.00076 ± 0.00006	0.00094 ± 0.00009
Casting condition		0.00012

In the as-deposited condition, the PTA coatings performed better than the HVOF ones, although its Vickers hardness was smaller. One can attributed this difference to the presence of porous in the HVOF-sprayed coatings. In a previous investigation [8], the porous amount measured in Figure 3a was 0.23%. Using the same procedures, and avoiding the oxidized region, this amount decrease to 0.11% in Figure 3b.

After heat treating, a significant variation in the wear resistance was observed. Nonetheless, the effect of thermal exposure resulting in an increase of 21% for HVOF-sprayed coatings, while a reduction of 20% occurred in PTA-welded ones.

The abrasion resistance of an as-cast nickel aluminide was described elsewhere [8], comparing it with that observed for sprayed-HVOF coating. Now, the post-treatment applied for HVOF process resulted in a wear rate in the same order of magnitude of that observed for the as-cast material.

The similar wear rates between treated HVOF coating and PTA-welded is another important result. For Fe-based alloys [4], although the heat treatment could mean an increase in the wear resistance of HVOF-sprayed coatings, the resistance of PTA-welded ones was significantly superior, for any metallurgical condition. In addition, the described comparisons between HVOF-sprayed and PTA-welded coatings the

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latter uses to have a better wear performance, including Ni-base alloys [5, 6]. The results presented in Table 2 shows that similar behaviors can be obtained, in spite the presence of surface defects on HVOF coatings.
Figure 3 shows the worn surfaces of tested coatings, revealed in SEM. One can observe from Figure 3 that ploughing and cutting micro-mechanisms are present in all cases. It is worthwhile that the level of cutting is the lowest, which agrees with the wear resistances described in Table 2, i.e., this coating presented the better wear resistance. The relation between the presence of cutting micro-mechanism and wear resistance for the other conditions is also reasonable, considering the small difference among them.

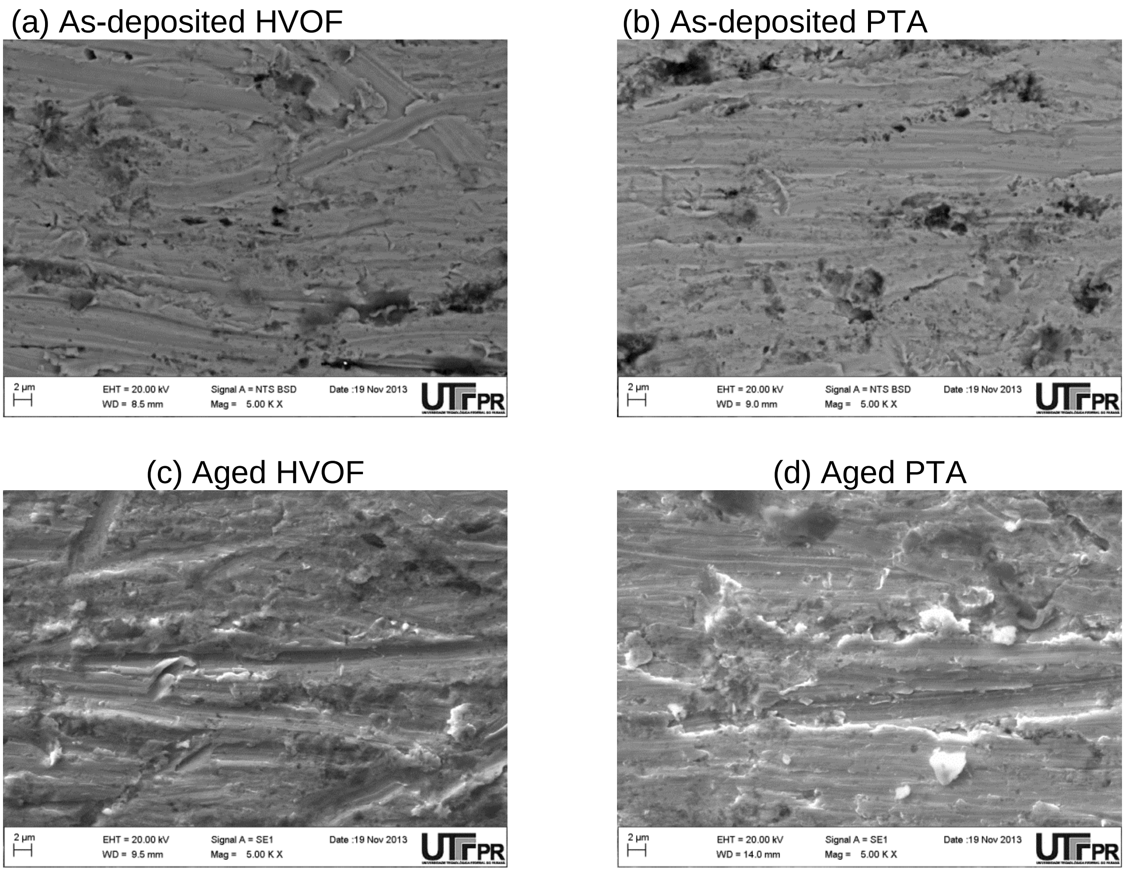

Figure 3. Worn surfaces of tested coatings, revealed in SEM: a) as-deposited HVOF coating; b) as-deposited PTA coating; c) aged HVOF coating; and d) aged PTA coating.

The wear behavior of PTA coatings has a relation with their hardness: the higher the hardness, the higher the wear resistance. For HVOF process, other aspects are more important, especially the amount of porous and the continuity of coating-substrate interface. Both effects were already described elsewhere for Fe-based HVOF coatings [10]. The heat treating reduces the amount of porous, clearly observed in the Figure 1. The worn depth is relatively higher than the depth where oxides were detected, once their importance to the wear process can be neglected.

4 CONCLUSIONS

Nickel aluminide coatings were processed during PTA and HVOF depositions onto 316L stainless steel. Rubber wheel abrasion tests were conducted, allowed concluding:

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- As-deposited coatings processed by PTA performed better than those processed by HVOF with respect to the abrasive wear;
- The abrasive wear resistance of PTA coatings was directly related to the hardness. After heat treating, the hardness of PTA coatings decreased, as well as their wear resistance. For these cases, the microstructure changes played a key role on the hardness and wear resistance;
- Heat treating changes the amount of porous in HVOF coatings, reducing their mass loss, which is comparable with that observed for PTA-welded ones.

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REFERENCES

1 Simunovic K, Saric T, Simunovic G. Different Approaches to the Investigation and Testing of the Ni-Based Self-Fluxing Alloy Coatings-A Review. Part 1: General Facts, Wear and Corrosion Investigations. Tribology Trans., 2014;57:955-979.
2 Kim H-J, Grossi S, Kweon Y-G. Wear performance of metamorphic alloy coatings. Wear, 1999;232(1): 51-60.
3 Kim H-J, Grossi S, and Kweon Y-G. Characterization of Fe-Cr-B based coatings produced by HVOF and PTA processes. Metals and Materials, 1999;5(1):63-72.
4 Hill H, Kunze M, Heet C, Petsch A, Weber S, Reiter R, Giese P, Theisen W, Wielage B, Wesling V. Correlation of processing route and heat treatment with the abrasive wear resistance of a plastic mold steel. Materialwissenschaft und Werkstofftechnik, 2012;43(8):711-718.
5 Hart KWD, Harper DH, Gill MJ, Case studies in wear resistance using HVOF, PTAW and Spray Fusion surfacing, in: 1st International Thermal Spray Conference, Materials Park, OH, ASM International, Montreal, Canada, 2000, pp. 1117–1125.
6 Kulu P, Tarbe R, Žikin A, Sarjas H, Surženkov A. Abrasive wear resistance of recycled hardmetal reinforced thick coating. Key Eng. Mater., 2013;527:185-190.
7 Da Silva WS, Souza RM, Mello JDB, Goldenstein H. Room temperature mechanical properties and tribology of NICRALC and Stellite casting alloys. Wear. 2011;271(9):1819-1827.
8 Benegra M, Magnani M, Goldenstein H, Maranho O, Pintaude G. Abrasion and corrosion resistance of new Ni–based coating deposited by HVOF thermal spray process. Surface Engineering, 2010;26(6):463-468.
9 Benegra M, Pintaude G, D'Oliveira ASCM, Goldenstein H. Characterization of NiCrAlC PTA coatings. Materials Research, 2012;15(5):775-778.
10 Maranho O, Rodrigues D, Boccalini Jr. M, Sinatora A. Mass loss and wear mechanisms of HVOF-sprayed multi-component white cast iron coatings. Wear, 2012;274:162-167.
11 Benegra M, Pintaude G, Ribas GO, D'Oliveira ASCM. Microstructural stability of nickel aluminide coatings processed by PTA with different contents of aluminum. Acta Microscópica, 2014; 23:70-77.
12 Almeida VB, Takano EH, Mazzaro, I, D'Oliveira ASCM. Evaluation of Ni-Al coatings processed by plasma transferred arc. Surface Eng., 2011;27(4):266-271.
13 Farina AB, Silva W, de Campos MF, Goldenstein H. In: Proc. 17th Brazilian Cong. on 'Materials science and engineering', Foz do Iguaçu, Brazil, October 2006, Instituto de Pesquisas Energéticas e Nucleares (IPEN), Paper 302–138.
14 Standard test method for measuring abrasion using the dry sand/rubber wheel apparatus', G65-04, ASTM, Philadelphia, PA, USA.