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Effect of Fuel-to-Oxygen Ratio to Tungsten Carbide-Nickel (WC-Ni) High Velocity Oxy Fuel (HVOF) Deposition

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Abstract: Carbon steel widely used in the industrial world at diverse applications such as marine, nuclear/fossil fuel power plants, shipping, chemical processing, mining, building, and metal processing equipment. The surface of carbon steel easy to rust towards time cause by high temperature and environmental surrounding that consists air and the solution of the problem is use coating to protect the carbon steel. High velocity oxy – fuel was use for method of coating and base of material coating use during coating process is powder. Therefore, the first objective of the study is to determine the suitable value of the oxygen to fuel ratio on WC-Ni coating but to make sure WC-Ni coating is the best coating, The coating material use for this investigation such as tungsten carbide-nickel (WC-Ni) and tungsten carbide-cobalt chromium (WC-CoCr) coating will use to make the comparison on wear and hardness test that focus only High velocity oxy-fuel (HVOF) method. The second objective of the study is to determine suitable type of fuel used on coating spray on porosity, hardness, particle velocity, and particle temperature. The effect of fuel to oxygen ratio can see on image of porosity of scanning electron microscope (SEM). Coating with the higher hardness value combined with the lower wear is attainable for fuel-to-oxygen ratio about 1.3 and kerosene fuel is suitable for coating process.

Keywords: Carbon Steel, HVOF Coating, Fuel-to-oxygen Ratio, Wear, Hardness

1. Introduction

Carbon steel as a substrate to the research have gained most attention because of their excellent mechanical and thermophysical properties as thermal-structural components in aerospace and re-entry vehicles. The weakness of carbon steel easily to rust due to several factors such as exposure to temperature and environmental surrounding, strain and during manufacturing [1]. Coating used to coat the surface of substrate. The engineering applications are growing the composite coating criteria that are demanding to protect the substrate to maintain its mechanical strength and increase its wear and corrosion resistance especially in petroleum industry, marine, anaerobic digestion and construction [2].

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Thermal spraying is a method of depositing metallic and nonmetallic producs on the surface o f the soil, either in a liquefied or semi liquified condition, which tends to provide excellent resistance to degradation, oxidation, and corrosion [3]. The deposition technique is highly versatile and is available in a range of versions, such as APS (air plasma spray), high velocity oxy fuel (HVOF) and HVAF (high velocity air-fuel), laser deposit (LD), spark plasma sintering (SPS) and vacuum or atmospheric plasma spraying (VPS or APS) but for this research focus on HVOF because it more suitable for WC-Ni coating [4].

HVOF is used to deposit composite coatings that are high in density, superior bond strengths and relatively low decarburization due to the high particle speeds induced during the deposition process and relatively low particle temperatures. To enhance the wear resistance of various engineering components in different industrial and agricultural environments [2]. HVOF thermal spray method has shown significant benefits compared to other surface hardening techniques because of the versatile, the toughness of the hardening step and the cheap price in depositing WC-oriented layers such as laser cladding, electrical deposition and chemical / physical vapor deposition (CVD / PVD) [5]. HVOF thermal spray method provides low porosity and low oxide coatings, as well as strong adhesion to substrates.

Tungsten carbide (WC) has received considerable attention due to many of the desirable catalytic properties with regard to hydrogen oxidation and hydrogenolysis reactions [6]. The WC grid induces some plasticity and high ductility breaking while maintaining high carbide strength. Tungsten carbide-nickel (WC-Ni) composites are known as high density, strength, heat stability and excellent wear resistance and durability which developed by first pressing a mixture of WC and Fe powders and then melting Ni in a quantity corresponding to less volume than the preforms porosity to ensure high WC material [7,8]. Nickel-based alloys are widely used for high wear resistance and corrosion resistance in severe environments due to high temperature, wear, corrosion, impact and fatigue [9].

2. Effect of Ratio on Fuel to Oxygen to the Substrate

This subchapter discuss about the mechanical properties of different value of ratio. This subtopic uses to prove or support one of the criteria on the research objective. The output of this chapter will reveal the suitable value of fuel to oxygen ratio. Based on the previous work that had similar research objective such as fuel to oxygen ratio coating using on substrate. The coating material use for this investigation such as WC-Ni and WC-CoCr. According to the result presented in Table 1, nine sample with different value of fuel to oxygen ratio as shown in Table 1 and the summary of the value of fuel to oxygen ratio shown in Figure 1 and 2.

Table 1 above shows the microhardness and wear rate result for WC coating for different value of fuel to oxygen ratio. The highest result of hardness is 1375 HV and lowest value of hardness is 1210 HV. The hardness of WCC-CoCr has higher hardness on low fuel-to-oxygen ratio and WC-Ni has higher hardness on high fuel – to – oxygen ratio because the flame temperature depends on fuel – to oxygen ratio and gas pressure to melted the powder coating which can affect the coating properties such as hardness [12].

The highest wear rate at ratio of 1.05 which value is $8.7\times10^{-18}mm^3/(mN)$. The lowest wear rate at ratio of 1.1 which value is $0.51\times10^{-18}mm^3/(mN)$. For wear rate, it better to choose the result of low wear rate because it can reduce possibility to have fracture for long period of time [13].

Table 1: Comparison between different values of fuel-to-oxygen ratio.

Method	Spray Parameter		Mechanical Properties		References
	Coating material	Fuel-to-oxygen ratio	Microhardness (HV)	Wear rate ($\times 10^{-18}$ $mm^3/(mN)$)	
HVOF	WC-Ni	1.1	1244	0.51	[10]
		1.2	1264	0.57	
		1.3	1366	0.68	
	WC-CoCr	1.05	1220	8.7	[11]
		1.08	1220	7.5	
		1.15	1210	7.1	
	WC-CoCr	0.38	1375	7.8	[11]
		0.40	1355	5.4	
		0.45	1339	3.7	

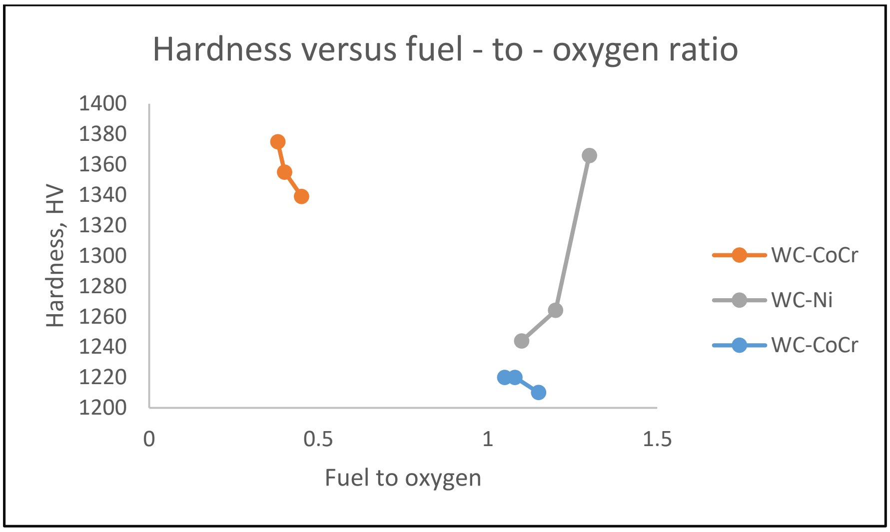

Figure 2: Graph hardness versus fuel-to-oxygen ratio [10,11]

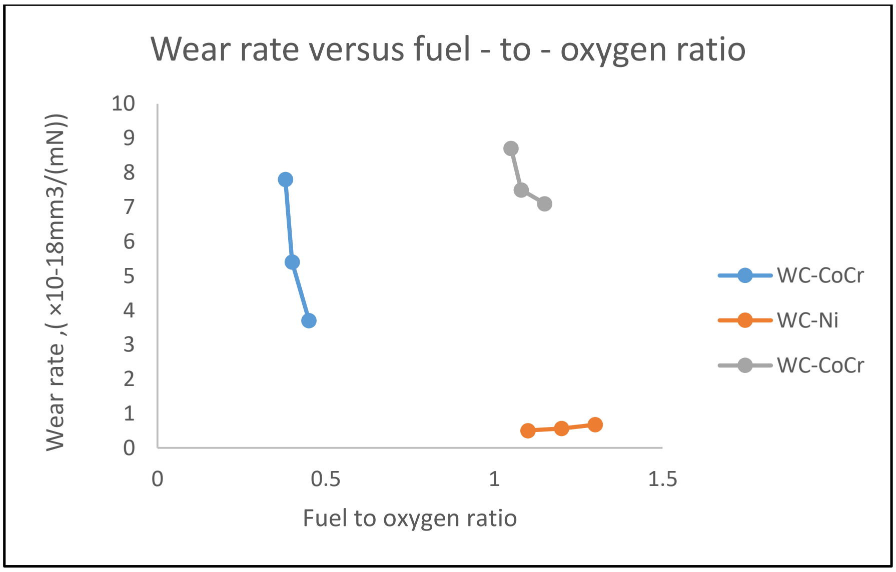

Figure 3: Graph wear rate versus fuel-to-oxygen ratio [10,11]

Based on the Figure 2 and 3, there shown illustrated of fuel to oxygen ratio that using hardness and wear rate test for the mechanical behaviour illustrate from Table 1. From the graph, it shows that highest value of hardness on ratio 0.38 is 1375 and high in wear rate value is $7.8\times10^{-18}mm^3/(mN)$ which it not best to choose as the suitable value of fuel to oxygen ratio. Meanwhile, the lowest value of wear rate on ratio of 1.1 is $0.51\times10^{-18}mm^3/(mN)$ but it also low in hardness value is 1244 HV. Based on the graph, the most suitable for fuel to oxygen ratio is 1.3 because it has good value of hardness is 1366 HV and the low value of wear is $0.68\times10^{-18}mm^3/(mN)$. The previous researcher mention that fuel to oxygen ratio change the quality of coating which had greater hardness value [14][13]. The coating that use on fuel to oxygen ratio of 1.3 is WC-Ni. So, WC-Ni coating is best material of coating use in the research. Figure 3 show the image of wear rate of different value of fuel to oxygen ratio on WC-Ni coating.

3. Effect of Different Type of Fuel to the Substrate

This subtopic will explain and prove that which one is better type of fuel that can be used at coating spray. Based on the investigation, the author had found four different type of fuel which can be discuss on this subtopic. Table 2 below show the comparison of result on different type of fuel on fuel to oxygen ratio based on the previous researcher which specifically for HVOF method.

Table 2: The result between different types of fuel to oxygen ratio use HVOF method.

Spray parameter		Mechanical properties				
Type of fuel	Fuel-to-oxygen ratio	Hardness (HV)	Particle temperature (°C)	Porosity (%)	Particle velocity (m/s)	References
Propene	0.219	1352	1764	12.1	675	[15]
	0.240	1196	1824	13.9	570	
	0.220	1151	1762	11.4	675	
Propene	0.15	600	-	4	-	[16]
	0.188	1180		8		
	0.25	1000		12		
Hydrogen	1.46	1103	1925	3.7	325	[17]
	1.60	1186	1850	3.5	325	
	1.67	1143	1800	2.8	335	
Hydrogen	0.38	1375	1879	0.43	643	[11]
	0.40	1339	1867	0.50	632	
	0.45	1355	1890	0.40	666	
Kerosene	1.05	1220	1840	0.45	761	[11]
	1.08	1220	1842	0.57	770	
	1.15	1210	1835	0.50	779	
Kerosene	1.10	645	-	2.6	-	[14]
	1.04	640		2.63		
	0.98	696		1.42		
Kerosene	1.1	1220	-	1	600	[10]
	1.2	1240		2.5	590	
	1.3	1350		4.5	570	
Methane	0.773	-	2230	-	410	[18]
	0.875		2210		430	
	1		2200		440	

Table 2 that the result of different type of fuel that can be used on the coating spray. It shows the result between four different type of fuel which are kerosene, hydrogen, methane, and propene. The highest value of hardness based on the table above is hydrogen which the value of hardness is 1375 HV while for lowest value of hardness is propene which the value is 600 HV. The highest value of particle temperature of different type of fuel is methane which the value is 2230°C while the lowest value of particle temperature is propane which the value is 1762°C. The highest value of porosity of different type of fuel is propene which the value is 13.9% while the lowest porosity is hydrogen which the value is 0.40%. The highest value of particle velocity of different type of fuel is kerosene which the value is 779 m/s while the lowest particle velocity is hydrogen which the value is 325 m/s.

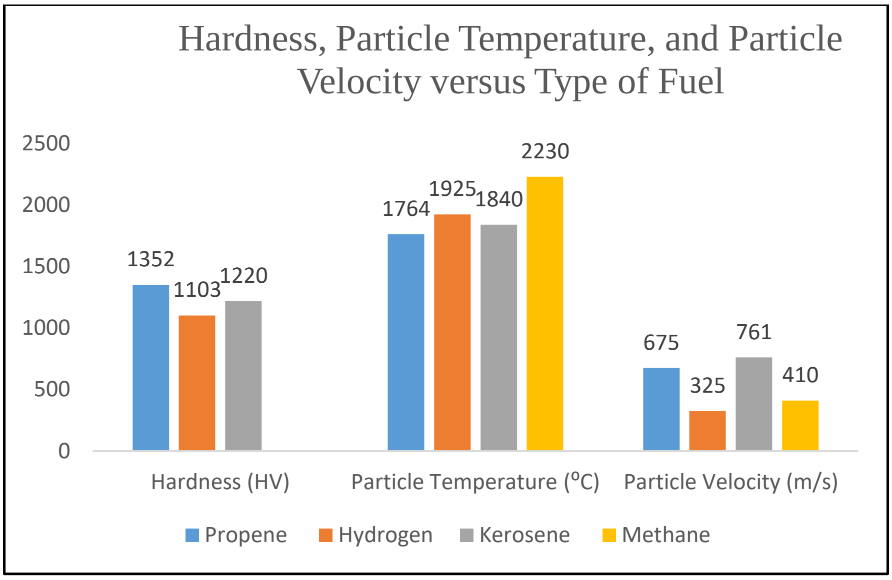

Figure 4: Hardness, Particle Temperature, and Particle Velocity versus Type of Fuel [10,14,16]

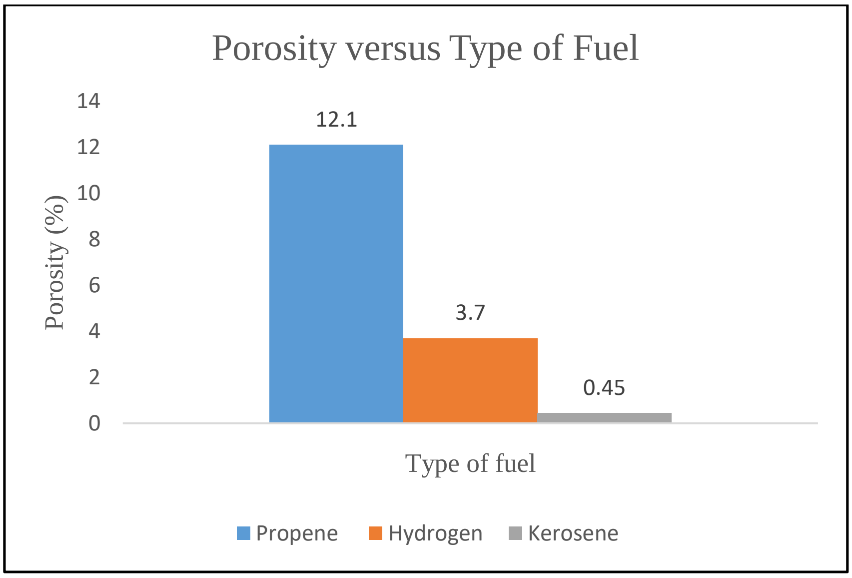

Figure 5: Porosity versus Type of Fuel [10,14,16]

From the graph show in Figure 4 and 5, it shows different of fuel such as propene, hydrogen, kerosene, and methane will compare with hardness, particle temperature, porosity and particle velocity. From the graph it shows that hydrogen and kerosene is better than propene on the type of fuel because hydrogen and kerosene have low porosity compare to propene which has higher in porosity. The fuel of methane cannot be compared with porosity because it has no data to compare.

But comparison hydrogen and kerosene, it shown that kerosene to oxygen clearly is better than hydrogen to oxygen which it can be seen in the table of result. The kerosene better than hydrogen because it has low in particle temperature compare to hydrogen. For both fuels, the amount of porosity got decreases and the particle velocity and temperature tended to increase.

4. Microstructure Mechanism of Substrate Sprayed by Coating

This subtopic discusses about the structure of coating material in term of porosity. Based on the image of structure substrate had been captured by SEM. The structure observation can be made based on Figure 6. From the figure, the shape of porosity was occurred on image of different fuel to oxygen ratio. The porosity is a pore a formed of black holes that occurred on surface of substrate. The substrate surface structure significantly affects the toughness of the coating because different substrate surface structures can strengthen or weaken.

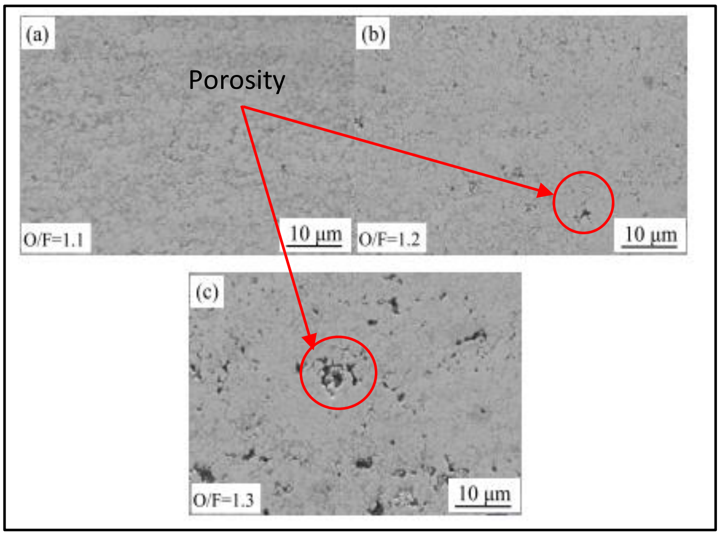

Figure 6: Diagram of SEM image with different fuel-to-oxygen ratio a) ratio value of 1.1, b) ratio value of 1.2, and c) ratio value of 1.3 in WC-10Ni coating [10]

Coating and substrate adhesion and coating debris flow. The pores can reserve some varnish for porous substrate under the cutting movement, thus providing a longer life [19].The existence of the pore can affect the substrate from processing of the bulk coating. From the image, it shows that porosity that occur on different fuel to oxygen ratio. The ratio value of 1.1 show a little no existent of pore. The ratio value of 1.2 show the small amount of pore which it not too effect. Lastly, ratio value of 1.3, there are apparently increase with number and size of pore and size of pore bigger than ratio value of 1.2.

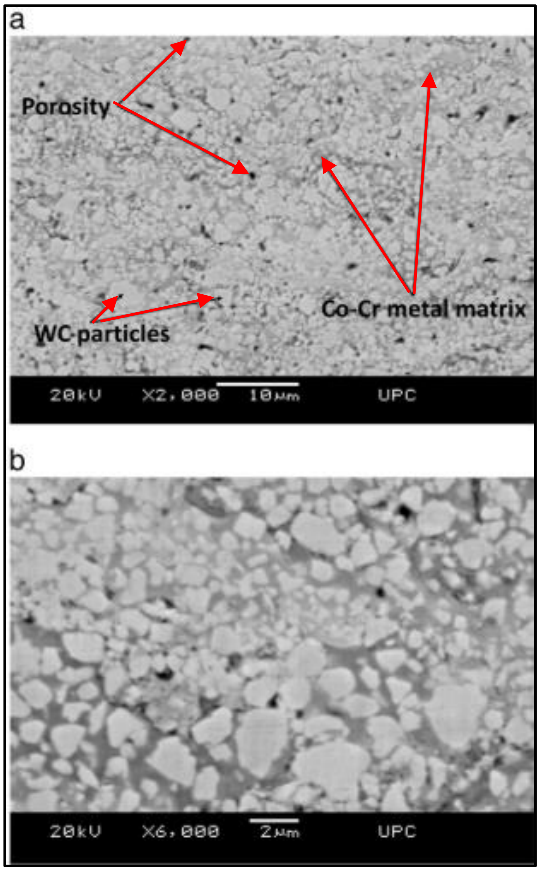

Figure 7: (a) Micrograph of coating material WC-CoCr using (Wokajet-400); (b) image of detail on microstructure using material WC-CoCr coating (DJ2600) [11]

For Figure 7, there are 2 different image that present different type of fuel occurred. For image (a), the fuel that use on process of coating is kerosene and for image (b) fuel that use on process of coating is hydrogen. The image of (b) was taken closely than image of (a) based on the revolution. The durability and porosity of the surface are related to the temperature and velocity of the agglomerates during spraying [11]. These features decreased with increased spray particle temperature and an improved melting degree of particles. The combination of high temperature and velocity will help to deform the layer after impact, so that solidifying splats will balance the surface and fill pores and defects in the previously deposited layer.

5. Conclusion

This study focused on the effect of fuel to oxygen ratio deposition of thermal spray process on HVOF-spraying method of coating powder on steel substrate. Based on the result, the fuel-to-oxygen ratio influences the result on hardness and wear because flame on spray has oxidation reaction that can lead to an increased the equilibrium constant. The greater value of hardness and the lower value of wear rate produce suitable value of fuel-to-oxygen ratio. The result also shows the coating material on better value of fuel-to-oxygen ratio is WC-Ni coating compared to WC-CoCr. Meanwhile, the suitable fuel used for spray coating was kerosene compared to propane, hydrogen, and methane which it resulted higher in particle velocity and lower on particle temperature.

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References

[1] Ahmad NA, Kamdi Z, Tobi ALM. Wear and corrosion behavior of tungsten carbide based coating on carbon steel. Int J Integr Eng 2018;10:119–25. doi:https://doi.org/10.30880/ijie.2018.10.04.020.

[2] Fayyazi S, Bahrololoom ME, Kasraei M. Optimizing High-Velocity Oxygen Fuel-Sprayed WC--17Co Coating Using Taguchi Experimental Design to Improve Tribological Properties. Trans Indian Inst Met 2018;71:3045–62.

[3] Padmavathi G, Sarada BN, Shanmuganathan SP, Padmini B V, Mohan N. Effects of high velocity oxy fuel thermal spray coating on mechanical and tribological properties of materials--A review. Mater Today Proc 2020;27:2152–7.

[4] Lamana MS, Pukasiewicz AGM, Sampath S. Influence of cobalt content and HVOF deposition process on the cavitation erosion resistance of WC-Co coatings. Wear 2018;398–399:209–19. doi:10.1016/j.wear.2017.12.009.

[5] Song B, Murray JW, Wellman RG, Pala Z, Hussain T. Dry sliding wear behaviour of HVOF thermal sprayed WC-Co-Cr and WC-CrxCy-Ni coatings. Wear 2020;442:203114.

[6] Munakata H. Development of nanoparticle composite technique for low pt-loading PEFCs. 2012. doi:10.1016/B978-0-444-56336-1.50073-4.

[7] Cramer CL, Preston AD, Elliott AM, Lowden RA. Highly dense, inexpensive composites via melt infiltration of Ni into WC/Fe preforms. Int J Refract Met Hard Mater 2019;82:255–8.

[8] Zhang FG. Friction and wear behavior of WC/Ni cemented carbide tool material irradiated by high-intensity pulsed electron beam. Ceram Int 2019;45:15327–33.

[9] Weng Z, Wang A, Wu X, Wang Y, Yang Z. Wear resistance of diode laser-clad Ni/WC composite coatings at different temperatures. Surf Coatings Technol 2016;304:283–92.

[10] Zhu XP, Du PC, Meng Y, Lei MK, Guo DM. Correlation of process parameters to surface integrity responsible for wear resistance of HVOF sprayed WC-NI coatings. ASME 2017 12th Int Manuf Sci Eng Conf MSEC 2017 Collocated with JSME/ASME 2017 6th Int Conf Mater Process 2017;1:1–8. doi:10.1115/MSEC20172927.

[11] Picas JA, Punset M, Baile MT, Martín E, Forn A. Effect of oxygen/fuel ratio on the in-flight particle parameters and properties of HVOF WC-CoCr coatings. Surf Coat Technol 2011;205:S364–8. doi:10.1016/j.surfcoat.2011.03.129.

[12] Oksa M, Turunen E, Suhonen T, Varis T, Hannula S-P. Optimization and characterization of high velocity oxy-fuel sprayed coatings: techniques, materials, and applications. Coatings 2011;1:17–52.

[13] Korobov Y, Shalimov M. Energy efficiency by thermal spraying. WIT Trans Ecol Environ 2014;190:455–66.

[14] Feitosa FRP, Gomes RM, Silva MMR, De Lima SJG, Dubois JM. Effect of oxygen/fuel ratio on the microstructure and properties of HVOF-sprayed Al59Cu25. 5Fe12. 5B3 quasicrystalline coatings. Surf Coatings Technol 2018;353:171–8.

[15] Ludwig GA, Malfatti CF, Schroeder RM, Ferrari VZ, Muller IL. WC10Co4Cr coatings

deposited by HVOF on martensitic stainless steel for use in hydraulic turbines: Resistance to corrosion and slurry erosion. Surf Coatings Technol 2019;377:124918.

[16] Yao H-L, Yang C, Yi D-L, Zhang M-X, Wang H-T, Chen Q-Y, et al. Microstructure and mechanical property of high velocity oxy-fuel sprayed WC-Cr3C2-Ni coatings. Surf Coatings Technol 2020;397:126010.

[17] Guo X, Planche M-P, Chen J, Liao H. Relationships between in-flight particle characteristics and properties of HVOF sprayed WC-CoCr coatings. J Mater Process Technol 2014;214:456–61.

[18] Planche MP, Normand B, Liao H, Rannou G, Coddet C. Influence of HVOF spraying parameters on in-flight characteristics of Inconel 718 particles and correlation with the electrochemical behaviour of the coating. Surf Coatings Technol 2002;157:247–56.

[19] Yang J, Fridrici V, Messaadi M, Kapsa P. The effect of porous substrate on the tribological performance of a MoS2 based coating in fretting by statistical analysis. Wear 2015;330:122–35.