ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 41 (2012) 1689 – 1695

Engineering Procedia

www.elsevier.com/locate/procedia

International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012)

Impact of Plasma Spray Variables Parameters on Mechanical and Wear Behaviour of Plasma Sprayed Al_2O_3 3%wt TiO_2 Coating in Abrasion and Erosion Application

Abdul Rahim Mahamad Sahab[a]*, Nor Hayati Saad[b], Salmiah Kasolang[b], and Juri Saedon[b]

[a]*AMREC, SIRIM Berhad, No. 1, Persiaran Dato' Menteri, P.O. Box 7035, Shah Alam, Selangor, 40700, Malaysia*
[b]*Faculty of Mechanical Engineering, Universiti Technologi MARA Shah Alam, Selangor, 40450, Malaysia*

Abstract

Alumina-titania coatings produced by plasma spray processes are being developed for a wide variety of applications that require resistance to wear, erosion, cracking and spallation. Consideration of parameters setting will develop reliable coatings with high performance properties for demanding coating application. Al_2O_3 3%wt TiO_2 coating was produced onto metal substrate using Praxair Plasma Spray System with SG-100 Gun. This paper discusses the experimental and testing performance analysis of the coating which prepared based on three varied process parameters (current, powder flow rate and stand-off-distance). With the varied coating parameters, test results showed that increasing current from 550A to 650A and powder flow rate from 22.5g/min to 26 g/min increased the performance of mechanical properties of coating (adhesion strength & hardness) and gave the lowest friction coefficient value (i.e. best wear resistance) of coating. Increasing stand-off-distance from 75mm to 90mm also increased hardness performance and provided the lowest friction coefficient value of coating. However increasing stand-off-distance has decreased adhesion strength at setting powder flow rate of 26g/min and 650A current. The behavior of such parameters setting significantly influenced the production of optimum Al_2O_3 3%wt TiO_2 coating onto metal substrate.

Keywords: Plasma sprays; process parameters; ceramics coating; mechanical properties; wear behaviour.

---

1. Introduction

Thermal spraying is one of the advance hard facing engineering technologies for surface preparation and protection [1]. The technology has been used extensively as a remedy to combat wear, corrosion, heat, oxidation and other problems occurring across the whole spectrum of the manufacturing and engineering industries [2]. The diversity of thermal spraying processes used for hard coating is due to the variety of applications and the required properties, as well as consideration of economic aspects [3]. Basically, thermal spray coatings are produced by melting and projecting a powder material and building up a surface coating at the substrate [4]. The different coating microstructures and properties are depending on the spray technique, powder properties and spray parameters of the coating [5]. The coating condition such as porosity, closed pores and un-melted particles are always the cause of defects in coatings. There are advanced tests or performance tests techniques of plasma sprayed ceramic coatings in order to determine the coating properties such as mechanical tests, chemical tests and thermal tests [6].

---

* Corresponding author. Tel.: +603-55446862; fax: +603-55446867.
E-mail address: rahimms@sirim.my

doi:10.1016/j.proeng.2012.07.369

Plasma spray technique is currently the primary method used commercially to produce thick coating. The applications involve wear, heat and corrosion resistance, surface restoration and others basically required in aircraft, automobile, power plant and oil and gas industries [7]. Alumina (Al_2O_3) and mixed alumina with titania are widely used in plasma sprayed as coating materials. The high hardness of alumina properties contributes wear resistant coating and electrical insulation properties [8]. Alumina is also highly thermal conductivity insulated for any substrate. Alumina with approximately 3, 13 and 40 wt% titania are used extensively as wear resistance coating. The hardness and friction coefficients of coating are decreased with greater levels of titania content [9]. A number of variables parameters are selected to produce the desired coating; these include the plasma spray, powder feedstock, material injection and processing variables. Plasma spray processing variables include the gun configuration, process gases, pressures, flow rates, voltage, amperage and carrier gases. The powder variables include chemistry, morphology, particle size distribution and manufacturing method. Material injection variables include powder feed rate, carrier gas flow, number of injectors, angle of injection and location of injection, while processing variables include the number of passes, spray distance, spray trajectory, traverse speed, tool fixture and part cooling [10].

2. Experimental Details

2.1. Materials and substrate preparation

In this experiment steel plate, JISG3101: SS 400 with thickness of 4.5 mm and 7.85 g/cm^2 density was selected for metal substrate. The steel plate selected is a technical delivery conditions for general purpose structural steel which is used to build ship, bridge, etc. Ceramic feedstock Al_2O_3 3%wt TiO_2 was used as the main coating. Ni 5%wt Al powder was used as bond coat coating. Table 1 shows materials specifications used for coating measured by Shimadzu 1700 XRF analysis.

The metal substrate samples were cut to 130 mm length and 25mm width each. Every substrate then was cleaned from any oxide and grease with acetone. The cleaned metal substrates surface were grit blasted using aluminium oxide blasting media at 35 PSI blasted pressure and approximately 15 mm stand-off-distance. The metal substrate was sprayed parallel to the blasting gun with a step distance of 5mm using 40 mesh grit media.

2.2. Plasma spray and coating deposition

The prepared substrate was fixed in the spraying chamber and coated with bond coat coating Ni 5%wt Al feedstock and followed by the top coat coating of Al_2O_3 3%wt TiO_2 using Praxair Plasma Spray System with SG-100 Gun. Before both coating processes, the substrate surface was heated by plasma flame at transverse speed of 500 mm/s and at 90 mm, a distance between plasma head and substrate. The temperature range of the substrate was between 100^{o}C and 200^{o}C. During coating process, 3 passes were sprayed for the bond coat and 10 passes for the top coat coating. After coating process, the samples were cooled in room temperature and collected for testing and analysis. Table 2 shows the parameters setting used for bond coat, top coat coating processes and also the varied setting process parameters for the top coat (i.e. current, powder feed rate and stand-off-distance).

Table 1. Feedstock specification for bond and top coat coating

Materials	Chemical Composition	Weight, *(%)*	Average particle size, *(µ)*
Al_2O_3 3% TiO_2	Al_2O_3	94.5	-53 micron
	TiO_2	2.66	
	SiO_2	2.11	
	Fe_2O_3	0.26	
	MgO	0.26	
	Others	0.24	
Ni 5%wt Al	Al	4.14	-106 + 45 m
	Ni	95.86	

Table 2. Process parameters used for bond Coat (Ni 5%wt Al) and top coat coating (Al_2O_3 3% TiO_2)

No	Variables parameters	Bond coat coating	Top coat coating
1	Primary gas (Argon), PSI	50	50
2	Carrier gas (Argon), PSI	30	30
3	Voltage, V	40	40
4	Current, Amp	650	Varying (550 and 650)
5	Powder flow rate, g/min	22.5	Varying (22.5 and26)
6	Stand-off-distance, mm	90	Varying (75 and 90)
7	Transverse speed, mm/s	500	300
8	Spray angle, ^{O}	90	90

2.3. Testing of coating and analysis procedure

In mechanical test measurement the coated samples were evaluated for adhesion strength using ASTM Standard C633-01. The coating sample was bonded with araldite precision long lasting epoxy glue for both surfaces (coated and without coating surface) and then pulled out using Shimadzu AG 500 Universal Testing Machine. While hardness tests measurement was measured using Matsuzawa Microhardness Tester at a polished cross-section surface of the coated sample. Wear test (Pin-On-Disc) was applied to determine the performance of the coating sample in sliding wear. The coated sample was determined using CSEM Tribometer Equipment (single pin contact) at a rotational speed of 394 rpm, 500 m sliding distance and 5 N load. The microstructure analysis of the coating was measured using Hitachi S-2500 Scanning Electron Microscopy Equipment.

3. Test result and discussion

3.1. Adhesion Strength

Adhesion strength is one of the major requirement test technique being applied for hard coating technology. The composite specimen was loaded in tension until it is failed perpendicular to the coating surface and the maximum load before failed was measured to calculate the adhesion strength.

3.1.1. Adhesion strength and stand-off-distance

Fig. 1 shows the graph of adhesion strength versus stand-off-distance at 75mm and 90mm of Al_2O_3 3%wt TiO_2 coatings. The highest and lowest adhesion strength of coating at spraying distances of 75mm are 11.4 MPa (S2) and 5.0 MPa (S3). The highest and lowest adhesion strength of coating at spraying distance of 90mm are 8.4 MPa (S6) and 6.5 MPa (S7). The highest adhesion strength was identified at the setting parameters for the powder flow rate of 26 g/min and current setting at 650A. At the specified parameters setting, increasing stand-off-distance from 75mm to 90mm reduced the adhesion strength of coating. Scientifically, optimum stand-off-distance is important to ensure good adherence of coating bonding. Too short spraying distance will produce lower adherence due to overheating and resulting internal stress inside the coating. In contrast, too long spraying distance will decrease the adherence bonding due to cooling and deceleration of the particles flying in the plasma beam.

3.1.2. Adhesion strength and powder flow rate

Fig. 2 shows the graph of adhesion strength versus powder flow rate at 22.5 g/min and 26 g/min for the Al_2O_3 3%wt TiO_2 coating. The highest adhesion strength for the powder flow rates of 22.5 g/min and 26 g/min are 8.1 MPa (S1) and 11.4 MPa (S2), where both samples were set at spraying distance of 75 mm and current setting of 650A. The graph pattern shows that increasing powder flow rate will increase the adhesion strength of coating. The coating samples at spraying distance of 75 mm and current setting of 650A presented the highest adhesion strength of coating.

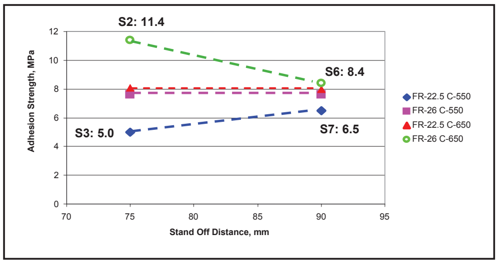


Fig. 1. Adhesion strength versus stand-off-distance

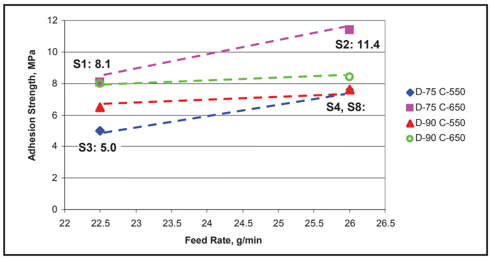


Fig. 2. Adhesion strength versus powder flow rate

3.1.3. Adhesion strength and current

Fig. 3 shows the graph of adhesion strength versus current setting at 550A and 650A. The highest and lowest adhesion strength for the current setting of 550A is 7.6 MPa (S4 & S8) and 5.0 MPa (S3). The highest and lowest adhesion strength for the current setting of 650A is 11.4 MPa (S2) and 8.0 MPa (S5). It can be observed that the highest adhesion strength was identified at the spraying distance of 75mm and powder flow rate of 26 g/min. Graph pattern shows that increasing current will increase the adhesion strength of coating. At the specified setting parameters, the sample set at 650A portrayed the highest adhesion strength compared to the other samples. By increasing the current, the temperature of process increased (the current and gas volume supplied to the plasma arc significantly affect the thermal content of plasma gas and heat transfer to the sprayed powder). Therefore, more particles were melted, and hence high adhesion strength of coatings were produced.

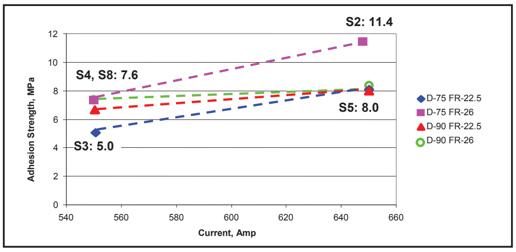


Fig. 3. Adhesion strength versus current

3.2. Hardness

Al_2O_3 3%wt TiO_2 coating was measured for the hardness at the polished cross section surface. The diamond indentation tip area was determined by measuring the indentation size by an optical microscope at 50X magnification after the sample being unloaded. Fig. 4 shows an example of indentation surface of the Al_2O_3 3%wt TiO_2 coating under SEM observation.

3.2.1. Hardness and stand-off-distance

Fig. 5 shows a graph of hardness versus stand-off-distance set at 75mm and 90mm. The highest and lowest hardness of coating sample at spraying distance of 75mm were 736.7 Hv (S2) and 473.1 Hv (S3). The highest and lowest hardness of coating samples at spraying distance of 90mm were 772.7 Hv (S6) and 587.0 Hv (S7). The highest hardness of samples for both spraying distance (75mm and 90mm) was identified at current setting of 650A and powder flow rate of 26 g/min. The graph pattern shows that by increasing the spraying distance, the hardness of coating will increase. At shorter distances the plasma beam hits the substrate and overheats it considerably, causing excessively molten particles to splash, creating a less dense coating [11]. Since coarse-grained feedstock was used (refer to Table 1), therefore, longer spraying distances are required. It is believed that longer spraying distance provided sufficient time for the powder to dwell and melt properly and hence produced high hardness of coating.

Fig. 4. Diamond indentation profile of the hardness test measurement under SEM

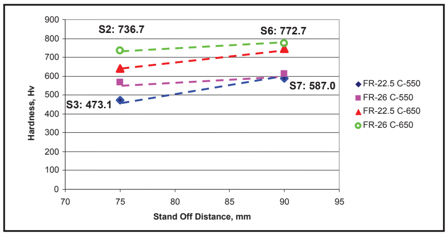


Fig. 5. Hardness versus powder flow rate

3.2.2. Hardness and powder flow rate

Fig. 6 shows a graph of hardness versus powder flow rate setting at 22.5 g/min and 26 g/min. The highest and lowest hardness of samples at powder flow rate of 22.5 g/min were 744.9 Hv (S5) and 473.1 (S3). The highest and lowest hardness of samples at powder flow rate set at 26 g/min were 772.7 Hv (S6) and 567.3 Hv (S4). The graph pattern shows that by increasing powder flow rate, it will increase the hardness of coating. It is expected that by increasing the powder flow rate, rate of deposited material increased. Therefore, the hardness of coating increased. However, in ensuring homogenous and less porosity coating layers, the current also should be increased to ensure the powders is melted properly when the powder flow rate was increased. The highest hardness of samples for both setting powder flow rate (22.5 g/min and 26 g/min) was identified at spraying distance of 90mm and current setting of 650A.

3.2.3. Hardness and current

Fig. 7 shows a graph of hardness versus current setting at 550A and 650A. The highest and lowest hardness of samples at current setting of 550A were 611.6 Hv (S8) and 473.1 Hv (S3). The highest and lowest hardness of samples at current setting of 650A were 772.7 Hv (S6) and 640.5 Hv (S1). The highest hardness of samples for both current setting (650A and 550A) was identified at spraying distance of 90mm and powder flow rate of 26 g/min. The graph pattern shows that by increasing the current setting, it will increase the hardness of coating. By increasing the current setting, more energy was provided to the plasma beam. As a result, more particles melted and hence the hardness of coating increased.

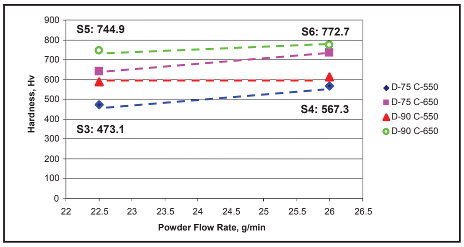


Fig. 6. Hardness versus powder flow rate

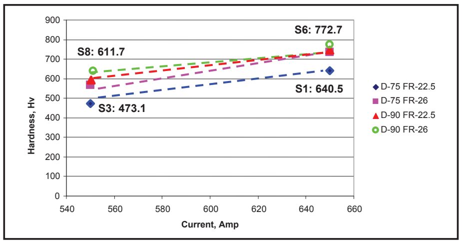


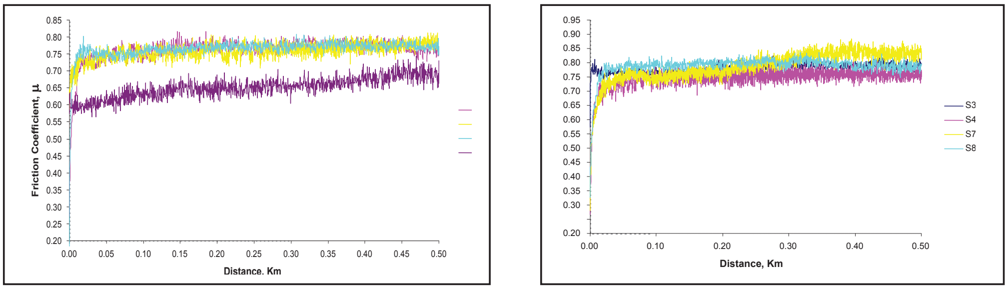
Fig. 7. Hardness versus current

3.2.4. Wear behaviour

Table 3 shows test results for the friction coefficient of Al_2O_3 3%wt TiO_2 coating. Fig. 8(a) and Fig. 8(b) show results of evaluated friction coefficient during sliding test at 650A and 550A current setting respectively. Two distinct regions were identified in the plotted graph. The first and second region is called running-in and stabilization regions respectively. The first region is related to the running of the materials against themselves. The second region is considered based on the system of the part (coating sample) and the counterpart (alumina ball) [12]. During the running-in stage, as the roughness of the materials is reduced, the friction coefficient increases rapidly due to particle generation from mating surfaces. Then the friction coefficient stabilized representing the wear behaviour of couple materials which is shown in the second region [13]. The estimation of the mean friction coefficient value is referred to the stabilization regime data.

Table 3. Test results for the friction coefficient of Al_2O_3 3%wt TiO_2 coating

Sample	Current, *Amp*	Powder flow rate, *g/min*	Stand-off-distance, *mm*	Friction Coefficient, $\mu(-) \pm \sigma(-)$
S1	650	22.5	75	0.774 ± 0.027
S2	650	26	75	0.768 ± 0.025
S3	550	22.5	75	0.784 ± 0.013
S4	550	26	75	0.750 ± 0.031
S5	650	22.5	90	0.772 ± 0.023
S6	650	26	90	0.678 ± 0.038
S7	550	22.5	90	0.801 ± 0.049
S8	550	26	90	0.772 ± 0.026



(a) Sliding test at 650A current setting

(b) Sliding test at 550A current setting

Fig. 8. Test results of evaluated friction coefficient during sliding test

The value of the friction coefficients of the samples were varied according to the setting parameters as shown in Table 3. The best wear resistance (i.e. the lowest friction coefficient) was obtained for the sample S6 (0.678 ± 0.038) corresponding to the 650A current setting, 26 g/min powder flow rate and 90mm stand-off-distance. The highest coefficient friction occurred for the sample S7 (0.801 ± 0.049) corresponding to 550A current setting, 22.5 g/min powder flow rate and 90mm stand-off-distance. Referring to the graphs pattern (Fig. 8(a) and Fig. 8(b)) and Table 3 show that by increasing powder flow rate from 22.5 g/min to 26 g/min reduced the value of coefficient friction. Increasing current setting from 550A to 650A reduced the value of coefficient friction except for the samples S2 and S4. By Increasing the spraying distance from 75mm to 90mm reduced the coefficient of friction except for samples S3 and S7.

The best wear resistance (sample S6) was obtained corresponding to combination of three setting parameters (650A current setting, 26 g/min powder flow rate and 90mm stand-off-distance). It can be explained by an effect on the available energy for powder particle heating and acceleration before substrate impingement and sufficient amount of melted powder which was deposited on the surface to form good coating. The increase of the plasma energy (with the increase of arc current) and the increase of amount of melted powder improved flattening process of particles as their viscosity and surface tension decreased. This in turn reduced porosity level between lamellas and increased inter-lamellar cohesion. Cohesion improvement is responsible for a good wear resistance and can explain the decrease of friction coefficient [13]. However, increasing the arc current intensity and the spraying distance also had consequence to increase the friction coefficient (sample S2 and S4; and S3 and S7 respectively). Bounazef et al., 2004 emphasized that high current setting may induce high stress on the powder particle. The stress effect acts against the particle characteristic by decreasing inter-lamellar cohesion. The increase of spraying distance may also decrease the inter-lamellar cohesion due to the decrease of depth of the particle penetration in the plasma jet [12]. Thus, low wear resistance of coating is produced.

4. Conclusion

- The parameters setting such as powder flow rate, current and stand-off-distance has provided evidence to directly influence the properties and performance of Al_2O_3 3%wt TiO_2 coating. The hardness, adhesion strength and wear behaviour of Al_2O_3 3%wt TiO_2 coating varied depending on the process parameters setting.

- Increasing the parameters setting powder flow rate and current setting improved the adhesion strength and hardness of Al_2O_3 3%wt TiO_2 coating. Increasing stand-off-distance increased hardness and decreased adhesion strength of Al_2O_3 3%wt TiO_2 coating.

- Increasing the parameters setting powder flow rate, current and stand-off-distance produced the best wear resistance (i.e. the lowest friction coefficient) of Al_2O_3 3%wt TiO_2 coating.

- Process parameters setting of coating material (feedstock) selection gives significant effects on the mechanical, physical properties and performance of the coating.

- Other elements such as substrate preparation, bond coating and substrate heating during coating process have to be crucially considered in order to produce good coating quality.

Acknowledgements

This research is supported by SIRIM Berhad and Ministry of Sciences, Technology and Innovation (MOSTI), Malaysia under IRPA grant no: 09-1-01-10002 EAR. The authors wish to thank individuals who were involved directly and indirectly to the success of the research study.

References

[1] Knotek O., 2001. Thermal spraying and detonation gun process, Hand Book of Hard Coating, R.F. Bunshah, Editor. Noyes Publications, New Jersey, USA, p. 77-107.
[2] Harrisson K.A-Metco Ltd., 1996. Thermal spraying - An overview, Surface Engineering Casebook: Solutions to corrosion and wear-related failures, Burnell J.S., Datta P.K., Editors. Woodhead Publishing Limited, Cambridge, England, p. 73-92.
[3] Grainger S., Blunt J., 1998. Engineering Coatings - Design and Application, Grainger S., Blunt J., Editors. William Andrew Publishing, Second Edition, p. 1-7.
[4] Berndt C.C., 1980. The Adhesion of Flame and Plasma Sprayed Coatings. Thesis for PhD, Department of Material Engineering, Monash University, Australia.
[5] Li J.F., Liao H., Wang X.Y., Coddet C., Chen H., Ding C.X., 2004. Plasma spraying of nanostructured partially yttria stabilized zirconia powders. Thin Solid Films 460, p. 101-115.
[6] Herman H., Berndt C.C., Wang H., 1993. Plasma Sprayed Ceramic Coatings, Ceramic Films and Coating Hand Books, Wachtman J.B., Haber R.A., Editors. Noyes Publications, New Jersey, USA, p. 131-188.
[7] Reeve C.,2001. Thermal Spray – Coating: Better performance for less. Machine Design, p.73-76.
[8] Pantelis D.I., Psyllaki, Alexopoulos N., 2000. Triboligical behaviour of plasma-sprayed Al_2O_3 coatings under severe wear conditions. Wear 237, p. 197-204.
[9] Zatorski R.A., Herman. H., 1991. High Performance Ceramic Films and Coatings. Elsevier, Amsterdam, p. 591-601.
[10] Gansert R.V., 2002. Plasma Sprayed Ceramic Coatings. Ceramic Industry.
[11] Matejka D., Benko B, 1989. Plasma Spraying of Metallic and Ceramic Materials. John Wiley & Sons, United Kingdom.
[12]Bounazef M., Guessasma S., Montavon G., Coddet C, 2004. Effect of APS process parameters on wear behaviour of alumina-titania coatings. Materia1 letters 58, p. 2451-2455.
[13]Guessasma S., Bounazef M., Coddet C, 2004. Note POD test parameters to study wear behaviour of alumina-titania coatings. Materials Characterizations 52, p. 237-241.