SPRAYING PARAMETERS OPTIMIZATION FOR WEAR AND ABRASION RESISTANCE OF CR_2O_3 COATING DEPOSITED WITH CASCADED PLASMA TORCH

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Abstract

Atmospheric plasma sprayed (APS) chromia coating provides excellent wear behaviour combined with corrosion resistance even in aggressive environments. In this paper, the influence of variable spraying parameters on the mechanical properties and microstructure of chromia coatings is investigated. Main goal for this optimization is to achieve high wear and abrasive resistance. APS ceramic coatings such as chromia could perform in some industrial applications as well as more commonly used HVOF (high velocity oxygen fuel) cermet coatings, especially in wear and abrasion resistance. In order to be able to compete with hard and wear resistant cermet HVOF coatings, optimization of spraying parameters for this particular chromia powder is required. High throughput cascaded plasma troch is used for the spraying process. Set of five different spraying parameters is used varying only primary plasma gas flow rate and input electrical current with rest of spraying parameters set constant, including carrier gas flow. Critical plasma spraying parameter or CPSP is also utilized in the design stage of experiment. Coatings sprayed on low carbon steel substrate underwent superficial Rockwell indentation, optical microscopy on polished cross section, adhesion strength testing and dry sand abrasion test. No significant correlation between CPSP values and hardness, adhesive strength or abrasion resistance was observed. High input electrical current combined with rather high plasma gas flow provided better abrasion resistance than lower input electrical current and flow rates. Coating performing best in abrasion test also displayed by far the highest adhesive strength to substrate material, so presumably having also the highest cohesion strength between splats may lead to less inter splat decohesion or chipping during dry sand abrasion.

Keywords: Thermal spraying, atmospheric plasma spraying, APS, cascaded plasma torch, Cr_2O_3, chromia coating, abrasion resistance

1. INTRODUCTION

One of the chief industrial use of thermal sprayed coatings is protection against wear. Whereas HVOF (high velocity oxygen fuel) sprayed cermets such as WC-Co, WC-CoCr or Cr_3C_2-NiCr are usually used for many kinds of wear and abrasion resistant protective coatings and are quite common as an alternative to conventional wear protection (such as hard chrome), plasma sprayed ceramics (e. g. Al_2O_3 or Cr_2O_3) can perform in many cases as well as HVOF sprayed cermets. HVOF cermet-based wear resistant coatings have superior quality compared to plasma sprayed cermet coatings, concerning much lower porosity, lower oxidation of melted powder and splats and overall low carbide decomposition [1]. On the other hand, plasma spraying with its extremely high temperatures between 15 000 to 20 000 K provided by plasma jet allows melting of ceramic materials, something that is impossible or at least very problematic with HVOF spraying due to HVOF much lower temperature provided by combustion of oxygen and kerosene mixture. Oxidation due to the higher temperature and lower jet velocities of plasma jet is no longer an issue with oxide ceramic materials, since the powder material is already in form of fully oxidized compounds. An additional considerable factor is also cost of powders, with fine cermets for HVOF spraying being overall more expensive than oxide ceramic powders for plasma spraying. The only remaining issue in comparison of HVOF cermet coatings and plasma sprayed ceramics can be considerable higher porosity of the latter. [1,2]

One of possible plasma wear and abrasion resistant material is chromia – Cr_2O_3. This paper concerns an atmospheric plasma sprayed (APS) chromia coating deposited with unconventional cascaded design plasma torch. Main goal for this paper is to present optimization of spraying parameters with intention to achieve coating with high dry particles abrasion resistance. To test the abrasive resistance of coatings, dry sand - rubber wheel testing machine according to ASTM G-65 standard was used. Possible objective for abrasive and wear resistant APS chromia coating can be replacement of HVOF cermet in some industrial applications. Optimization of spraying process parameters of commercial chromia powder with high throughput unconventional atmospheric plasma torch is carried out and results with possible conclusions are presented further in this paper.

2. POWDER AND SPECIMEN MATERIAL

Pure chromia commercial powder Metco 6155 by Oerlikon Metco with nominal particle size distribution between 15 and 45 micrometers was chosen as the default material. Manufacturing method for this powder is sintering and crushing. Manufacturer guarantees typical amount 99.7 wt. % of Cr_2O_3. Trace amount of other oxide ceramics in the powder is presented (TiO_2, SiO_2, Al_2O_3).

S235 construction steel served as the substrate material. Specimens of cross section of 25 mm x 5 mm and 75 mm in length were used for Dry sand rubber wheel test and specimens of same cross section and 50 mm length for metallography and indentation. In additional five cylindrical samples of 25 mm diameter and 6 mm height were used per every set of parameter to evaluate adhesion or cohesion strength.

3. SPRAYING PARAMETERS AND SETUP

Spraying parameter for atmospheric plasma torches include primary and secondary plasma gas flow rates and input electrical current. Plasma gas flowrate and composition in combination with input electrical current determinate the formation of plasma jet – the final velocity of jet and its temperature. This plasma jet formation is also influenced by the diameter of torch nozzle as well as the overall construction of plasma torch. For this particular spraying, cascaded plasma troch SinplexPro from Oerlikon Metco with 9 mm nozzle diameter was used. Plasma gas was mixture of argon as primary gas and hydrogen as secondary gas. Other spraying parameters directly influencing spraying process and consequently final properties of the coating are spraying distance (i. e. distance between torch nozzle and substrate material), powder mass flow and carrier gas flow rate. All parameter listed above determinate velocity and temperature (or state of melting) of powder particles. Kinetic and thermal energy of particles in combination witch substrate temperature and heat transfer rate have major effect on the formation of splat morphology and crystallization of the coating.

It was decided to simplify this optimization as much as possible in order to get reasonable results and not to spend excessive amount of time and resources. Knowledges from previously sprayed ceramic materials with same torch were utilized as well as recommendations from manufacturer of troch and powder (Oerlikon Metco for both). Constant spraying distance of 105 mm was used, as well as constant powder mass flow of 76 g/min. Argon served as a carrier gas, with optimized flow rate set for this particular spraying setup. Flow rate of hydrogen as secondary plasma gas was also set constant to 5 l/min. Argon flow rate as primary plasma gas and input electrical current was chosen as the only two variable parameters. This is because these two are proved to have principal influence on the formation of plasma jet and thus influencing final functional properties of ceramic materials, where heat energy amount and transfer during spraying process plays a significant role.

And as stated above, plasma gas flow rate and input electrical current are most important factors influencing velocity and temperature of plasma jet.

Input electrical current was varied on 5 levels: 450 A, 520 A, 530 A, 593 A and 600 A. Argon flow rate was chosen on to levels: 40 l/min and 50 l/min. Those variable parameters create two dimensional matrix 5x2 as seen below in **Table 1**. This matrix provides totally 10 possible combination of spraying parameters. To reduce final number of variable spraying parameter sets and especially to avoid possible duplication of parameters with respect to final kinetic and heat conditions, critical plasma spraying parameter (CPSP) was utilized [3]. This parameter allows rough estimation of proportion between kinetic energy and heat flux in the plasma jet (see equation (1) below [3]).

$$CPSP = \frac{P\ [kW]}{\dot{V}_{Ar}\ [sl/m]} \tag{1}$$

where:

CPSP – critical plasma spraying parameter (kW/slpm)

P – indicated power input (kW)

$\dot{V}_{Ar}$ – argon flow rate (slpm)

Table 1 Optimization matrix of variable spraying parameters (each cell contains number of given set and *CPSP value in italics*)

Input electrical current (A)	**Primary argon flow rate (l/min)**	
	40	**50**
450	N.1 *CPSP 1.01*	
520	N.2 *CPSP 1.18*	
530		N.4 *CPSP 1.02*
593	N.3 *CPSP 1.38*	
600		N.5 *CPSP 1.17*

Totally 5 sets of variable spraying parameters were chosen taking three different levels of CPSP value into account. CPSP value starting just about 1.01 for the lowest level (parameter sets N.1 and N.4), raising over 1.18 for the second level (parameter sets N.2 and N.5) and ending up to value of 1.38 as the highest value (parameter set N.3).

4. TESTING METHODS

Specimens from all spraying sets underwent optical metallography on polished cross section of the coating. Superficial Rockwell indentation HR15N (120° diamond cone, load force 147.1 N) according to ISO 6508-1 was carried out on the fine ground surface of the coated specimen of every set (10 indents each). Abrasive resistance to dry sand was tested according to ASTM G-65 standard (Dry sand rubber wheel test) on three samples from every set. Standard test method for adhesion or cohesion strength of thermal spray coatings according to ASTM C633 - 13(2017) were performed on five samples of 25 mm diameter from each set.

5. RESULTS

Results of HR15N indentation with approximate conversion to HRC (conversion according to ASTM E140) as well as slope of abrasive line of cumulative mass loss from Dry Sand Rubber Wheel Test are shown in **Table 2** with correlation to variable spraying parameters (input current, argon flow rate and CPSP). Highest superficial hardness displayed samples of N.3 (CPSP 1.02) and N.5 (CPSP 1.17) parameter sets with HRC valuing up to 61. Of these two sets, the latter also performed best in dry sand abrasion testing with the lowest slope of abrasive line (**Figure 1**) and had by far highest adhesive strength of all sets with average adhesive strength of 44 MPa. No significant differences in microstructure between individual samples were observed (**Figure 2**). Like in most atmospheric plasma sprayed ceramic materials, micro cracks and relatively significant porosity is presented in the coatings.

Table 2 Results of superficial Rockwell indentation (HR15N), approximate conversion of HR15N to HRC and slope of abrasive line of cumulative mass loss (the lower the more resistant to dry sand abrasion)

Parameter set	Input electrical current [A]	Argon flow [l/min]	CPSP [kW/(sl·min^{-1})]	HR15N	approx. HRC	slope of abrasive line of cumulative mass loss	Adhesive strength [MPa]
N.1	450	40	1.01	89.3 ± 0.7	58-59	0.369	28.7 ± 0.3
N.2	520	40	1.18	86.2 ± 2.7	50-53	0.438	31.9 ± 6.8
N.3	530	40	1.02	90.4 ± 1.6	60-61	0.401	29.1 ± 8.0
N.4	593	50	1.38	89.1 ± 1.6	57-58	0.348	30.2 ± 3.4
N.5	600	50	1.17	90.1 ± 1.8	59-61	0.286	44 ± 7.0

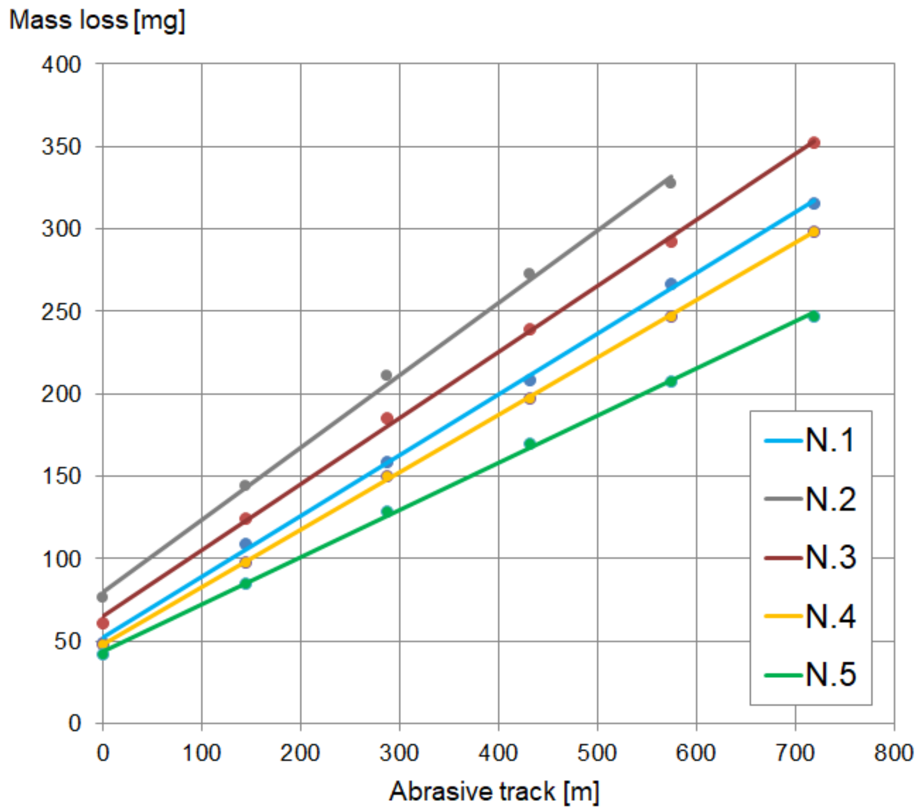

Figure 1 Dependance of cumulative mass loss on abrassive track (Dry Sand Rubber Wheel testing)

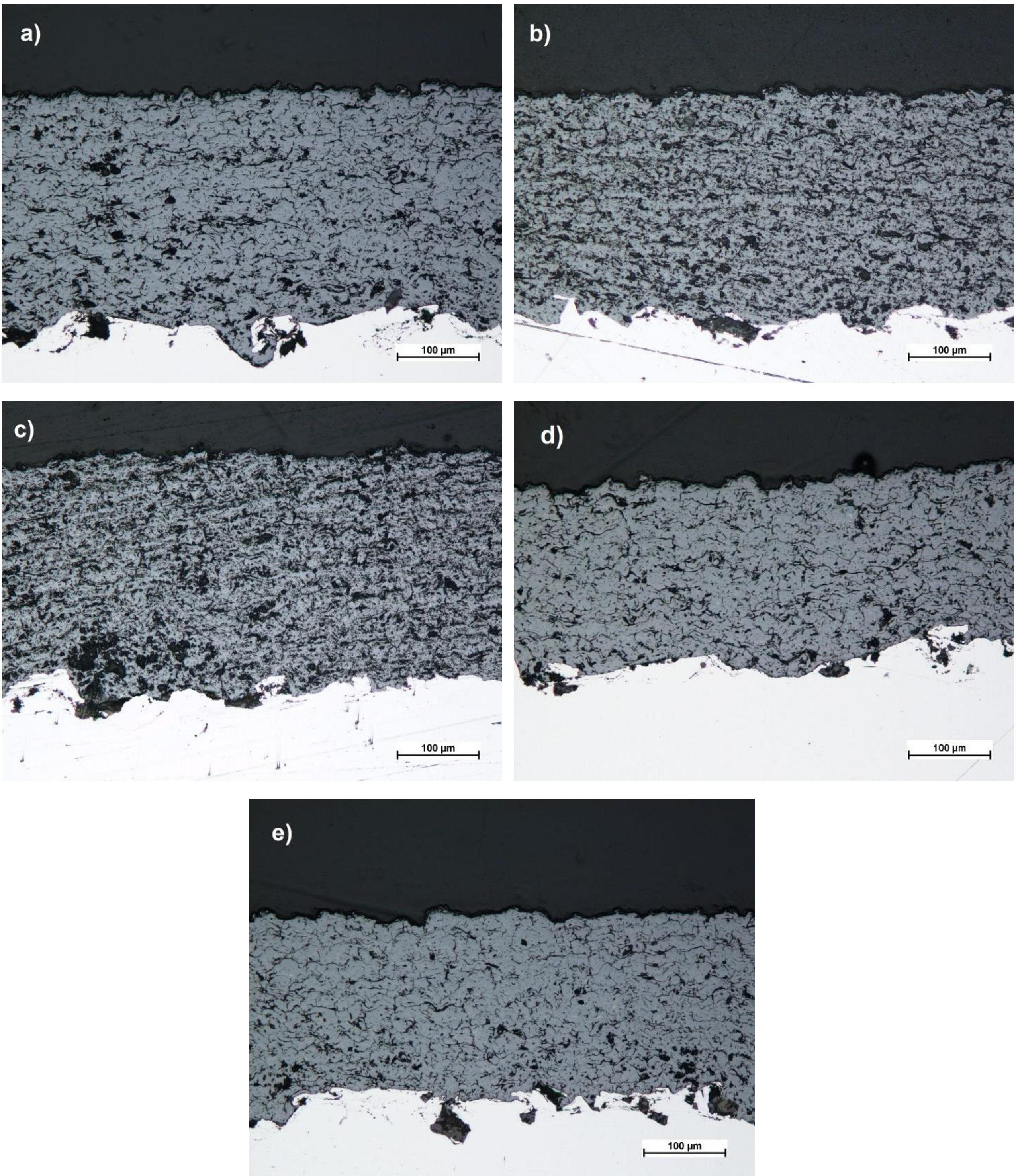

Figure 2 Optical images of Cr_2O_3 coatings cross sections (200x), steel substrate below (light grey): a) N.1 b) N.2 c) N.3 d) N.4 e) N.5

6. CONCLUSION

Five different spraying parameters variating argon flow as primary plasma gas and input electrical current were used to spray Cr_2O_3 coating on low carbon steel samples. As the main parameter in choosing argon flow rate and input electrical current, CPSP or critical plasma spraying parameter were utilized. From five sprayed sets, three different levels of CPSP were used: values about 1.01, 1.18 and 1.38. A relative large variation in superficial hardness was observed with HRC valuing from only around 50-53 on N.2 sample, sprayed with medium level of 1.18 CPSP, up to 61 HRC on samples N.3 (CPSP 1.02) and N.5. Resistance to dry sand abrasion also showed no correlation with CPSP values, with the N.5 sample performing best of all. N.3 sample, having same hardness as N.5, performed approximately 40 % worse than N.5 in abrasion test. So no significant correlation between hardness and abrasion resistance can be observed. Possible explanation of best abrasion resistance in N.5 specimens is better cohesion between individual splats, leading to less inter splat chipping and thus losing less weight during abrasion testing. This hypothesis can be supported by adhesion test results of N.5 samples (having 44 MPa, circa 40 % more than other samples), presuming positive correlation between adhesion strength of coating to substrate and coating cohesion. If relative high porosity of plasma sprayed ceramic coatings is considered, it is probable that cohesion between individual splats plays the most significant role in wear behaviour as well as in abrasion resistance. The main goal in designing process parameters for achieving wear and abrasion resistant plasma sprayed ceramic coatings could be not only gaining right phase composition of hard phases, but also obtaining coating with high inter splat cohesion.

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REFERENCES

[1] BOLELLI, G., CANNILLO, V., LUSVARGHI, L., MANFREDINI, T. *Wear behaviour of thermally sprayed ceramic oxide coatings*. Wear, 26, 2006, pp. 1298-1315.

[2] KNUUTTILA, J., AHMANIEMI, S., MÄNTYLÄ, T. *Wet abrasion and slurry erosion resistance of thermally sprayed oxide coatings*. Wear, 232, 1999, pp. 207-212.

[3] CHIDAMBARAM SESHADRI, R., SAMPATH, S. *Characteristics of Conventional and Cascaded Arc Plasma Spray-Deposited Ceramic Under Standard and High-Throughput Conditions*. Journal of Thermal Spray Technology [online]. January 2019, 28(4), stránky 690-705.