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Internal Diameter HVAF Spraying for Wear and Corrosion Applications

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Electrolytic hard chrome (EHC) methods are still widely utilized in the printing, automotive and off-shore industries. Alternative methods to EHC have been widely developed in the past decade by conventional HVOF processes and more recently HVAF systems, which are processing at higher kinetic energy and more particularly at lower temperature, significantly increasing wear and corrosion resistance properties. A dedicated internal diameter HVAF system is here presented, and coatings characteristics are compared to the one obtained by standard HVAF coatings. Specially R&D designed fixtures with inside bore of 200 mm have been manufactured for this purpose, with a possibility to spray samples at increasing depth up to 400 mm while simulating closed bottom bore spraying. WC-based and Cr_3C_2-based powder feedstock materials have been deposited onto high-strength steel substrates. Respective coating microstructures, thermally induced stresses and corrosion resistance are discussed for further optimization of coating performances. The fact that the ID-HVAF system is utilized both for spraying and gritblasting procedures is also given a particular interest.

Keywords cermet, grit blasting, HVAF, inner diameter HVAF

1. Introduction

Industrial hard chromium, also known as electrolytic hard chrome (EHC), is one of the most extensively used protective coatings for wear and corrosion applications in the aerospace, automotive, printing and oil & gas industries (Ref 1). Landing gear components, hydraulic actuators, turbine engine shafts, bearings, and propeller hubs, crankshafts, valves, hydraulic components, piston rings and inside bores are typical applications nowadays. The main issues affecting usage of chromium plating are process toxicity (Cr(VI)), low plating bath efficiency (around 15%) that leads to high energy consumption (Ref 2), the presence of cracks causing inconsistent corrosion performance, thickness uniformity and the necessity of post-treatment machining, and hydrogen embrittlement in steel substrates. Recent restrictions in the use of carcinogenic hexavalent form of chrome element have driven the need of replacing EHC deposition by environmentally benign material/process combinations with equivalent tribological properties (Ref 3, 4). Among dry deposition technologies, alternatives for coating large components and external surfaces, high-velocity oxy-fuel (Ref 5), detonation gun (Ref 6) and air plasma spraying (Ref 7) of Cermets materials have been the leading processes of choice for most applications (Ref 1, 8). One of the latest low-temperature high-kinetic thermal spray processes, named as HVAF-M3, recently outperformed its predecessor HVOF systems (Ref 9). However, the wet electro-deposited and electroless technologies, such as trivalent chromium and Nickel deposition are still needed for internal surfaces coverage, where line-of-sight spray technologies are limited (Ref 1, 10). Among many types of ID spraying (plasma, flame and HVOF torches), most ID spray applications are performed by ID-APS Ni-based coatings, utilizing a specially developed F-300 plasma gun from Sulzer Metco (Ref 10). In the present study, a dedicated internal diameter high-velocity air fuel (ID-HVAF) system has been introduced by UniqueCoat technology. The objective is to study the feasibility of spraying inner diameter component (about 200 mm) with the newly developed ID-HVAF system, for wear and corrosion applications. The use of compressed air instead of pure oxygen compared to standard HVOF systems offers economic advantages well perceived by the industry. Moreover, the fact that gritblasting procedure is operated with the HVAF gun itself offers a processing flexibility as well as new opportunity in optimizing substrate topography by supersonic gritblasting conditions for improved coating adhesion (Ref 11). Standard WC-based and Cr_3C_2-based powder feedstock materials have been deposited onto high-strength steel substrates and respective coating properties compared to standard HVAF-M3 system. Microstructure, crack properties and thickness uniformity observed at different depth of ID surface coverage is given a particular interest.

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2. Experimental Procedure

2.1 Spray Process and Feedstock Materials

A newly developed internal diameter high-velocity air fuel (ID-HVAF) spray system (UniqueCoat Technologies, Virginia, US) was utilized both for gritblasting (Alumina grit #180) and spraying operations utilizing propylene gas. The ID-HVAF gun is a miniaturized version of the actual HVAF-M3 system (Ref 9, 12), with length of 95 mm that allows spraying internal diameters above 140 to 150 mm, at a 50-mm stand-off distance. Two feedstock materials were deposited to target thicknesses of 300 µm: a spheroidal agglomerated and HIP-densified Cr_3C_2-25NiCr powder (WOKA 7310) and an agglomerated and sintered WC-CoCr powder (PRAXAIR 731-6), with (−25 + 5) and (−31 + 5.5 µm) particle size distributions, respectively. Spray rates were 5 kg/h for WC-CoCr and 7 kg/h for Cr_3C_2-25NiCr. Both powders were sprayed continuously, without waiting time between each pass, but using an external air cooling unit during both gritblasting and spraying operations. High-strength steel substrates samples (Domex355) were positioned on a conventional outer diameter fixture (OD) (Fig. 1a), and an Inner Diameter specially designed fixture (Fig. 1b) with an inside bore of 200 mm and cover plates to simulate real component wall (Fig. 2). Samples

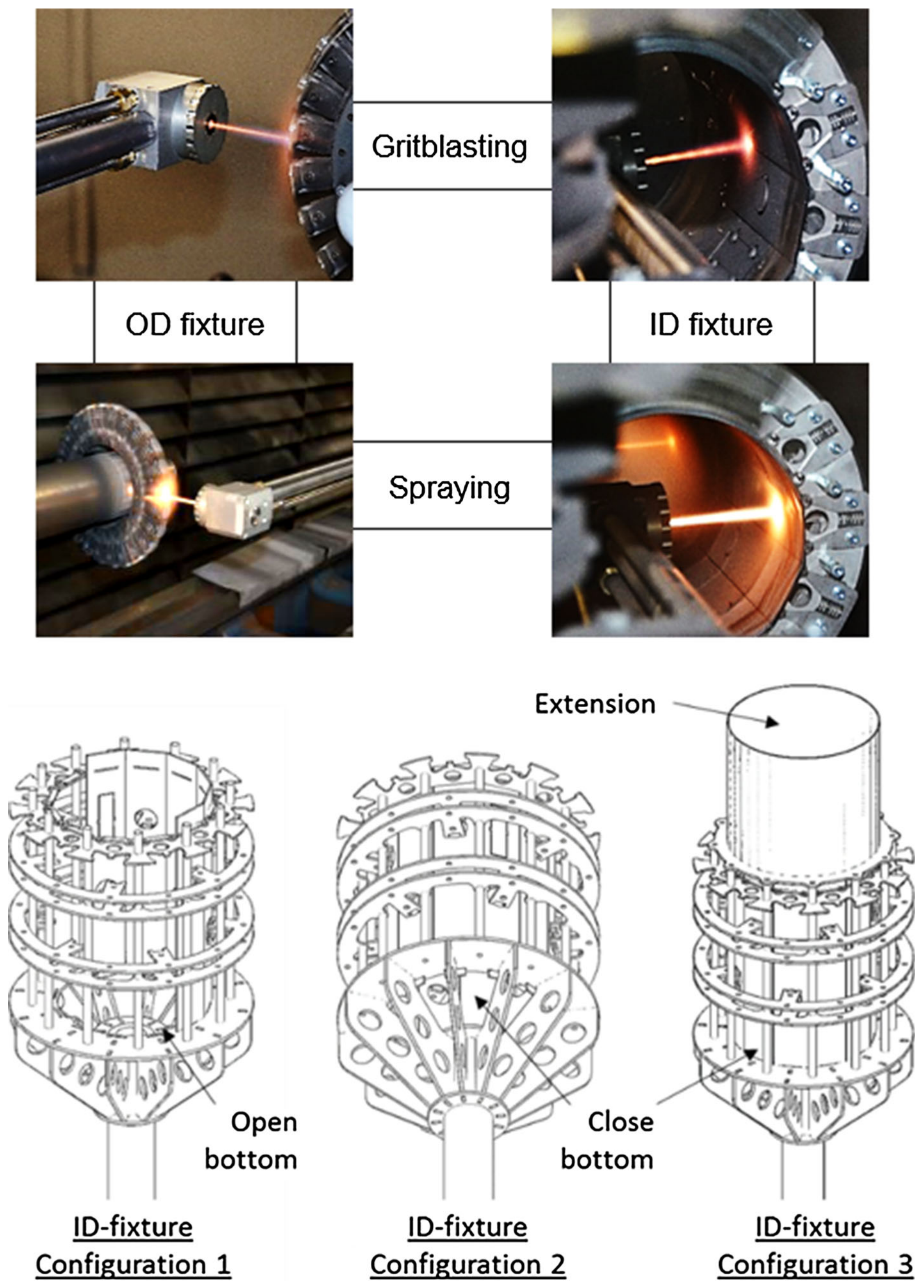

Fig. 1 Specially designed outer diameter (OD) and inner diameter (ID) sample holder for ID-HVAF system

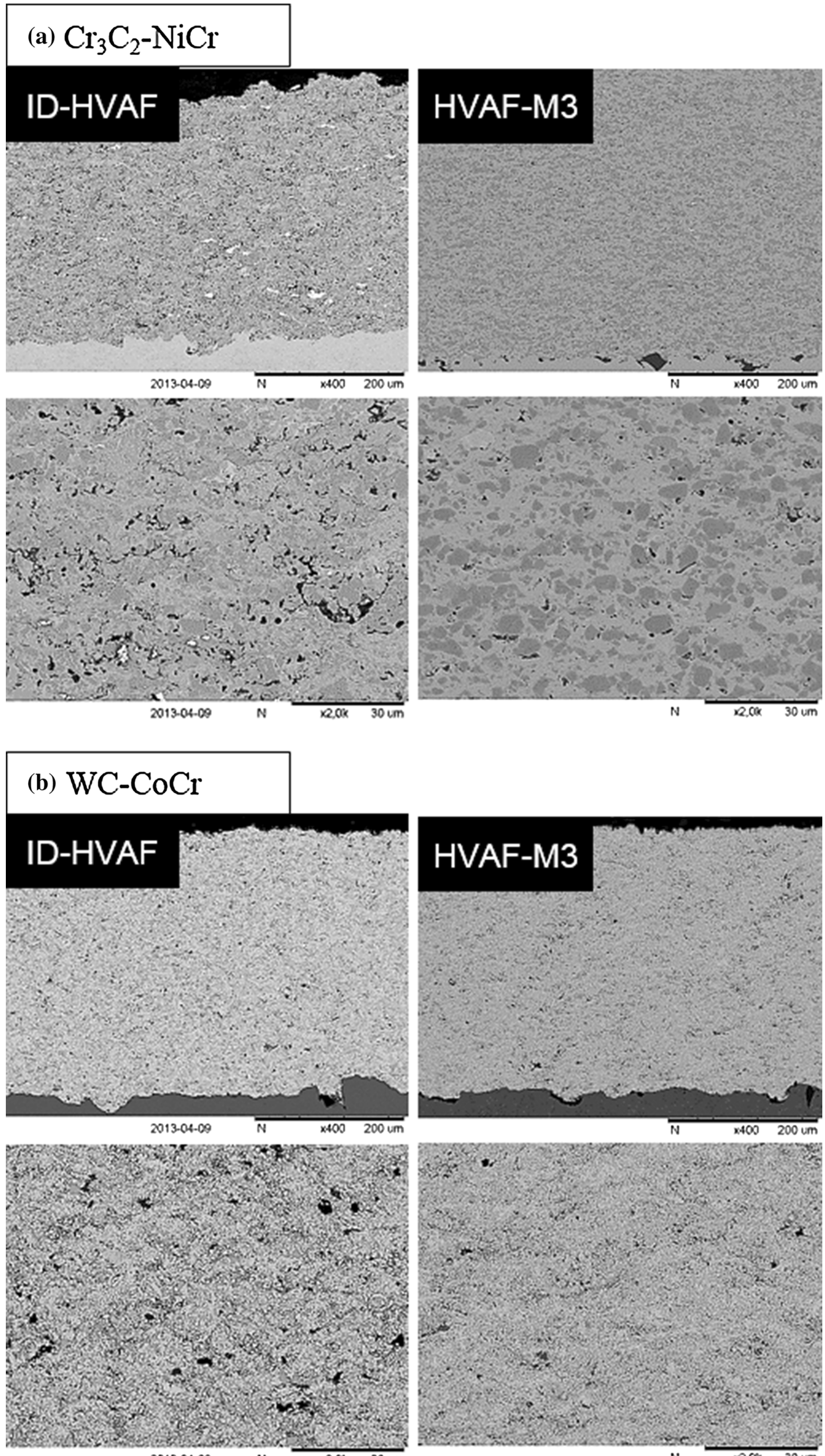

Fig. 2 Comparison of coatings sprayed by ID-HVAF gun and HVAF-M3 system on OD sample holder for (a) Cr_3C_2-NiCr and (b) WC-CoCr feedstock materials

were held by different cover plates at two positions at 100 mm (*Low*) and 200 mm (*High*) depth (Table 1). For each material, three bore configurations have been selected: (i) open bottom (*Config. 1*), (ii) closed bottom (*Config. 2*) and (iii) closed bottom with a 200-mm extension (*Config. 3*), in order to study the influence of the bore length on coating properties (dust frame-up and turbulence effects).

Table 1 Samples references and spray configurations

Materials	Config. 1	Config. 2	Config. 3
Cr_3C_2-NiCr	Cr-1-L/Cr-1-H	Cr-2-L/Cr-2-H	Cr-3-L/Cr-3-H
WC-CoCr	W-1-L/W-1-H	W-2-L/W-2-H	W-3-L/W-3-H

2.2 Characterization Methods

2.2.1 Microstructure. Coating cross sections were analysed utilizing a scanning electron microscope table top micrograph (Hitachi TM3000) with acceleration voltage of 15 kV. A specially developed image thresholding algorithms utilizing the image analysis Aphelion® software was applied on 20 SEM pictures (X7000) per samples, in order to identify the volume fraction of porosity (Ref 13).

2.2.2 Microhardness. Microhardness measurements were performed following the ASTM E384-10 by carrying out 20 indentations on a coating cross section at different loads, respectively 0.1, 0.3 and 0.5 kg.

2.2.3 Coating Roughness. The arithmetical mean roughness (*Ra*) and maximum peak-to-peak height (*Rz*) over 20 profile lines—5 mm long were evaluated per sample, utilizing Surftest-301 instrument (Mitutoyo).

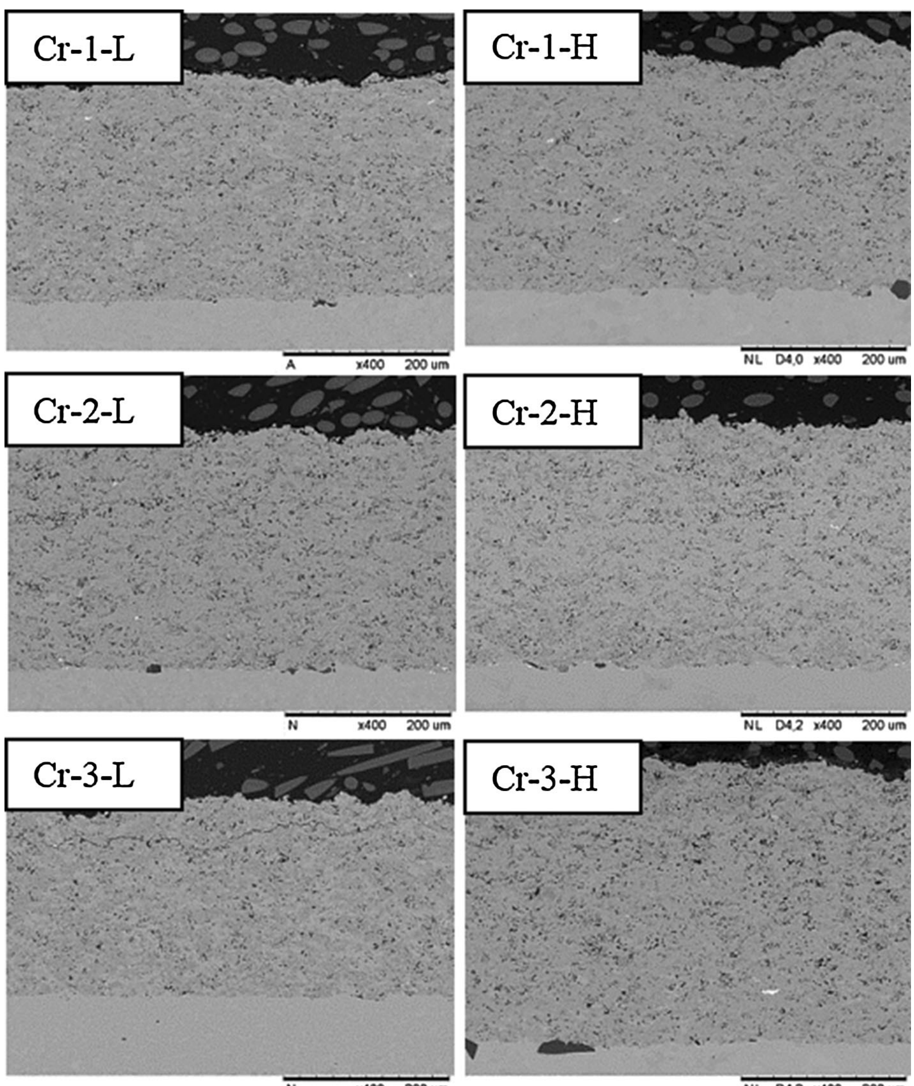

Fig. 3 Cr_3C_2-NiCr coatings sprayed on ID sample holder

2.2.4 Corrosion Resistance. Neutral Salt Spray test (NSS) formalized as an ASTM B117 specification by the American Society for Testing and Materials (ASTM) was performed to evaluate the relative corrosion resistance of coated materials exposed to a salt spray (pH 6.5 to 7.2) pre-conditioned to the operating temperature of 35 ± 2 °C and fogging a 5% salt solution at a condensate collection rate of 1.0 to 2.0 ml/h per 80 m^2.

3. Results and Discussions

3.1 Microstructure

Preliminary investigations were conducted to compare coating microstructures were obtained from the ID-HVAF gun and the standard HVAF-M3 gun, while utilizing both OD/ID fixtures (Fig. 2). Both feedstock materials exhibited high deposition efficiency and low residual coatings porosity, respectively, 2% for Cr_3C_2-NiCr and 1% for WC-CoCr feedstock materials. Higher porosity level and lower density were noticed for resulting ID-HVAF-sprayed coatings likely due to (i) lower kinetic energy of in-flight particles compared to standard HVAF-M3 and (ii) shorter stand-off distance. When utilizing the ID fixture, high coating density was obtained independently of the configuration closed/opened bottom or with/without extension (Fig. 3 and 4). A slight, but not significant, tendency of decreasing deposition efficiency from 52 to 50% was observed while increasing the bore length of the inner diameter fixture. However, few cracks were observed in several locations in the WC-CoCr coatings, located preferentially in the middle plane of the coating, highlighting the sensitivity of the material to temperature gradient with surrounding environment. Generation of tensile residual stresses probably due to overcooling the substrate from the outside diameter of the fixture, likely lead to a higher thermal gradient and therefore cross-like cracking through the coating thickness. This phenomena

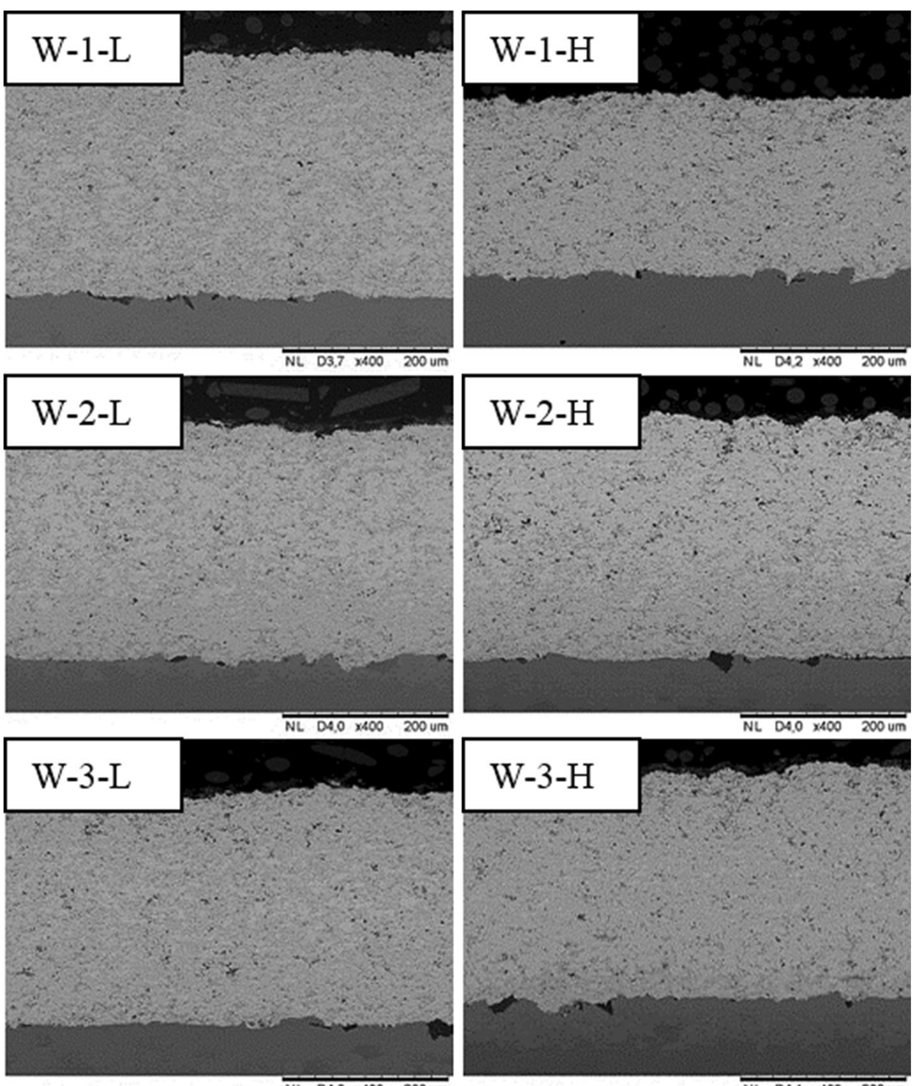

Fig. 4 WC-CoCr coatings sprayed on ID sample holder

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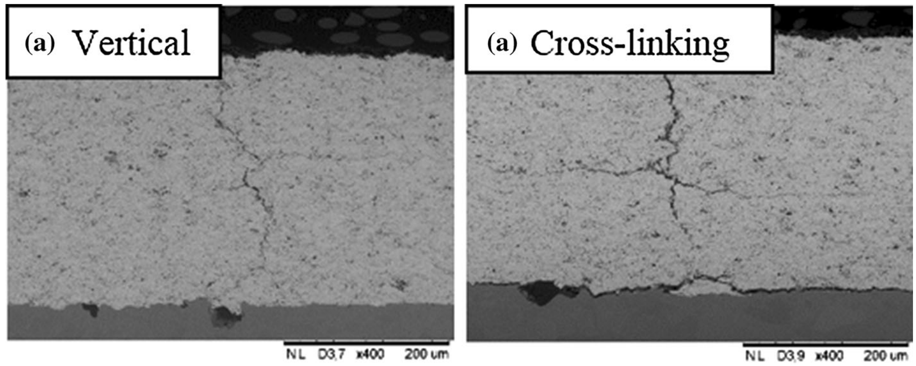

Fig. 5 Crack patterns encountered for WC-CoCr coatings

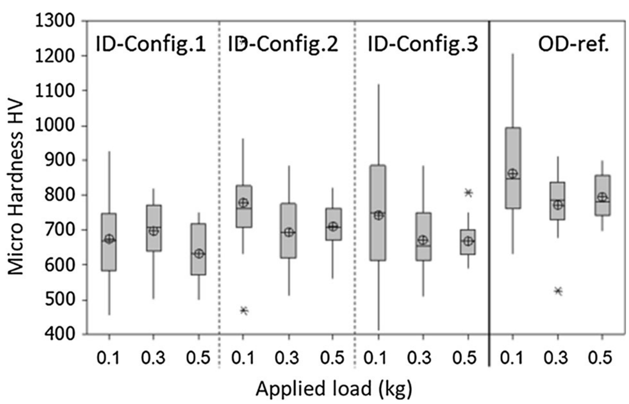

Fig. 6 Boxplot representations of ASTM E384-10 microhardness values of Cr_3C_2-NiCr ID-HVAF coatings

raises a fundamental question how to engineer the spraying of such high-kinetic energy powerful gun design, where spraying and cooling sequences set-ups become more critical than conventional spraying technologies. The influence of the ID-fixture design on coating properties, sounds however controversial regarding expectations. The original objective of introducing an extension to the fixture (*configuration 3*) was to simulate longer bore length as encountered in industrial applications, in order to study the effect on coating properties of dust and spray particles entrapped in a long and confined tube geometry. More dust was observed in configuration 3 than shorter configuration. However, the dust likely caused a cleaning/blasting effect being injected by the jet providing likely a constant inner cooling upshot, which could explain the lower substrate deposition temperature. In order to frame the significance of this effect, complementary coatings cross sections were investigated, not on stiff coupons samples as previously observed (Fig. 3 and 4), but on the cover plates simulating the inner walls of the ID fixture. Those plates, with lower thickness and high length-to-width ratio, are more sensitive to thermal gradients and consequently bending moments, and therefore were used as internal residual stress sensor to highlight potential risk to cracking. Those additional observations revealed the presence of a low frequency of cracks for WC-CoCr coatings, but patterned in reproducible and characteristic modes, respectively, named as *vertical* and *cross-linking.* Whereas configurations 1 and 2 lead to few vertical cracks (Fig. 5a) and cross-linking (Fig. 5b), none was observed for the configuration 3, confirming colder deposition conditions as previously observed. Those cracks could not be found on Cr_3C_2-NiCr-coated plates. This phenomena is mostly related to the lower mismatch of the coefficients of thermal expansion between steel substrate (14×10^{-6} °C^{-1}) and Cr_3C_2-NiCr (10×10^{-6} °C^{-1}), compared to WC-CoCr materials (7×10^{-6} °C^{-1}) (Ref 14-16). In order to support the discussion about the effect of bore length onto the deposition temperature, acquisition of the substrate backside temperature during deposition, and diagnostic of in-flight particles (DPV2000) will be carried out in the qualification procedure of the ID-HVAF system.

3.2 Microhardness

Distributions of 20 indentations carried out on each coating cross sections are here displayed by their respective boxplot representations. Microhardness boxplot values were evaluated for three different applied loads on Cr_3C_2-NiCr coatings (Fig. 6) and on WC-CoCr coatings (Fig. 8). Compared to HVAF-M3-coated systems, ID-HVAF coatings exhibit 15 and 20% lower microhardness values, respectively. Broadening of the distributions at low load (0.1 kg), which can be observed for both feedstock materials, highlights the presence of localised cracks and delaminations through the coating thickness. The probability that small indentations hit only either hard phases or only defects is higher, leading to widening the distribution of recorded HV values. Regarding Cr_3C_2-NiCr coatings, increasing the gauged volume by increasing the applied load (Fig. 7) leads to a drop in microhardness values (Fig. 6), emphasizing (i) that the distribution of defects through the coating thickness is homogeneous, and therefore (ii) that the hardness information is mostly carried by a large amount of defects that are averaged to the hard phases of the material when solicited by the applied load. Regarding WC-CoCr coatings, the opposite trend is observed (Fig. 8). Indentations at higher loads (i.e. higher gauged volume) exhibit higher microhardness values, emphasizing that (i) the defects are localised or non-homogeneously distributed through the coating

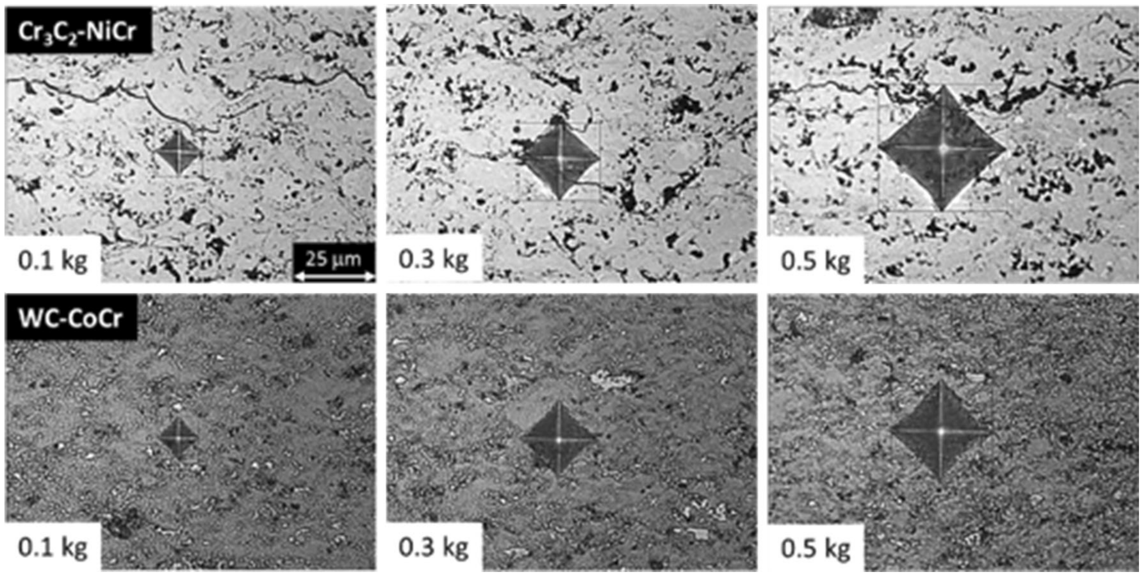

Fig. 7 Optical micrographs of Vickers indentations

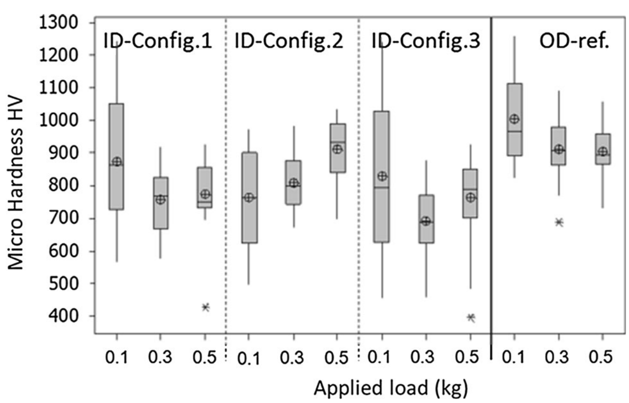

Fig. 8 Boxplot representations of ASTM E384-10 microhardness values of WC-CoCr ID-HVAF coatings

thickness, and therefore (ii) that the hardness information is mostly carried by the hard phase of the material. When comparing samples sprayed on OD versus ID fixtures, higher microhardness values are recorded for OD conditions, due to different cooling conditions.

3.3 Coating Roughness

ID-HVAF-sprayed coatings exhibit here a really smooth texture, around 4.8 (*Ra*) for Cr_3C_2-NiCr coatings (Fig. 9a) and 3.5 (*Ra*) for WC-CoCr ones (Fig. 9b). Compared to HVAF-M3-coated systems, ID-HVAF-deposited surfaces exhibit a 17 and 12% higher roughness, respectively. Coated surfaces with low roughness profile are extremely attractive when hard phase materials such as Cr-/WC-based feedstock are being coated. Achieving lower coating roughness can drastically reduce time-consuming industrial machining costs.

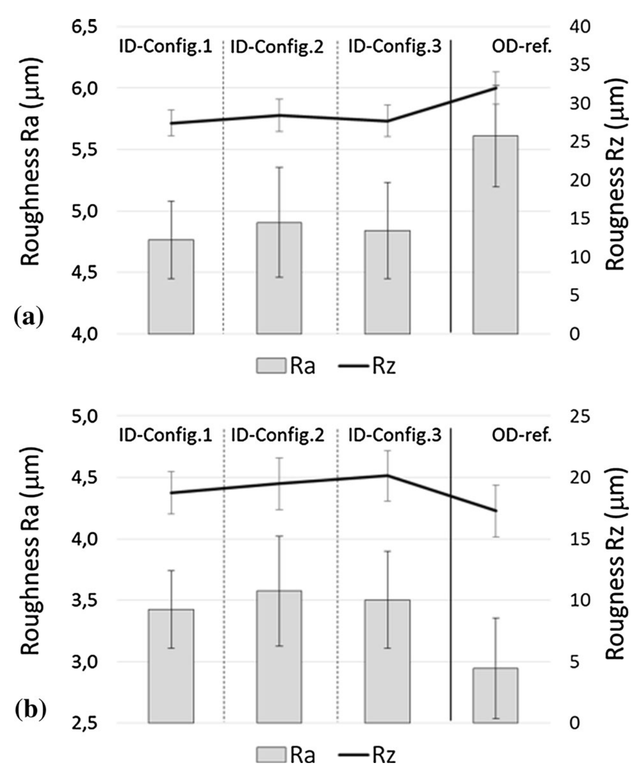

Fig. 9 2D Roughness measurements for (a) Cr_3C_2-NiCr and (b) WC-CoCr ID-HVAF-sprayed coatings

3.4 Corrosion Resistance

Coated materials sprayed on coupon substrates have been grinded to *Ra* 0.5 and exposed to NSS environment. After 96 h exposure in neutral salt fog environment, which is a minimal requirement imposed by industrial valida-

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Table. 2 Exposure time to NSS environment

		NSS, h			
Feedstock material	**Ref.**	**96**	**144**	**168**	**192**
Cr_3C_2-NiCr	OD	*Fail*			
Cr_3C_2-NiCr	ID-1	*Fail*			
Cr_3C_2-NiCr	ID-2	*Fail*			
Cr_3C_2-NiCr	ID-3	*Fail*			
WC-CoCr	OD	Ok	OK	OK	*Fail*
WC-CoCr	ID-1	Ok	OK	OK	*Fail*
WC-CoCr	ID-2	Ok	OK	OK	*Fail*
WC-CoCr	ID-3	Ok	OK	OK	*Fail*

Fail refers to the fact that coated systems corroded after the correspoding exposure time to NSS environment

tions, all Cr_3C_2-NiCr coatings corrode, whereas all WC-CoCr coatings surpass the test (Table 2). Exposure time has been prolonged up to 168 h, without noticing pitting corrosion onto exposed coated surfaces. After 192 h, all coatings corroded, therefore no influence of spraying configuration OD/ID could be noticed on coatings corrosion resistance. The most probable scenario is that corrosion is due to pre-existing interconnected pores. Cr_3C_2-NiCr coatings with 2% porosity exhibit a higher corrosion rate than the WC-CoCr coatings which globally present a higher compaction with a network of smaller pore size than Cr_3C_2-NiCr deposit.

4. Conclusion

The practicability of applying carbide-based materials onto the inner diameter of cylindrical components by the ID-HVAF system has been demonstrated in this work. The main results can be summarized as follows:

- The feasibility of gritblasting and spraying internal surface with the ID-HVAF system has been demonstrated.
- Compared to conventional HVAF-M3, ID-HVAF-sprayed coatings exhibit lower compaction, lower hardness and higher porosity, due to lower particle velocity and shorter stand-off distance conditions.
- Cr_3C_2-NiCr material was successfully deposited onto internal surface with low porosity (2%) and relative high hardness 700(HV0.3).
- WC-CoCr material was successfully deposited onto internal surface with even lower porosity (1%) and higher hardness 900(HV0.3).
- The introduction of different ID-fixture configurations highlights the influence of the bore length onto coating properties, as well as how critical the external outer and inner cooling units need to be engineered in order to prevent crack initiation.
- The cover plates simulating the component wall were used as internal stress sensor and highlighted the sensitivity of thermal mismatch between coating and substrate materials, and were used to demonstrate the importance of cooling conditions to prevent the residual stress build up in case of configuration 3.
- Corrosion performance in NSS environment was very high for low-porosity WC-CoCr-coated materials, compared to higher porosity Cr_3C_2-NiCr systems.

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