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Mechanical, Tribological and Microstructure Characteristics of HVOF and Plasma Sprayed Cr₃C₂-PS.ZrO₂ Coatings

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ABSTRACT: The microstructure, mechanical properties and tribological behaviour of Cr₃C₂(Chromium carbide) - PS.ZrO₂ (Partially stabilized Zirconia) composite coatings prepared with atmospheric plasma spraying and high velocity oxyfuel spraying (HVOF) technologies were systematically investigated. X-ray diffraction and transmission electron microscopy analyses showed that the three kinds of Cr₃C₂-PS.ZrO₂ coatings were mainly consistent with the designed feedstock powders. The three kinds of Cr₃C₂-PS.ZrO₂ coatings have similar and high microhardness. The HVOF Cr₃C₂-PS.ZrO₂ coatings have lower porosity and higher adhesive strength in comparison to the plasma sprayed Cr₃C₂-PS.ZrO₂ coating. The friction coefficients of the HVOF were lower than that of the plasma sprayed coating, and the HVOF coatings displayed better wear resistance. The lower coefficients friction and rate wear of the three coatings at elevated temperatures were attributed to the formation of a compact PS.ZrO₂eutectic lubricating layer on the worn surface.

KEYWORDS: Thermal spray, Hard coating, Solid lubrication, Mechanical properties, Wear

I. INTRODUCTION

Among the existing techniques used for surface engineering, coatings deposited by thermal spraying can provide a cost effective solution for tribological applications in rolling/sliding contact. Some applications include aerospace, turbo engines, heavy machinery, rolls and wear resistant dies, drill bits, wear resistant nozzles and wear components used in the oil exploration and mining industries. However, the properties of coatings deposited by different technologies have significant differences because of the remarkably different flame temperature and the particle's velocity in the spraying process. It is inferred that high velocity oxyfuel spraying (HVOF) and detonation gun spraying (DS) are superior to plasma spraying for manufacturing wear resistant metallic and cermet coatings.[1,2] Plasma spraying is widely used for ceramics due to its high flame temperature.[3] There were limited studies on the comparison of different coatings deposited by thermal spraying techniques. and most of the studies were concentrated on the comparison of plasma and HVOF coatings.[4–8] The comparison of coatings deposited by three thermal spray technologies (plasma, detonation gun and HVOF spraying) has not been reported,[9–11] especially for thermally sprayed wear resistant solid lubrication coatings. Thermally sprayed Cr₃C₂ coatings can significantly improve the wear resistance of various sliding components in automotive applications.[12,13]. In order to reduce the friction coefficient of Cr₃C₂ coatings, Ag, CaF₂ and BaF₂.CaF₂ eutectic have been used as solid lubricants to improve their tribological properties.[14–19] Although PS.ZrO₂ eutectic is a well known solid lubricant additive and has been used in different antiwear applications, hardly any literature has reported on the comparison of coatings prepared by different thermal spraying technologies using PS.ZrO₂eutectic as a solid lubricant. In the present work, an attempt was made to fabricate three kinds of thermally

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sprayed Cr₃C₂-PS.ZrO₂ coatings, and the microstructure, mechanical properties and tribological behaviour of three coatings were systematically studied.

II. EXPERIMENTAL WORK

For different thermal spraying technologies, preparation methods of feedstock powders and their properties, such as shape, size distribution, density and flowability, have significant influences on the coating's performances.[20–22] Therefore, it is not easy and suitable to fabricate different thermal spraying coatings with the same powder. In the present work, three kinds of powders were prepared according to the optimisation of particle sizes, distribution and compositions to be suitable for plasma, HVOF and DS technologies respectively. The powder for plasma spraying was prepared with mixture of nichrome clad Cr₃C₂ and PS.ZrO₂ eutectic. The powders for HVOF and DS were prepared by high speed centrifugal and low pressure spray granulating and drying methods respectively. The compositions and part of properties of the three-feedstock powders are shown in Table 1. A Hall flowmeter was used to test the flowability and apparent density of three Cr₃C₂-PS.ZrO₂ feedstock powders. The Cr₃C₂-PS.ZrO₂ coatings were deposited on low carbon steel substrates by atmospheric plasma spraying (APS) 2000K plasma spraying system, JP-5000 HVOF spraying system and Dnepr-III DS system respectively. The plasma spray power was 30–40 kW, and the spraying distance was 110 mm, with a powder feedrate of 30–40 g min⁻¹. Before coating, the substrate was blast cleaned with coarse Al₂O₃ particles and plasma sprayed with a NiAl bond coat. The HVOF spraying distance was 350 mm, and the oxygen and kerosene fluxes were 50 m³ h⁻¹ and 21 L h⁻¹, with a powder feedrate of 30–40 g min⁻¹. The DS distance was 180 mm, and the acetylene and a oxygen fluxes were 1 m³ h⁻¹ and 1.25 , with a powder feedrate of 25–30 g min⁻¹. of the as The sprayed Cr₃C₂-PS.ZrO₂ coatings Micro structural details was studied using FEI Quanta 200 FEG scanning electron microscope (SEM), equipped dispersive X-ray analysis system (EDX). The porosity of the sprayed Cr₃C₂-PS.ZrO₂ coatings was derived by image analysis. The constituents of the Cr₃C₂-PS.ZrO₂ powders and derived coatings were studied by X-ray diffraction (XRD) using filtered Cu K α radiation. Transmission electron microscopy was used to study the details of the phases in the as sprayed Cr₃C₂-PS.ZrO₂ coatings. A Vickers hardness tester with 1.96 N test load and a dwell time of 15 s on polished cross-sections was used to test the Cr₃C₂-PS.ZrO₂ coating's microhardness. The tensile strength of Cr₃C₂-PS.ZrO₂ was tested WDW-100E microcomputer controlled material testing machine. The friction and wear tests were found out using a HT-1000 ball on disc high temperature tribometer (Ducom Instruments), as shown in Fig.6. [25] The friction and wear tests were carried out with a load of 9.8 N and a sliding speed of 0.188 m s⁻¹, from room temperature to 800°C and 20 min test duration. The coupled balls are Si₃N₄ ceramic balls with a surface roughness of 0.02 mm (Ra). Before the wear test, the composite Cr₃C₂-PS.ZrO₂ coatings were carefully polished to obtain a surface roughness of 0.2 mm (Ra). The wear volumes of coatings were measured using the Rank Taylor Hobson Talysurf 5P-120 surface profilometer. The wear rates of specimens were calculated as $k5W/FS$, where W is the wear volume in cubic millimeters, F is the normal load in newtons and S is the total sliding distance in meters. Tests were performed repeatedly for each frictional pair, and the averaged results of the three repeat tests are reported in this article. The wear volume of Si₃N₄ removed from the coupled balls was acquired by using a geometric technique, measuring the diameter of the wear scar formed on the ball with an optical microscope and assuming that the wear scar is perfectly circular and flat in order to simplify the calculations. SEM with EDX to identify the lubrication mechanism examined the morphology and chemical compositions of the worn surfaces on the composite Cr₃C₂-PS.ZrO₂ coatings and the counter faces.

III. RESULTS AND DISCUSSION

Characteristics of feedstock powders and as sprayed coatings Figure 1 presents the typical morphologies of three spraying powders. From Fig. 1a, it can be seen that the plasma spraying powder is fine and uniform, with a size range from 38 to 90 nm. The powder is clearly seen to be irregular in shape and possesses sharp edges. From Fig. 1b, the size ranges of detonation gun obtain spheric and round shape particles and HVOF spraying are mainly 38–75 and 15–45 nm respectively.

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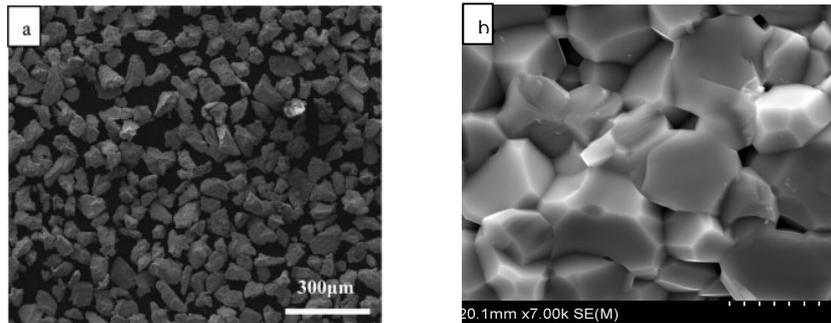


Fig.1: Morphologies (SEM) of Cr₃C₂-PS.ZrO₂ powders for (a) APS, and (b) HVOF

The three powders contain high nichrome alloy matrix, Cr₃C₂ reinforced phase and PS.ZrO₂eutectic solid lubricant. The nickel alloy 80Ni–20Cr offers excellent high temperature oxidation/corrosion resistance and mechanical strength. The high temperature strength is further enhanced by chromium carbide particles, which function as a hardener to enhance the antiwear performance of the coating. The PS.ZrO₂eutectic functions as a solid lubricant.

Table 1: Composition and properties of Cr₃C₂– PS.ZrO₂powders

Properties	APS	HVOF
PS.ZrO ₂ /mass-%	8-12	5-9
Cr ₃ C ₂ /mass-%	25:75	25:75
Apparent density /g cm ⁻³	2.3-2.5	1.8-2.0
Flowability / s/50 g	30-35	55-60
Particle size /µm	-90+38	-45+15

Table 1 shows the nominal compositions and some properties of the three-feedstock powders. It can be seen that all the powders show excellent flowability and apparent density, which can guarantee uniform powder feeding in the spraying process to avoid nozzle clogging and ensure the powder to feed into the flame centre to maintain well melting characteristics.

The results of XRD analyses, as shown in Fig. 2, indicate that the major constitutional phases of the three thermally sprayed composite Cr₃C₂-PS.ZrO₂ coatings are nearly the same as that in the feedstock powders

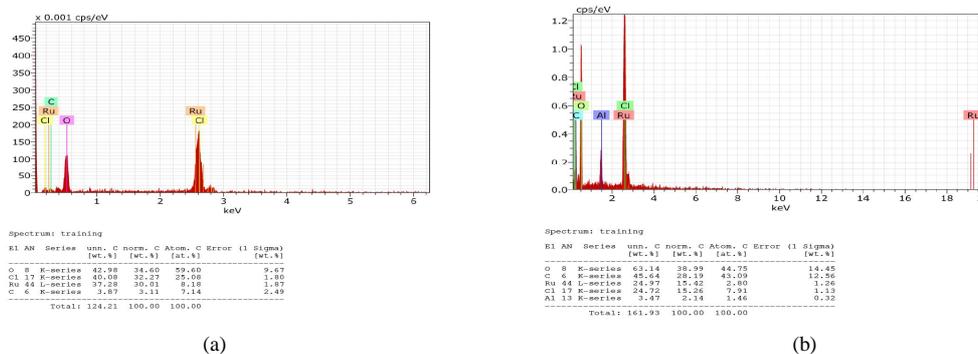


Fig.2 : X-ray diffraction analyses of Cr₃C₂-PS.ZrO₂ powders and their derived coatings: (a) APS; (b) HVOF

This demonstrated that no significant decomposition and oxidation of materials occurred during the spraying and resolidification process. From Fig. 2a, it can be found that compared with feedstock powder, only a small number of

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oxide (Cr₂O₃ and NiO) peaks appeared in the coating, and no obvious Cr₇C₃ and Cr₂₃C₆ peaks were found. The analyses of detonation gun and HVOF coating showed that no obvious oxide and other carbide were found. From Fig. 2, it can also be seen that some diffraction peaks of the coatings became broad, which were related to the grain refinement in the spraying process. However, as pointed out by Zimmermann, the presence of Cr₇C₃ and Cr₂₃C₆ in the as sprayed Cr₃C₂ coating cannot be proven solely by the XRD approach because their main diffraction peaks coincide with the lines referring to Cr₃C₂. [26]

The TEM observation shown in Fig. 3 was conducted in order to reveal all the phases in the plasma sprayed Cr₃C₂-PS.ZrO₂ coating.

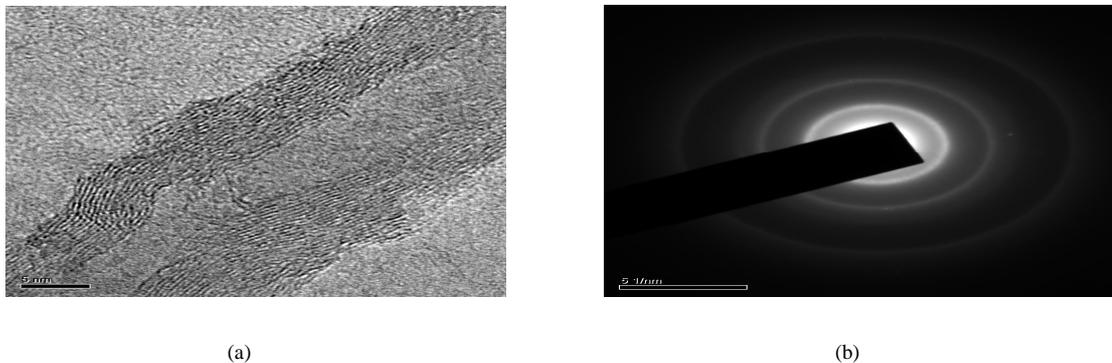


Fig.3: Morphologies (TEM) and corresponding diffraction patterns of phases observed in plasma sprayed Cr₃C₂-PS.ZrO₂ coating: (a) Cr₇C₃; Cr₂₃C₆; (b) ZrCrO₄; CrC₄

It was found that, except the obvious phases appearing in XRD analysis, trace amounts of Cr₇C₃, Cr₂₃C₆, NiCrO₄, BaCrO₄ and CaCrO₄ phases were also seen. Further examination showed that Cr₇C₃ was observed in the area just around the big block of Cr₃C₂ carbide particles, and Cr₂₃C₆ was found within the NiCr alloy matrix. This fact suggests that Cr₇C₃ resulted from the decarburisation of Cr₃C₂ owing to the overheating of the particles in the spraying process, and Cr₂₃C₆ in the plasma sprayed coating was precipitated during the coating deposition process. The cross-sectional optical micrographs of the three as sprayed Cr₃C₂-PS.ZrO₂ coatings are shown in Figure 4

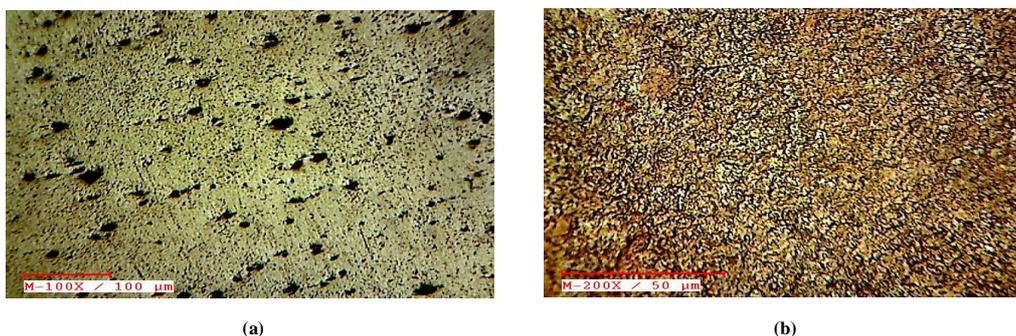


Fig.4: Morphologies (TEM) and corresponding diffraction patterns of phases observed in plasma sprayed Cr₃C₂-PS.ZrO₂ coating: (a) Cr₇C₃; Cr₂₃C₆; (b) ZrCrO₄; CrC₄

It can be seen that the coatings and substrates had a very good mechanical bonding, which indicated the coatings high bonding strength. From Fig. 4, it can also be seen that the plasma sprayed Cr₃C₂-PS.ZrO₂ coating had more porosity and less compact microstructure in comparison to detonation gun and HVOF sprayed Cr₃C₂-PS.ZrO₂ coatings. The detonation gun and HVOF sprayed Cr₃C₂-PS.ZrO₂ coatings were more compact and lamellar than the plasma sprayed coating and had no obvious delamination, crack and big pores. Table 2 shows the porosity of three thermally sprayed Cr₃C₂-PS.ZrO₂ coatings. The HVOF sprayed coating showed the lowest porosity, which was 1%. The average porosities of HVOF and detonation gun coatings were 0.98 and 1.4% respectively, which were significantly lower than the porosity in plasma sprayed coating (average 6.8%). Owing to the higher jet velocity, the particles will have more

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sufficient deformation during impacting on the substrate in the HVOF and DS processes, leading to a more compact coating microstructure. Figure 5 shows the cross-sectional backscattered electron (BSE) images of the three as sprayed Cr₃C₂-PS.ZrO₂ coatings.

From Fig.5, it can be found that the three composite coatings exhibited a typical thermal sprayed lamellar structure.

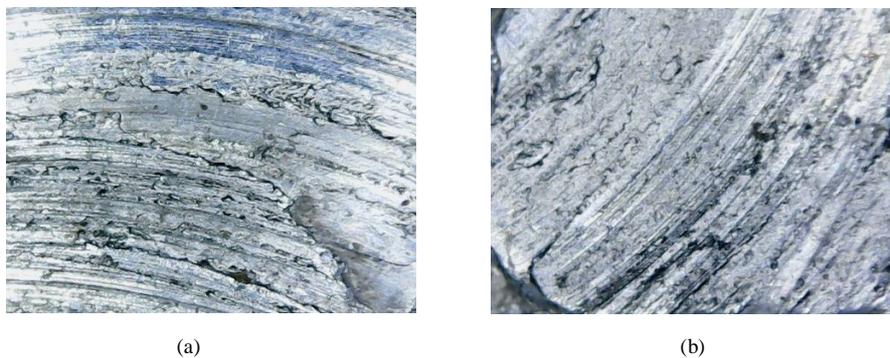


Fig.5: Cross-sectional BSE images of microstructure of three as sprayed Cr₃C₂-PS.ZrO₂ coatings: (a) APS; (b) HVOF

The main defect structures in the composite coatings were pores and internal boundaries. The morphology and distribution of different constituents in three Cr₃C₂- PS.ZrO₂ coatings can be clearly found in Fig. 5. Cr₃C₂ (grey regions), PS.ZrO₂ eutectic and little oxide (dark regions) constituents are evident and can be easily identified, mainly as fine, typical lamellar structures with different grey levels in BSE mode. X-ray dot mapping analysis showed that the elements of Ba, Ca and F were in the same splat, which indicated that the eutectic was not decomposed and oxidized during the thermal spraying process. From Fig. 5, it can also be concluded that the detonation gun and the HVOF sprayed Cr₃C₂-PS.ZrO₂ coatings had a more compact and fine microstructure than the plasma sprayed Cr₃C₂-PS.ZrO₂ coating. The microhardness and tensile strength of three as sprayed Cr₃C₂-PS.ZrO₂ coatings are shown in Table 2.

Table 2 : Properties of three as sprayed Cr₃C₂- PS.ZrO₂ coating

Properties	APS	HVOF
Porosity %	6.8 ± 0.8	0.98 ± 0.1
Micro Hardness /	410-1001	680 ± 33
Tensile strength /MPa	28±4	50 ± 5

It can be seen that all three coatings have high microhardness. The tensile strengths of detonation gun and HVOF sprayed Cr₃C₂-PS.ZrO₂ coatings are close to each other, but notably higher than that of the plasma sprayed Cr₃C₂-PS.ZrO₂ coating. This can be attributed to the higher particle velocity in the HVOF and DS processes, which make the particles have more sufficient deformation during impacting on the substrate, leading to a more compact microstructure. The more uniform phase distribution of detonation gun and HVOF sprayed Cr₃C₂-PS.ZrO₂ coatings also play an important role on higher microhardness and cohesive strength. However, for the plasma sprayed Cr₃C₂-PS.ZrO₂ coating, microhardness has a higher variation due to the bigger particle size and the broader size distribution in the feedstock powder and relatively insufficient particle deformation during impacting on the substrate. The microhardness of hard carbide and the soft eutectic phase area in the plasma sprayed Cr₃C₂-PS.ZrO₂ coating are about 930 and 450 respectively. Because of the protection of NiCr layer on particle surface, the decarburization and oxidation of carbide were restricted, which lead to high microhardness for the plasma sprayed coating. The average microhardness values of detonation gun and HVOF sprayed Cr₃C₂-PS.ZrO₂ coatings are 628.6 and 680.7 respectively. The average microhardness of the DS Cr₃C₂-PS.ZrO₂ coating is little lower than that of the HVOF coating. This may be due to the slightly higher PS.ZrO₂ content in the DS coating. Generally speaking, the wear resistance of a material

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increases with its hardness. Therefore, the high microhardness of three coatings is very helpful to improve their wear resistance.

Sliding friction and wear behaviours of three kinds of coatings Figure 6 presents the friction coefficients of three Cr₃C₂-PS.ZrO₂ coatings sliding against Si₃N₄ balls from room temperature to 800uC



Fig.6 : Experimental photograph of four ball tribometer

The plasma sprayed 25NiCr–75Cr₃C₂ coating was used for comparison. It can be seen that the friction coefficients of the Cr₃C₂ coating are always higher than three Cr₃C₂–PS.ZrO₂ coatings at all test temperatures. At room temperature, the friction coefficients of three kinds of Cr₃C₂-PS.ZrO₂ coatings are close to that of NiCr/Cr₃C₂ coating and decrease with increasing ambient temperatures. When the temperature is up to 500uC, the friction coefficients of three Cr₃C₂-PS.ZrO₂ coatings were all significantly lower than that of the NiCr/Cr₃C₂ coating, which indicates that only when the ambient temperature is sufficiently high can PS.ZrO₂ supply effective solid lubrication due to plastic transformation. It can also be seen that the friction coefficients of detonation gun and HVOF Cr₃C₂-PS.ZrO₂ coatings are generally lower than that of plasma sprayed Cr₃C₂-PS.ZrO₂ coating. However, they are almost the same at 700uC. The lowest friction coefficients of plasma, detonation gun and HVOF Cr₃C₂-PS.ZrO₂ coatings appear at 800uC, which are 0.38, 0.29 and 0.23 respectively. From 500 to 650uC, the friction coefficients of detonation gun and HVOF Cr₃C₂-PS.ZrO₂ coatings showed a slight increase, which may be due to the strong friction adhesion between NiCr and Si₃N₄. As the

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ambient temperature is up to 800°C, the plastic deformation of NiCr increases, resulting in a reduced surface tension, which can weaken the adhesion between NiCr and Si₃N₄. This phenomenon can also be found in the NiCr/Cr₃C₂ coating.

However, from Fig-7 it was found that the friction coefficient of the plasma sprayed Cr₃C₂-PS.ZrO₂ coating continuously decreases from 500 to 800°C, which is different from the other test coatings.

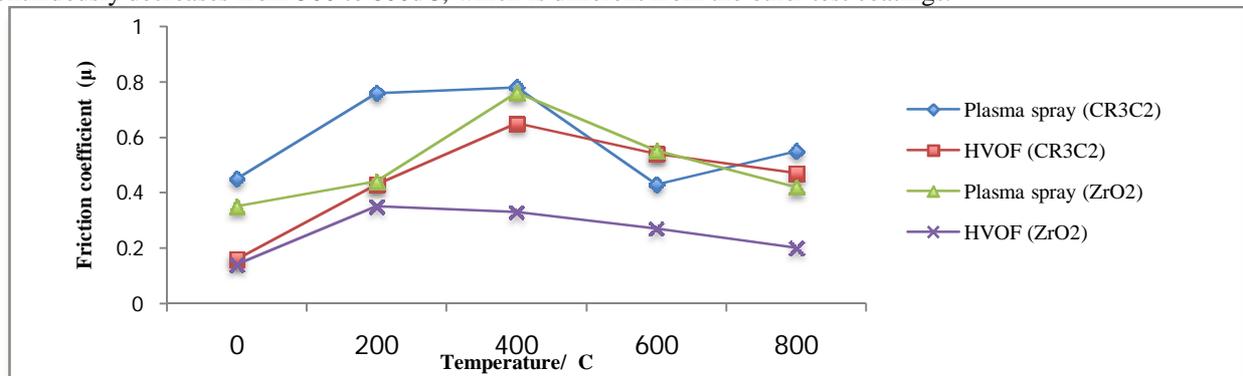


Fig.7 : Friction coefficients of three Cr₃C₂-PS.ZrO₂ coatings at different temperatures

That is because the porosity of the plasma sprayed Cr₃C₂-PS.ZrO₂ coating is much higher than the detonation gun and HVOF Cr₃C₂-PS.ZrO₂ coatings. The rough worn surface of the plasma sprayed Cr₃C₂-PS.ZrO₂ coating can effectively cut the adhesion between NiCr and Si₃N₄. Obviously, the PS.ZrO₂eutectic has been shown to be an effective solid lubricant above 400°C and plays an important role in the variation of friction coefficients. The friction reduction with temperature may also be affected by the presence of Cr₂O₃, which is an intrinsic solid lubricant above 500°C. [26,27] However, Cr₃C₂ and NiCr alloy are stable below 700°C, and mild oxidation may happen only when the temperature is above 800°C.

The effect of temperature on the wear rates of three Cr₃C₂-PS.ZrO₂ coatings are shown in Figures 8 and 9.

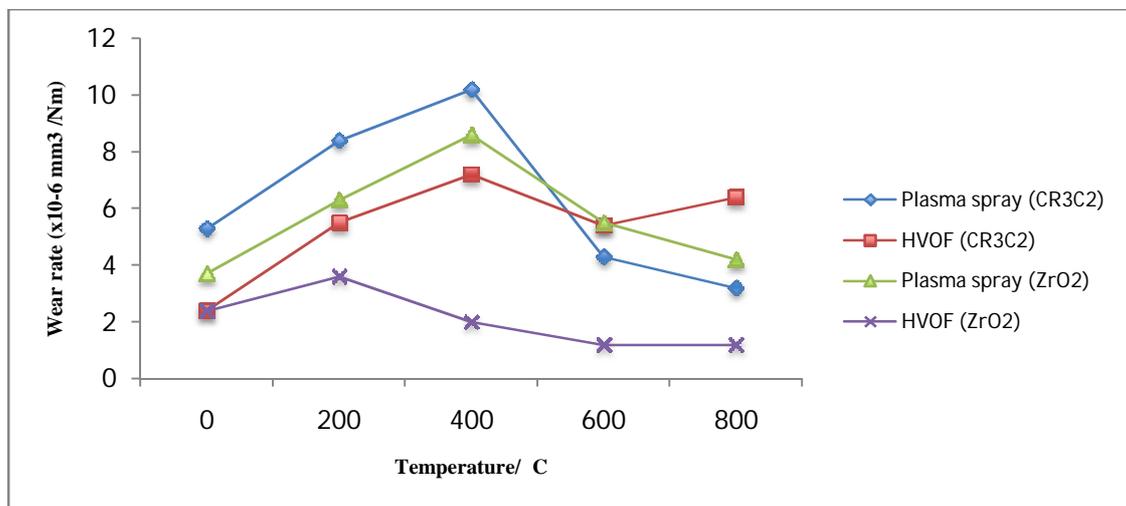


Fig.8 : Wear rates of three Cr₃C₂-PS.ZrO₂ coatings at different temperatures

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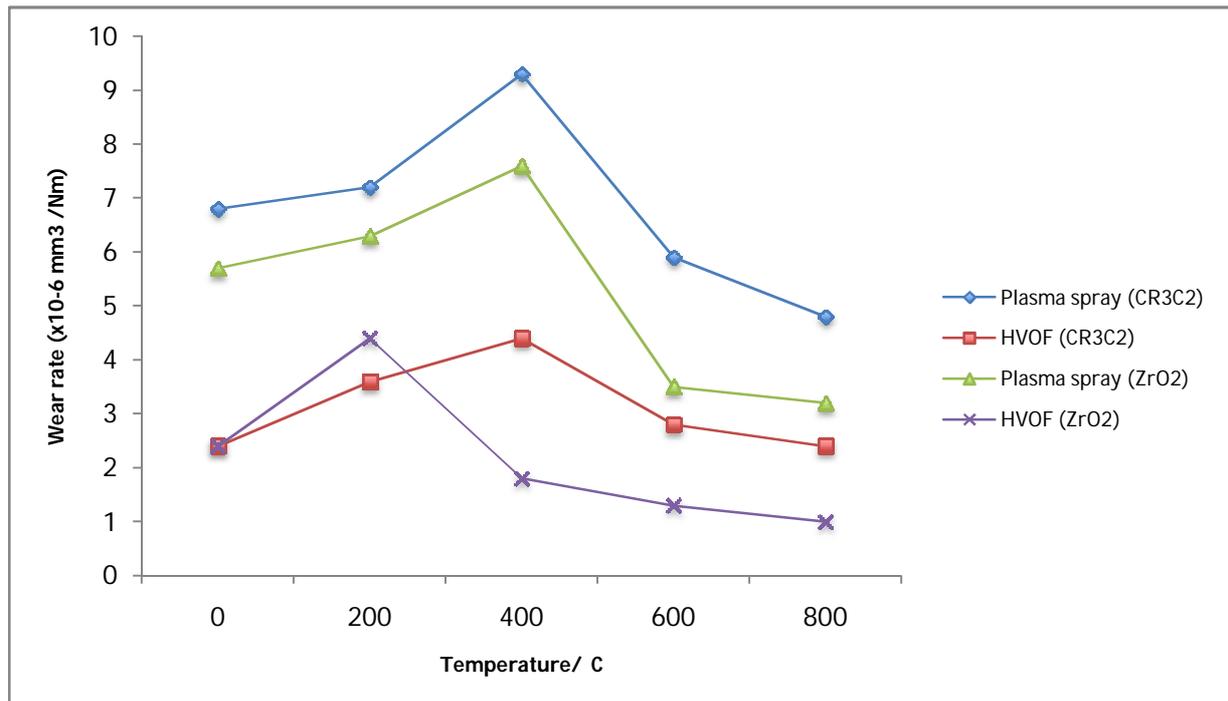


Fig.9 : Wear rates of three Cr3C2-PS.ZrO2 coatings at different

It can be seen that the wear rates of NiCr/Cr3C2 coatings at elevated temperatures are significantly higher than that at low temperatures. From room temperature to 800uC, the wear rates of detonation gun and HVOF sprayed Cr3C2-PS.ZrO2 coatings are lower than that of plasma sprayed Cr3C2-PS.ZrO2 coating at all times. Below 600uC, the wear rate of HVOF sprayed Cr3C2-PS.ZrO2 coating is notably lower than the DS coating but becomes similar when the temperature is above 600uC. The wear rates of detonation gun and plasma sprayed Cr3C2-PS.ZrO2 coatings decrease sharply when the temperature is above 400uC, which is attributed to the lubrication effect of the PS.ZrO2eutectic. However, the wear rate of HVOF sprayed Cr3C2-PS.ZrO2 coating just has a slight change and keeps a low value from room temperature to 800uC. As the microstructures of detonation gun and HVOF Cr3C2-PS.ZrO2 sprayed coatings are more dense and compact and have a lower porosity than the plasma sprayed coating, the extent of cracking and delamination of lamellar splats will be lower when exposed to continuous stress. This is the main reason why the wear rates of detonation gun and HVOF sprayed Cr3C2-PS.ZrO2 coatings are lower than that of plasma sprayed Cr3C2-PS.ZrO2coating. On the other hand, from Fig.9, it can be found the wear rates of Si3N4 balls have significantly decrease when sliding against three Cr3C2-PS.ZrO2coatings at elevated temperatures.

The wear rates of Si3N4 balls sliding against with three Cr3C2-PS.ZrO2 sprayed coatings are always lower in comparison to sliding against with Cr3C2 coating. This can be attributed to that the soft PS.ZrO2lubrication film releases the direct contact among hard particles.

For more information about the wear mechanism, the worn surface morphology was analysed by SEM with EDX. Worn surface morphology analysis Figure 10 shows the SEM morphologies of the worn surfaces of three thermal sprayed Cr3C2- PS.ZrO2coatings at room temperature, 500 and 600uC. [25] For the as sprayed Cr3C2-PS.ZrO2 coatings, pores, intersplat boundaries and other low-density areas pre-existed.

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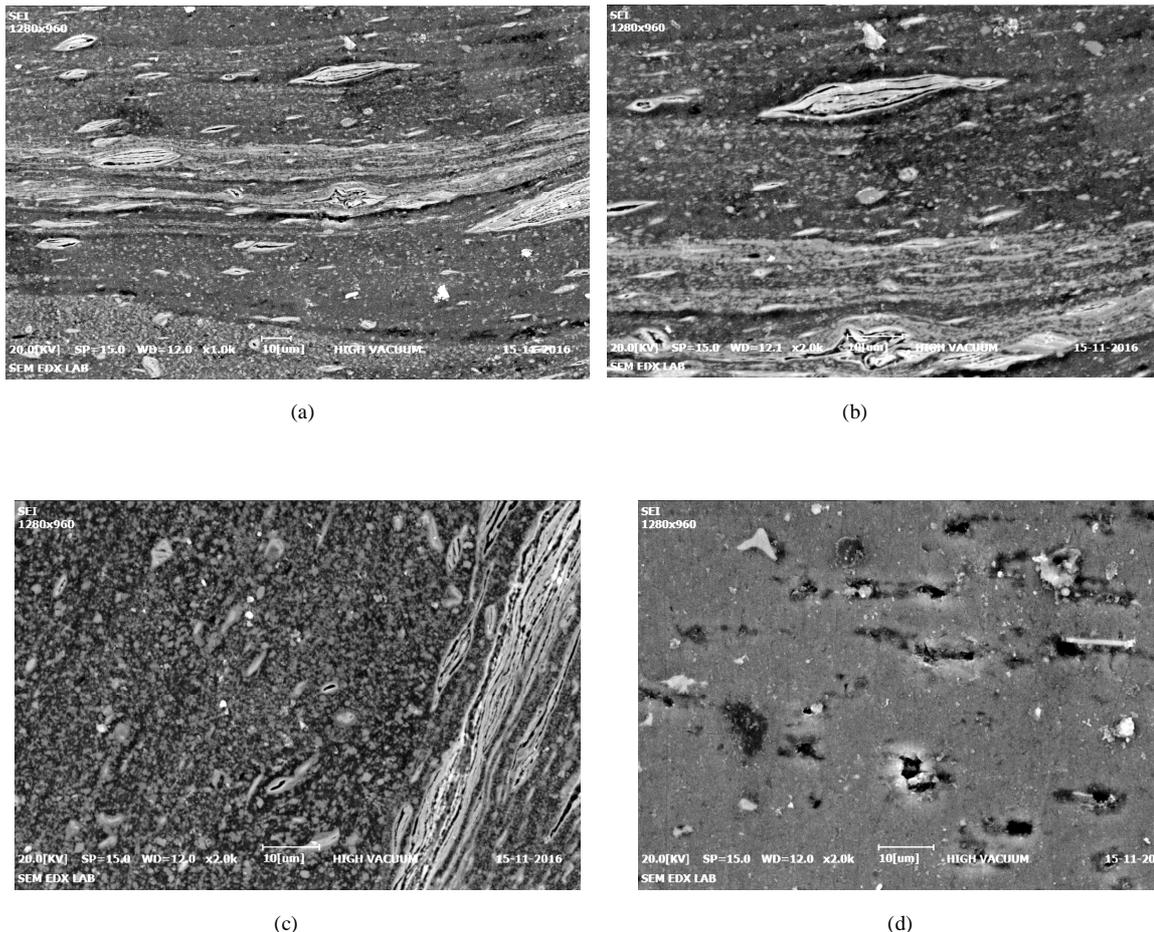


Fig.10 : Morphologies (SEM) of worn surfaces of three Cr₃C₂-PS.ZrO₂ coatings: (a) PS, at room temperature; (b) PS, at 600uC; (c) HVOF, at room temperature; (d) HVOF, at 500uC

On further deformation during wear tests carried out at room temperature, all these voids elongated and formed long cracks on the wear surface. At room temperature, typical brittle fractures were observed on the worn surface without obvious evidence of plastic deformation. Large wear debris and fine wear particles on the tribocontact surfaces were considered to result from microcracking, crack propagation and delamination. The plasma sprayed Cr₃C₂-PS.ZrO₂ coating has relatively lower intersplat and lamellar cohesive strength with higher porosity, resulting in higher wear rates when compared to detonation gun and HVOF sprayed coatings. At 500 and 600uC, the worn surfaces were covered with smooth PS.ZrO₂ eutectic material transfer films for all three coatings. The EDX exhibited that the film surface contained large amounts of Ba, Ca and F, indicating that fluoride particles were ejected out of the reservoirs due to plastic deformation, The higher superficial temperature rise at the contacting surface effectively activated the selflubrication property of the PS.ZrO₂ phase and subsequently significantly enhanced the wear resistance and reduced the friction coefficient of the coating. Plastic deformation and continuous formation of PS.ZrO₂ transfer films became the dominant wear mechanism at 500 and 600uC. Uniform dispersion of the PS.ZrO₂ solid lubricating phase is definitely beneficial for a more efficient exploitation of both the self-lubrication properties of PS.ZrO₂ and the wear resisting properties of Cr₃C₂-PS.ZrO₂ under dry sliding wear conditions.

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VI. CONCLUSIONS

Using three kinds of composite powders, high performance Cr₃C₂-PS.ZrO₂ coatings were successfully fabricated by plasma, detonation gun and HVOF spraying technologies. The Cr₃C₂-PS.ZrO₂ coatings deposited by HVOF and DS have lower porosity and higher bond strength and microhardness in comparison to the plasma sprayed coating. The friction coefficients of three kinds of Cr₃C₂-PS.ZrO₂ coatings decrease with increasing temperatures, and the high temperature friction coefficients were significantly lower than that at room temperature. The friction coefficients of HVOF and DS coatings were lower than plasma spraying coating and showed better wear resistance. The friction coefficients and the wear rates of three coatings as well as the wear rates of coupled Si₃N₄ balls were reduced due to the formation of PS.ZrO₂ lubrication films at elevated temperatures.

REFERENCES

- [1]. M. Benegra, M. Magnani, H. Goldenstein, O. Maranhão and G. Pintauro: "Abrasion and corrosion resistance of new Ni-based coating deposited by HVOF thermal spray process" *Surf. Eng.*, 2010, 26, 463–468.
- [2]. Y. Y. Santana, J. G. La Barbera-Sosa, J. Caro, E. S. Puchi-Cabrera and M. H. Staia "Mechanical properties and microstructure of WC–10Co–4Cr and WC–12Co thermal spray coatings deposited by HVOF": *Surf. Eng.*, 2008, 24, 374–382.
- [3]. Y. Wang, H. B. Guo, Z. Y. Li and S. K. Gong: "Segmented lanthanum cerium oxide thermal barrier coatings by atmospheric plasma spray" *Surf. Eng.*, 2009, 25, 555–558.
- [4]. Y. R. Liu, T. E. Fischer and A. Dent: "Comparison of HVOF and plasma-sprayed alumina/titania coatings—microstructure, mechanical properties and abrasion behaviour" *Surf. Coat. Technol.*, 2003, 167, 68–76.
- [5]. R. S. Lima and B. R. Marple "From APS to HVOF spraying of conventional and nanostructured titania feedstock powders: a study on the enhancement of the mechanical properties" *Surf. Coat. Technol.*, 2006, 200, 3428–3437.
- [6]. V. Higuero, F. J. Belzunce and J. Riba: "High temperature oxidation of plasma and HVOF thermal sprayed CoNiCrAlY coatings in simulated gas turbine and furnace environments" *Surf. Eng.*, 2009, 25, 319–325.
- [7]. W. R. Chen, X. Wu, B. R. Marple, D. R. Nagy and P. C. Patnaik: "TGO growth behaviour in TBCs with APS and HVOF bond coats" *Surf. Coat. Technol.*, 2008, 202, 2677–2683.
- [8]. J. M. Miguel, J. M. Guilemany and S. Vizcaino: "Tribological study of NiCrBSi coating obtained by different processes" *Tribol. Int.*, 2003, 36, 181–187.
- [9]. M. P. Planche, H. Liao, B. Normand and C. Coddet: "Relationships between NiCrBSi particle characteristics and corresponding coating properties using different thermal spraying processes" *Surf. Coat. Technol.*, 2005, 200, 2465–2473.
- [10]. S. Deshpande, T. S. Sampath and H. Zhang: "Mechanisms of oxidation and its role in microstructural evolution of metallic thermal spray coatings—Case study for Ni–Al" *Surf. Coat. Technol.*, 2006, 200, 5395–5406.
- [11]. J. M. Guilemany, N. Cinca, S. Dosta and A. V. Benedetti: "Corrosion behaviour of thermal sprayed nitinol coatings" *Corros. Sci.*, 2009, 51, 171–180.
- [12]. W. C. Lih, S. H. Yang, C. Y. Su, S. C. Huang, I. C. Hsua and M. S. Leu: "Effects of process parameters on molten particle speed and surface temperature and the properties of HVOF CrC/NiCr coatings" *Surf. Coat. Technol.*, 2000, 133–134, 54–60.
- [13]. J. A. Picas, A. Fornand and G. Matthaas: "HVOF coatings as an alternative to hard chrome for pistons and valves" *Wear*, 2006, 261, 477–484.
- [14]. H. Yang, C. Lee and S. Y. Hwang: "The effect of nano-sized Cr₂O₃ addition on the characteristics of NiCr–Cr₂O₃–Ag–BaF₂/CaF₂ coating" *Surf. Coat. Technol.*, 2006, 201, 38–44.
- [15]. U. Batra: "Thermal spray coating of abrasible Ni based composite" *Surf. Eng.*, 2009, 25, 284–286.
- [16]. C. H. Ding, P. L. Li, G. Ran and J. N. Zhou: "PM304 coating on a Ni-based superalloy by PM technique" *Mater. Sci. Eng. A*, 2008, A483–A484, 755.
- [17]. J. X. Deng and T. K. Cao: "Self-lubricating mechanisms via the in situ formed tribofilm of sintered ceramics with CaF₂ additions when sliding against hardened steel" *Int. J. Refract. Met. Hard Mater.*, 2007, 25, 189–197.
- [18]. H. E. Sliney: "Solid lubricant materials for high temperatures—a review" *Tribol. Int.*, 1982, 15, 303–315.
- [19]. M. K. Stanford and C. DellaCorte: "Atomization of metal fluorides for enhanced flow characteristics of a multicomponent powder" *Powder Technol.*, 2006, 161, 190–195.
- [20]. B. K. Kim, D. W. Lee and G. H. Ha: "Plasma spray coating of spray-dried Cr₂O₃/wt.% TiO₂ powder" *J. Therm. Spray Technol.*, 2001, 10, 133.
- [21]. L. Z. Du, C. B. Huang, W. G. Zhang, J. M. Zhang and W. Liu: "Effect of NiCr Clad BaF₂-CaF₂ Addition on Wear Performance of Plasma Sprayed Chromium Carbide-Nichrome Coating" *J. Therm. Spray Technol.*, 2010, 19, 551–557.
- [22]. C. B. Huang, L. Z. Du and W. G. Zhang: "Preparation and characterization of atmospheric plasma-sprayed NiCr/Cr₃C₂-BaF₂-CaF₂ composite coating" *Surf. Coat. Technol.*, 2009, 203, 3058–3065.
- [23]. S. Zimmermann and H. Kreye: "Chromium carbide coatings produced with various HVOF spray systems", *Proc. 9th Natl Thermal Spray Conf.*, 147–152; 1996, Materials Park, OH, ASM International.
- [24]. C. DellaCorte and J. A. Laskowski: "Tribological evaluation of PS300: a new chrome oxide based solid lubricant coating sliding against Al₂O₃ from 25 to 650Uc", NASA TM-107163, NASA, Washington, DC, USA, .
- [25]. G. H. Liu, R. Gras and J. Blouet: "Characterization of composite tribological coatings: composition, microstructure and mechanical properties" *Surf. Coat. Technol.*, 1993, 58, 199–203.
- [26]. W. C. Wang: "Application of a high temperature self-lubricating composite coating on steam turbine components" *Surf. Coat. Technol.*, 2004, 177–178, 12–17.
- [27]. G. Kim, H. Choi, C. Han, S. Uhm and C. Lee: "Characterization of atmospheric plasma spray NiCr–Cr₂O₃–Ag–CaF₂/BaF₂ coatings" *Surf. Coat. Technol.*, 2005, 195, 107–115.