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Thermal Spray Coating Applications in Tribology: Recent Case Studies

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ABSTRACT

Thermal spray coating techniques have been rooted deep down in the automotive industry providing groundbreaking solutions for different problems. This technology is capable of optimizing and revolutionizing the face of engineering in tribological applications and associated industrial problems. This paper reviews the development of wear resistant coating on cylinder surface of Al and Mg engine blocks and cylinder bores for improved corrosion and abrasion resistance. Wear mechanism and crack propagation can be prevented by [Cr + $(Cr,Al)_2O_3$] nanocomposite coating synthesized by plasma spraying technique which enhances the Al substrate properties by infusion with nanocomposites. This infusion results in the improvement of tribological characteristics. The recent developments in area of wear behavior and tribological characterization are discussed for the high velocity oxyfuel (HVOF) sprayed CrC and CrN coated piston ring applications and engine cylinder accounting for weight reduction, wear rate and the coefficient of friction (COF). The mechanical and tribological properties are compared for HVOF CrC75 (NiCr20)25 coatings sprayed from three different agglomerated feedstock powders with different size distributions.

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Introduction

Thermal spray is a collective term for a set of processes in which coating material is heated rapidly in a hot gaseous medium, and simultaneously projected at a high velocity onto a prepared substrate surface, where it deposits to produce the desired thickness of coating. Thermal spray is a technology that involves a group of techniques and coating processes that improve the performance of a component by adding functionality to surface. Its versatility makes this technology suitable for use against wear, corrosion and aggressive and high-temperature environments and for repair and restoration of components.

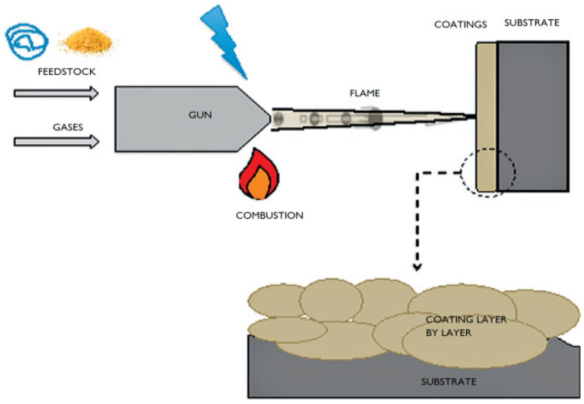

Figure 1: Schematic illustration of the thermal spray coating process [1]

Thermal spraying is a well-known industrial technique for surfacing and resurfacing engineered components. To form unique coating microstructures or near-net-shape components, metals, alloys, metal oxides, metal/ceramic blends, carbides, wires, rods, and assorted composite materials can be accumulated on a variety of substrate materials. Thermal spray coatings provide a fully functioning surface that has the potential to safeguard or reconfigure the behavior of a substratum and/or component. Restoration and repair; corrosion protection; various forms of wear such as abrasion, erosion, and scuff; heat insulation or conduction; oxidation and hot corrosion; electrical conductors or insulators; near-net-shape manufacturing; seals, engineered emissivity; abradable coatings; decorative items; and far more are some of the significant application functions. Thermal spray processes are simple to use, cost - effective to operate, and have characteristics that are beneficial for almost all industries. The key benefits of this technique include reduced costs, enhanced engineering performance, and increased component life. The implementation of thermal spray coating to automotive applications for tribological purposes is presented in this paper. Changing the coatings on various components such as monolithic engine blocks and cylinder bores to comprehend the influence of different coatings and their contribution to the augmentation of mechanical properties and operation life of the components are discussed through various case studies.

Spray materials

Coating materials in thermal spraying include pure metals, metal alloys, hard metals (carbides), oxide ceramics, plastics, ceramics, cermets, composites, and blended materials [14]. Thermal spray coating processes use powder, wire, or rod-shaped feedstock materials for coating manufacturing. Some of the spray processes, such as plasma, High Velocity Oxygen-fuel (HVOF), and powder flame spray systems, use only powder materials, and other

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processes, like electric wire arc and wire flame spraying, are based on wire materials as feedstock.

Properties of coatings

The structure and consequently the technical properties of thermally sprayed coatings are highly dependent on several factors, such as material composition, class, and feedstock material characteristics; particular spray process and process parameters used; coating formation, and post treatment procedures. The alloying of ternary TiAlN coatings with various elements has received considerable attention due to its ability to improve coating properties at high temperatures by solid solution hardening, grain refinement, formation of new phases, diffusion barriers, and self-lubricious trio-oxides [15].

Applications

Thermal spray coatings were originally used in the past only for repair and maintenance purposes; the technology indeed was called 'metal spraying.' However, soon the technology was adapted to several other application fields and today thermal spray coatings are used also much in new production, i.e., components and equipment are designed to have thermal spray coatings for high performance and durability. In mechanical engineering sectors, thermally sprayed coatings are widely used in restoration and in providing specific surface properties such as wear and corrosion protection, friction properties, and heat resistance. Applications of thermally sprayed coatings in the paper and pulp industry are numerous. The surface areas of paper machine rolls are large, which imposes several special requirements on the reliability of thermal spray processes. The use of spray materials in these applications is also large. Examples of applications in the pulp and paper industry are pulp digesters, blow tanks, suction rolls, calendar rolls, center press rolls, dryer rolls, yankee dryer cylinders, coater blades, and creping blades.

Nanomaterial based smart devices are now also being integrated with the textiles to perform various functions such as energy harvesting and storage, sensing, drug release and optics. These advancements have found wide applications in the fashion industry and are being developed for wider use in defense, healthcare, and on-body energy harnessing applications [17]. Various thermally sprayed coatings, particularly plasma-sprayed wear-resistant oxides, are used in machines in textile industry. Magnesium (Mg) and its alloys are promising candidates for use in bone tissue engineering due to their good biocompatibility and mechanical stability [16]. Different human spare parts like hip, knee, and tooth implants are today coated by vacuum and atmospheric plasma processes.

Case Study 1: Comparative study of Wire Arc, HVOF and Rotating Plasma Technique for engine blocks and cylinder bores

Barbezat, G. (2005) conducted studies to investigate the creation of a wear-resistant coating on the cylinder surface of aluminum and magnesium engines. After finishing, the obtained surface topography allowed for a decrease in coefficient of friction and a further reduction in fuel consumption from 2% to 4%. The mechanical properties were compared of Grey CFGGL, Compact Graphite GCV, and Al 18 Si used in monolithic engine blocks. Si content, primary crystal Si size, casting method, and composition, all had an impact on their use in engine blocks. Si cast alloys with hypoeutectic aluminum alloys were developed and used to reduce the weight, but they had poor tribological properties and required additional surface treatment and thermal spray coating. Comparison of Wire Arc, HVOF and Rotating Plasma Technique based on different criteria are presented in Table 1.

Table 1: Comparison of the thermal spray processes for the coating deposition in engine cylinder bores [2]

Criteria	**Processes**		
	Wire Arc (wire)	**HVOF (wire or powder)**	**Rotating plasma (powder)**
Versatility in the choice of material	Metallic alloy (Restricted choice of materials)	Metallic alloys carbides, composites (Limitations for refractory materials)	Metallic alloys, carbide, ceramics, composites (High versatility)
Heat transfer into the engine block	Medium	Very high	Low
Reliability of the melting process	Formation of the melted particle is difficult to control Medium	High (powder) and medium (wire)	High
Coating thickness as sprayed	500µm	200µm	200µm
Coating properties for cylinder bores	Medium	High	High
Process cost	Low	Very high	Low
Industrial status	Prototypes	Prototypes	In industrial production since many years

The researchers concluded that using the thermal spray coating (TSC) in cylinder bores allowed for a significant weight reduction of the engine block, a reduction in friction between piston rings and the inner surface, and a significant reduction in oil consumption.

Case Study 2: Cr+(Cr,Al)2O3 nanocomposite coating by Reactive Plasma Spraying Technique

The friction and wear properties of [Cr+(Cr, Al)2O3] nanocomposite coatings synthesized in situ by Reactive Plasma Spraying Al-Cr2O3-Al2O3 composite powder was investigated by Song et al., (2005). The researchers discovered that adding a certain number of additives (aAl2O3+bCr2O3) optimizes the microstructure and structure of the composite coating.

Al2O3 ceramic coatings have high hardness, wear resistance, and corrosion resistance, and are widely used in aerospace, manufacturing, and the chemical industry. The Cr2O3 has excellent friction and wear characteristics, as well as excellent high temperature resistance, making it superior to the traditional wear-resistant hard chromium coating, which is used in printing rollers, automobile piston rings, and cylinder sleeves to improve wear resistance and thus extend the service life of service workpieces.

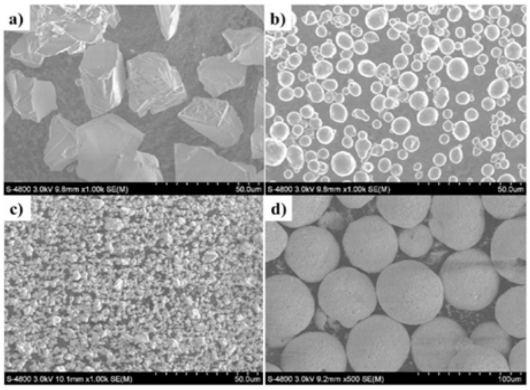

Figure 2: Microstructure morphology of powders: (a) Al, (b) Al2O3, (c) Cr2O3 and (d) composite powder of Al-Cr2O3-Al2O3 [3]

Although ceramic materials have a major disadvantage in that their poor plastic toughness limits their application in wear environments, they required some modification to improve their toughness. By using ultrasonic vibration and wet ball milling, Song et al., (2005) created a powder mixture by evenly mixing Al2O3 powder, Cr2O3 powder, and Al powder. Spray granulation was used to create an Al-Cr2O3-Al2O3 composite agglomerated powder, and the resulting composite powder is granulated 200+300 mesh sieves. Before the sample is sprayed, a suction sandblasting machine is used to pretreat the surface of the substrate and for removing dust, moisture, oil, and rust.

The coating parameters used are given in Table 2. A composite coating was applied on various samples to test for cross sectional and indentation morphology, phase analysis and friction and wear characteristics.

Table 2: Process parameters of plasma spraying [3]

Parameters	Composite Coatings	Ni-Al bond coating
Current (A)	500	400
Voltage (V)	60	70
Primary gas (Ar) flow rate (L/min-1)	80	70
Secondary gas(H2) flow rate (L/min-1)	20	20
Carrier gas (N2) flow rate (L/min-1)	10	10
Spray distance (mm)	100	110

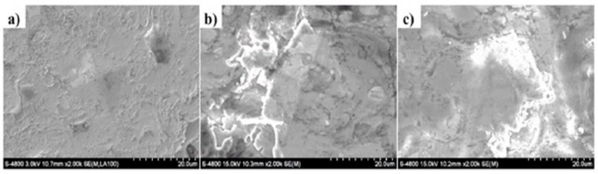

Figure 3: SEM Micrographs of indentation morphology and of three coatings (a) original coating (b) Al2O3 coating, (c) Cr2O3 [3]

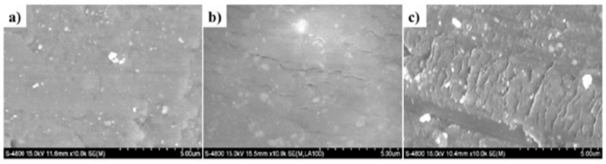

Figure 4: SEM Micrograph of wear surface morphology and of three coatings (a) original coating (b) Al2O3 coating, (c) Cr2O3 [3]

It was concluded that eutectic composite coatings with dimensions less than 10 nm have the best plastic toughness, friction, and wear properties. The wear resistance is 3.28 times that of the Al2O3 ceramic coating, and the microhardness is 1899HV0.3. Fatigue wear and slight adhesion wear were the wear mechanisms.

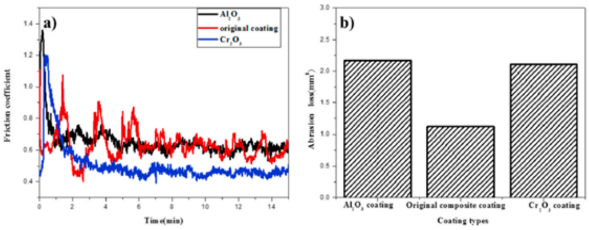

Figure 5: Friction coefficient and wear amount of three coatings (a) friction coefficient (b) wear amount [3]

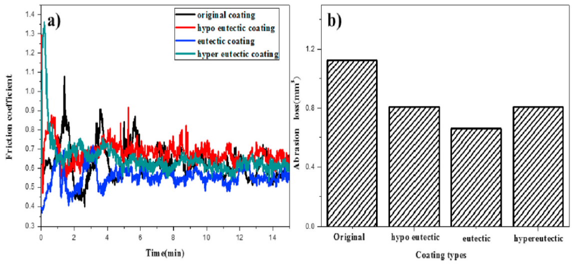

Figure 6: Friction coefficient and wear number of composite coatings (a) friction coefficient (b) wear amount [3].

Case Study 3: CrC-based compound coatings sprayed by HVOF and Plasma Spraying Technique for piston ring application

Gupta et al., (2021) conducted a study on the mechanical and microstructure characteristics of CrC-based compound coatings and sprayed onto different substrate materials utilizing High Velocity Oxy-Fuel (HVOF) and plasma spraying strategies to ascertain the functionality of CrC-based coatings for piston rings application. The wear and corrosion resistance of coated materials had enhanced significantly to dispersed components such as Ni and Cr carbide phases. The HVOF procedure resulted in significant wear and destructive resistance, notably in cermet coatings where powder materials had to be augmented to store on substrate materials. It was also unearthed that the substrate material's properties had a substantial impact on the coating characteristics.

The study revealed that only a few CrC-based compound combinations absolutely crush WC-Co powder coating. Thermal spray coating procedures and CrC-based blends have been regarded for piston ring application fields such as wear rate, weight reduction, and COF. It was found that individualized process optimization is required for different feedstocks due to extrinsic feedstock characteristics such as morphology, density, and heat transfer properties. So, the investigation for gas temperature, gas Mach number, gas velocity, gas pressure, and gas component were carried out for a better understanding of the particle and flame behaviour in an HVOF thermal spray process. Using HVOF spray process, an erosion/oxidation/corrosion resistance composite coating like HP2 [Cr_3C_2-NiCr +25%(WC-Co)] was deposited on T22 boiler steel. According to the study, HVOF Cr_2C_3 -NiCr

Coating produced using a high kinetic thermal spray process is a very promising solution for improving fatigue performance of steel components in industrial applications. The process parameters used were in the following order: oxygen flow rate, hydrogen flow rate, feed rate, and spray distance.

It was found that the influence of each parameter on hardness varies, and that the oxygen flow rate has the greatest effect on hardness when the levels are changed. The WC oxidation rate also increased, resulting in the formation of WO_3, which promotes cracking and subsequent spalling of the chromium oxide. The presence of hard but brittle phases formed during spraying due to the decarburization process accounts for the increased hardness of the HVOF coating. The impact of abrasive media on the grinded coatings demonstrated that both coatings have good wear resistance with comparable results, but the High Velocity Air-Fuel (HVAF) coating showed slightly lower wear loss. Both the methodology and the feedstock attributes significantly affect the hardness of thermal sprayed coatings. In the HVOF procedure, particle velocity is considerable while thermal energy is low, resulting in a greater hardness.

Three distinct techniques were utilized to deposit CrN, (Ti, Al)N, and CrC/C coatings. It was observed that coating wear is directly affected by both the substrate material and the coating parameters. The hardness of the substrate has a significant impact on the wear of the Physical Vapour Deposition (PVD) coatings and, as a result, on the friction characteristics and galling resistance of the coating/substrate composite.

According to the study by Gupta et al., (2021), the HVOF process has the lowest porosity due to the high impact velocity when compared to other spraying techniques, but proper optimization of the HVOF flame jet is recommended to reduce the extent of decomposition. Multilayer coatings outperform monolayer coatings in terms of anti-wear properties. The authors also investigated corrosion behavior and substrate materials, as well as CrC-NiCr phase analysis. The study's findings included the following: The coating was observed to be capable of replacing cancer-causing electroplated hard chromium coating on cylinder rings. CrC alloyed covered structure accomplishes more wear resistance, corrosion resistance and lower estimations of COF. In terms of tribological properties, Fine CrC-NiCr coating performs better than hard chrome.

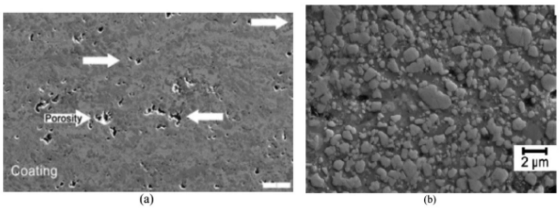

Figure 7: Surface morphology of NiCr coating [4, 5].

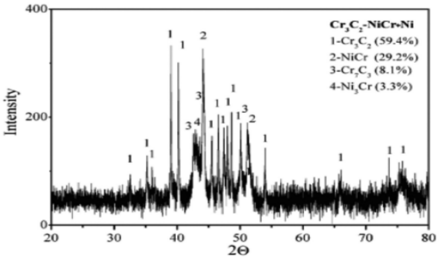

Figure 8: XRD analysis of Cr3C2-NiCr powder coating [4, 6]

Case Study 4: Surface properties of CrN coated engine cylinders

Oner el al., (2009) performed an experimental study on a single cylinder four stroke diesel engine. The cylinder was coated with CrN by Physical Vapour Deposition (PVD) and investigated its surface behaviors. The wear behaviors of the engines with CrN coated cylinder and with uncoated cast iron cylinder were also compared. They studied the effect of hardness, surface topography, microstructure and running conditions. Coating the combustion chamber, cylinder surface, and other parts with ceramic materials increases the thermal and frictional resistance and hence it improves the engine performance. Ceramic coatings are widely used against wear, corrosion, erosion and heat. In ceramic coatings, the coating layer provides wear resistance, while the substrate ensures resistance against thermal and mechanical shocks. PVD process is an atomistic deposition method that involves the vaporization and subsequent deposition of coating materials. Figure 9 represents the schematic representation of cathodic arc PVD system.

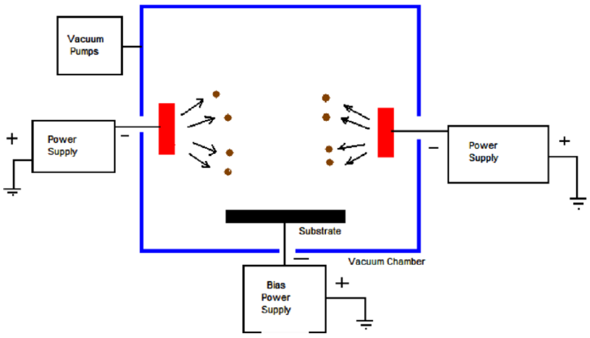

Figure 9: Schematic representation of cathodic arc PVD system [7]

The PVD can deposit coatings of metal, alloys, and ceramics on most materials and wide range of shapes. The inner face of cylinder tube, cast iron, was coated with CrN by PVD. For experimental work, cylinder surface of a single cylinder direct injection diesel engine was coated by CrN to 1.8 µm ± 0.2 thickness using cathodic arc PVD technique. The coating process was applied under the temperature of 250–300̊ C and pressure of 7.5×10^{-3} torr for 80 min with a cathode current of 90 A and bias voltage of 15V. PVD technique allows multilayer coatings without affecting the microstructure. The technique gives excellent adhering properties with CrN coating materials. A one-cylinder air cooling 6LD Lombardini diesel engine was used in experimental studies. The technical specification of the engine is given in Table 3.

Table 3: Technical specification of the engine used in the experiments [7]

Model	6LD 400 Lombardini
Number of stokes	4
Number of cylinder	1
Diameter of the cylinder	86 mm
Stroke length	68 mm
Power	6.25 kW (8.5 HP)
Maximum torque	19.6 Nm / 2000 rpm
Fuel	Diesel
Injection type	Direct injection
Injection pressure	20 MPa
Cooling	Air

Test unit contains a brake dynamometer, mechanism to measure air and fuel consumption, mechanism to measure pressure and temperature, and a control panel. The engine was run under specified conditions for 200 hours with coated cylinder and 200 hours with uncoated cylinder. To examine surface properties of the cylinder, scanning electron microscopy (SEM), X-ray diffraction (XRD) and surface roughness studies were performed. The samples were taken from top, middle, and bottom parts of the cylinder tube. The main objective was to compare the behaviors of coated and uncoated surfaces.

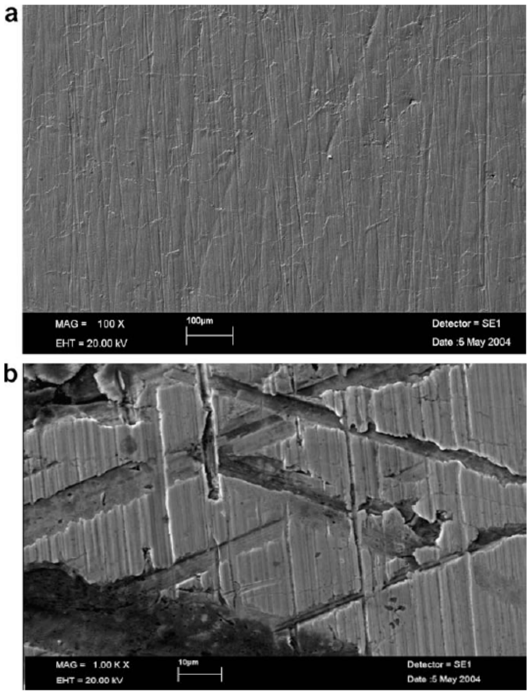

Figure 10: SEM micrographs of (a) coated and (b) uncoated cylinders after test runs [7]

Oner el al., (2009) observed almost no wear on CrN coated cylinders, while surface cracks, deep wear grooves and severe deformation were found on uncoated cast iron cylinder tubes. CrN coating helps to achieve hydrodynamic lubrication and hence reduces wear and deformation. The coating also helps to prevent wear in the whole cylinder-piston-ring system. It also improves hardness, microstructure and roughness values of the surface resulting in a longer life for the cylinder and the engine.

Case Study 5: HVOF coatings as an alternative to hard chrome for pistons and valves

Picas et al., (2006) studied the tribological properties of HVOF CrC75 (NiCr20) 25 coatings. They used three different agglomerated feedstock powders for the coatings. The main objective of this study was to apply these new HVOF coatings in valve stems and piston rings applications. And to avoid the blasting operation, the HVOF coatings are produced with fine powders. Backscattered electron-scanning electron microscopy (BSE–SEM) microscopy was observed for the coating microstructure. For the measurement of hardness and the elasto-plastic properties of the coatings, the ultra-microidentation technique was applied. To evaluate the friction and wear properties of the coatings, experiments were performed using a pin on disc tribometer, under lubricated and dry conditions.

Due to the low porosity, highly adherent coatings, and less oxide content, HVOF is the preferred thermal spray process for the chrome replacement. For the deposition of conventional Cr_3C_2 –NiCr feedstock powders, the HVOF thermal spray process considered the best method as the very high velocity of the flame shortens the time of interaction between flame and the powder [8]. It was concluded that CrC–NiCr HVOF coatings are superior in performance comparing to chrome plating.

Researchers studied Cr_3C_2 75% + NiCr20 25% weight deposited by HVOF coatings on a steel substrate with approximately thickness of 150 µm. As standard powder, the agglomerated and sintered powder (75% chrome carbide and 25% nickel chrome) was used. Three different 2075-NiCr powders, Standard, Fine-10 µm and Fine-5 µm were used as feedstock powder. A C-CJS HVOF gun with k5.2 nozzle configuration (Thermico, Germany) was used for thermal spraying of the different Cr_3C_2 –NiCr powders. This new configuration was developed allows spraying fine powders. Generally, for thermal spraying the material is agglomerated into powders in the range of 30–50 µm, but in this study fine powder (less than10 µm) was used. The results of the pin on disc test under lubricated and dry conditions are showed in Table 4.

Table 4: Pin on disc test results [9]

	Friction coefficient		Specific wear rate ($m^3/mN\times10^{-15}$)	
	Dry	Lubricated	Dry	Lubricated
Standard	0.24	0.11	17.0	5.3
Fine-10 µm	0.25	0.11	10.4	2.5
Fine-5 µm	0.25	0.11	8.1	2.2
Hard chrome	0.22	0.12	36.0	6.1

As shown in the Table 4, the specific wear rate of Fine-10 µm and Fine-5 µm CrC75–NiCr25 coatings are lower than hard chrome plating and standard CrC75–NiCr25 coating. When two surfaces are taking into sliding contact at the beginning, the soft ductile nickel–chromium matrix between CrC particles undergoes severe deformation.

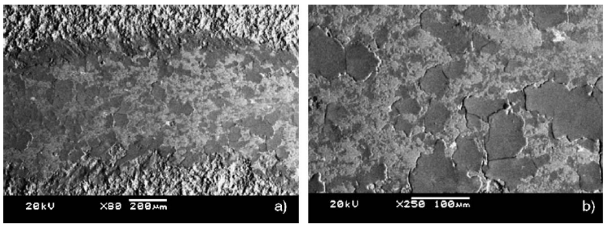

Figure 11: Wear track of CrC75–NiCr25 Fine-10 µm coating [9]

By sliding CW-6%Co ball onto fine-10 µm coatings with load of 40N, SEM of the wear track produced are shown in the Figure 11. It was concluded that the Fine CrC-NiCr agglomerates produce coatings with lower hardness and up to 50% better wear behavior as compared to standard CrC-NiCr coating. In the NI-Cr matrix, CrC particles formed the bimodal structure of Fine CrC–NiCr coatings with a size greater than 1 µm together with sub-micron carbides. Decrease in the size of the feedstock powder reduces the superficial coating roughness. Hence, blasting and grinding operations can be reduced and it could decrease the manufacturing time and can produce cheaper products.

Case Study 6: The wear resistant nanocomposite coating on aluminum alloys by Plasma Spraying Technique

Rajeshshyam et al., (2020) reviewed the wear resistant nano composite coatings on aluminum alloys by Plasma Spraying Technique. Nanocomposites like Al_2O_3, CeO_2, TiO_2, Mo, Ni, cast iron, Al-Si are introduced by the researchers to enhance the tribological properties of aluminum substrate. Aluminum alloys widely used in the machine building, defense, aerospace industry and offshore applications due to high specific strength, low density, and good thermal conductivity [10]. To reduce the weight of the vehicle in automobile industry, cast iron is replaced by lightweight aluminum alloys for producing the cylinder blocks. Introducing the cast aluminum cylinder block in the automobile sector reduces the block weight percentage upto 45% of gasoline engines. The tribological properties of Al_2O_3-CeO_2/Ni based composite coating on aluminum alloys were investigated in this study and composite coating were processed on AA 7075 alloy by plasma spray.

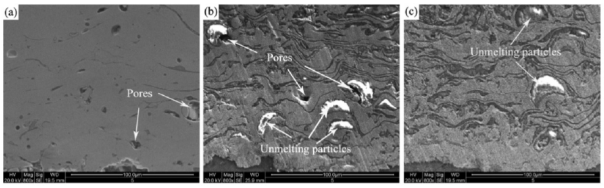

Figure 12: (a) Ni60-100wt% (b) 85wt% of Ni60 and 15wt% of Al_2O_3 (c) 83wt% of Ni, 15wt% of Al_2O_3 and 2 wt% of CeO_2 [10]

Figure 12 shows the cross-section images of combinations of three different coatings. Fig (a) reflects the uniform and high dense coating with few pores, as indicated in the figure. In images (b) formation of lamellar structure is formed.

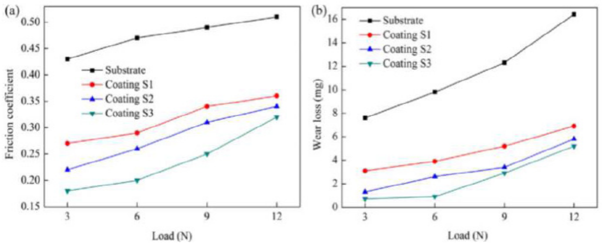

Figure 13: Friction coefficient and wear loss of three combinations of coating at different loads [10]

The result shows that the friction coefficient and wear loss of the coatings are minimal than the uncoated substrate, and the wear loss graph revealed that coating S3 had attained minimal wear loss than other coatings. The tribological outcomes of 10 wt% and 20 wt% of diamond reinforced Plasma-sprayed Molybdenum Coating was also investigated. The inclusions of the diamond reinforcements improved the hardness and elastic modulus. It was found that 20wt% of diamond reinforced molybdenum coating shows the higher wear resistance among the others.

The tribological characteristics of TiO_2 based ceramic coating on engine cylinder surface with the use of internal plasma spraying technique was investigated in this study. The continuous loading and unloading resulted in formation of surface cracks and a greater number of pitting on the surface.

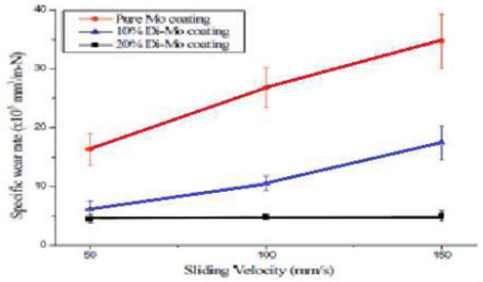

Figure 14: Plot exhibiting the comparison of specific wear rates of pure, 10wt% and 20wt% of diamond reinforced composite coating under 30 N load [11]

It was found that TiO_2 based ceramic coating has strong chemical stability during the friction and the co-efficient of friction is relatively less at high temperatures. There were profound changes in surface roughness compared to the uncoated substrate.

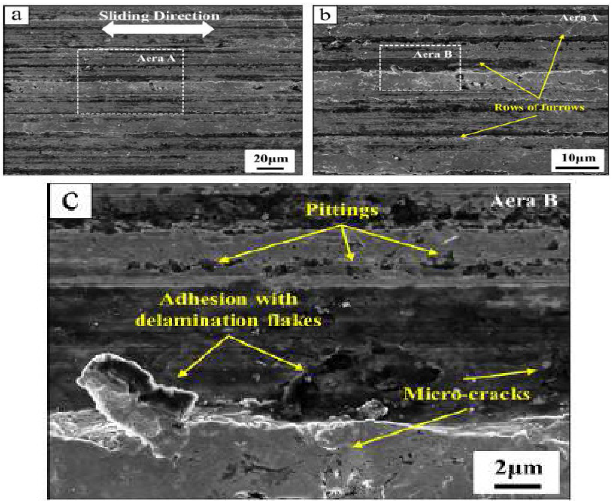

Figure 15: SEM micrograph of surface morphology after wear test (b) dilated view of area A, and B (c) enlarged the view of area B [12]

Rajeshshyam et al., (2020) concluded that the plasma spray coating with nanocomposites could be deposited successfully on the aluminum substrate by plasma spraying technique. New composite coated with aluminum alloy using plasma spray technique may fulfil new benefits and property in the future. Due to their useful physical and mechanical properties, these nanocomposite coatings have paid more attention to research community.

Conclusions

Different case studies showing improvement in properties of surfaces due to application of thermal spray coating technique are discussed in this paper. The commonly used materials for coating are presented with their properties. This paper focused on application of thermal spray coating in enhancement of the mechanical and the tribological properties of various components. Experimental studies of Wire Arc, HVOF, RPT, RPS, PST processes on component like engine block, cylinder bore, piston ring, engine cylinder, piston, and valves along with nanocomposite coating are discussed to highlight the successful utilization of thermal spray coating in tribology domain.

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