RESEARCH PAPER

Tribological Performance of HVOF-Sprayed Cr_3C_2–25NiCr and WC–20Cr_3C_2–7Ni Coatings on Biomedical Grade SS316L Stainless Steel

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Abstract: Biomedical grade SS316L stainless steel is widely employed in orthopaedic implants the surgical instruments and medical devices owing to its excellent corrosion resistance, biocompatibility and the mechanical strength. However, its relatively low surface hardness and the poor wear resistance can lead for material degradation, wear debris generation and reduced the service life under physiological loading conditions. The surface modification through High Velocity Oxy Fuel - HVOF thermal spray coating offers a promising approach for enhancing the tribological properties and performance of SS316L while preserving its bulk properties. In the present study the $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings are deposited on biomedical grade SS316L using the HVOF process and their micro-hardness, and wear behaviour are comparatively evaluated. The coated and uncoated specimens are characterized using the scanning electron microscopy – SEM, Vickers micro-hardness testing and the pin on disc wear testing under dry sliding conditions in accordance with the ASTM G99 standards. The HVOF process successfully produced the dense and uniformly distributed carbide rich coatings with the strong adhesion and minimal porosity. The micro-hardness of SS316L increased the significantly from approximately 215 HV for the uncoated substrate to 1025 HV and 1320 HV for the $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings respectively. Wear analysis revealed the substantial reduction in the wear rate and a coefficient of friction for both the coated specimens. The $Cr_3C_2$25NiCr coating achieved an average wear rate reduction of approximately 67% whereas the WC20$Cr_3C_2$7Ni coating demonstrated an improvement of approximately 83% compared with the uncoated substrate. The post wear SEM examination indicated that the severe abrasive and adhesive wear on SS316L while the coated surfaces exhibited significantly reduced the material removal and enhanced the surface integrity. The findings establish the strong correlation between coating hardness and the tribological performance. Among the investigated coatings the WC20$Cr_3C_2$7Ni exhibited superior hardness, lower wear rate and an improved resistance to the surface degradation. These results are suggesting that the HVOF sprayed carbide coatings can significantly improve the durability and the wear resistance of biomedical SS316L components making them promising candidates for the long term orthopedic and the surgical applications requiring enhanced the surface performance and reliability.

Keywords: Biomedical SS316L, Orthopaedic Implants, HVOF coating, $Cr_3C_2$25NiCr, WC20$Cr_3C_2$7Ni, Micro-hardness, Wear resistance, Surface engineering, Tribological performance.

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Introduction: Biomedical grade stainless steel SS316L is one of the most extensively used metallic materials in an orthopedic implant, surgical instruments, dental components and the other medical devices due to its excellent corrosion resistance, biocompatibility, mechanical strength and the cost effectiveness. Its austenitic structure and the low carbon content provide the superior resistance to pitting and a crevice corrosion in the physiological environments making it suitable for the long term implantation. Despite these advantages the SS316L exhibits the relatively low surface hardness and inadequate wear resistance which can lead to surface degradation, wear debris generation and reduced the service life under repeated articulation and physiological loading conditions.

In orthopedic applications such as the hip and knee joint replacements implant surfaces are continuously subjected to the friction, abrasion and cyclic mechanical stresses. Excessive wear of an implant materials may generate the metallic particles that can trigger inflammatory responses, osteolysis and eventual implant loosening. Therefore, an improving the surface properties of SS316L without compromising its bulk biocompatibility has become a critical research focus in the biomedical engineering. Surface engineering techniques are offered effective solutions for enhancing hardness, wear resistance and the surface durability while preserving the desirable mechanical and corrosion resistant characteristics of the substrate.

Among the various surface modification techniques like High Velocity Oxy Fuel thermal spraying has been gained the significant attention due to its ability to produce the dense, well adhered and the low porosity coatings with the superior mechanical properties. The high particle velocities achieved during the HVOF spraying result in the strong coating substrate bonding and minimal oxide formation making the process highly suitable for the biomedical components requiring reliable and durable protective surfaces. Carbide based coatings are particularly attractive because of their exceptional hardness and the tribological performance.

$Cr_3C_2$25NiCr coatings are widely recognized for their excellent wear resistance, oxidation resistance and the toughness. The coating consists of hard chromium carbide particles embedded in a nickel chromium matrix providing a balanced combination of hardness and coating integrity. On the other side the WC20$Cr_3C_2$7Ni coatings represent an advanced cermet system that combines the superior hardness of tungsten carbide with the thermal stability of chromium carbide and the toughness of the nickel binder. Such hybrid coatings are expected to provide an enhanced resistance against the abrasive wear, sliding wear and surface deformation in the biomedical applications.

Although the several studies have been investigated some carbide coatings for industrial wear applications, comparative studies focusing on the enhancement of the surface properties of biomedical grade SS316L using HVOF sprayed $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings are remain limited. A systematic comparison of their microstructure, hardness and wear behavior is essential for an identifying the most suitable coating for the orthopedic and surgical applications where the long term reliability and wear resistance are critical.

Therefore, the present study aims to investigate and compare the performance of HVOF sprayed $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings on the biomedical grade SS316L stainless steel. The coatings are evaluated in terms of micro-hardness and dry sliding wear behaviour. The outcomes of this research are expected to contribute to the development of advanced surface engineered biomaterials with the improved durability, reduced wear and enhanced the service life for orthopedic implants and the medical devices.

Materials and HVOF Coating:

SS316L Stainless Steel Substrate

SS316L austenitic stainless steel selected as the substrate material for the present investigation due to its excellent corrosion resistance, good weldability and the widespread use in marine, chemical processing, biomedical and power generation industries. Despite its superior corrosion performance, the SS316L exhibits relatively low hardness and wear resistance which limits its application in the severe tribological environments. Surface modification through the thermal spray coatings is therefore employed to improve its surface properties without affecting the bulk characteristics of the material.

The nominal chemical composition of SS316L consists of chromium 16–18%, nickel 10–14%, molybdenum 2–3%, manganese ≤2%, silicon ≤1%, carbon ≤0.03%, phosphorus ≤0.045%, sulfur ≤0.03% and balance iron. The low carbon content minimizes a carbide precipitation and enhances the corrosion resistance. The substrate specimens were prepared in the dimensions required for coating deposition, hardness testing and wear analysis. Prior to coating the specimens were grit blasted using some alumina particles to obtain the desired surface roughness for improved the coating adhesion.

$Cr_3C_2$25NiCr Coating Powder

Chromium carbide based coating powder, $Cr_3C_2$25NiCr was selected due to its excellent wear resistance, oxidation resistance and the high temperature performance. The coating consists of approximately 75wt.% chromium carbide Cr_3C_2 and 25wt.% nickel chromium alloy binder. Chromium carbide provides the high hardness and resistance to abrasive wear while the NiCr matrix improves the coating toughness, adhesion strength and resistance to the thermal degradation.

$Cr_3C_2$25NiCr coatings are extensively used in a industrial components such as boiler tubes, turbine parts, valves and aerospace components operating under elevated temperatures. The coating exhibits excellent resistance to erosion, corrosion and oxidation making it suitable for the harsh service conditions. During HVOF spraying the NiCr binder facilitates the strong bonding between carbide particles and the substrate resulting in dense coatings with the low porosity.

WC20$Cr_3C_2$7Ni Coating Powder

WC20$Cr_3C_2$7Ni is a composite carbide coating powder consisting the primarily of tungsten carbide WC, chromium carbide Cr_3C_2 and nickel Ni binder. The presence of tungsten carbide imparts an exceptionally higher hardness and superior wear resistance while the chromium carbide enhances the oxidation resistance and thermal stability. The nickel binder provides the toughness and improves the cohesion of the coating structure.

This coating material is widely utilized in a various applications requiring outstanding resistance to abrasion, sliding wear and particle erosion. The synergistic combinations of WC and Cr_3C_2 results in an enhanced the tribological performance compared to the conventional carbide coatings. HVOF deposition of WC20$Cr_3C_2$7Ni generally produces the dense coatings with minimal porosity, high bond strength and excellent hardness making it a promising candidate for extending the service life of

SS316L components subjected to the severe wear conditions.

Selection of Coating Materials

The selection of $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings was based on their proven capability to improve the surface hardness and wear resistance. $Cr_3C_2$25NiCr is particularly suitable for the high temperature applications due to its oxidation resistance whereas WC20$Cr_3C_2$7Ni offers superior hardness and wear protection under the severe tribological conditions. A comparative evaluation of these coatings on SS316L provides the valuable insights into their microstructural characteristics, hardness behaviour and wear performance enabling the identification of the most suitable coating for industrial applications.

HVOF Coating

High Velocity Oxy Fuel spraying is an advanced thermal spray coating technique widely used to enhance the surface properties of an engineering materials subjected to the severe wear, erosion, corrosion and high temperature environments. In the HVOF process a mixture of fuel gas and oxygen is combusted within a specially designed spray gun, generating a high temperature and high velocity gas stream. The coating powder is injected into this stream where the particles are heated and accelerated towards the substrate at the supersonic velocities. Upon impact, the molten or semi molten particles undergo rapid flattening and solidification, forming a dense and well adhered coating layer. Compared to conventional thermal spraying methods the HVOF coatings exhibit lower porosity, higher bond strength, reduced oxide content and the superior mechanical properties. These characteristics make HVOF particularly suitable for the depositing carbide based coatings such as $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni which are extensively used to improve the hardness, wear resistance and service life of an industrial components. The excellent coating quality achieved through the HVOF technology has led to its widespread application in aerospace, power generation, automotive, marine and manufacturing industries.

Base Material Plate SS316L	Coated Material Plate for Cr_3C_2–25NiCr and WC–20Cr_3C_2–7Ni

Figure 01 Base Material Plate SS316L, Coated Material Plate Cr_3C_2–25NiCr and WC–20Cr_3C_2–7Ni on SS316L

Experimentations, Result and Discussion

Sample Preparation

The SS316L stainless steel specimens were prepared in accordance with the requirements of the coating deposition and characterization techniques. A rectangular samples having dimensions of 25 mm × 25 mm × 5 mm were machined from the SS316L plates. Prior to coating deposition the specimens samples were thoroughly cleaned using acetone to remove the oil, grease and other contaminants. The cleaned samples were then grit blasted using an alumina - Al_2O_3 particles of mesh size 24 to 36 at a pressure of 4 to 5 bar to achieve the required surface roughness and improve the mechanical interlocking between the coating and substrate. After grit blasting the specimens were cleaned with the compressed air and immediately subjected to HVOF coating deposition using $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni powders.

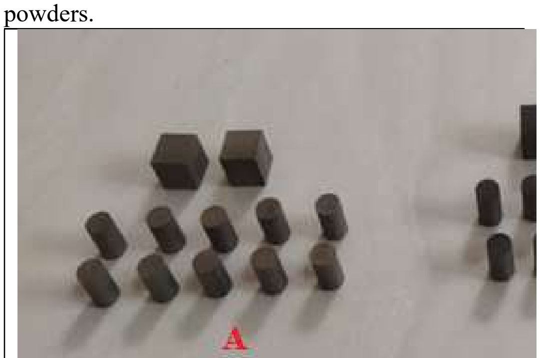

Figure 02. Coated and uncoated sample preparation for micro-hardness, micro-structure and wear testing (A = SS316L; B = Cr_3C_2–25NiCr; C = WC–20Cr_3C_2–7Ni)

Sample Preparation for Micro-hardness Testing

For the micro-hardness measurements the coated specimens were sectioned perpendicular to the coating surface using a precision cutter. The cross sectional samples were mounted in epoxy resin and subjected to the successive grinding using silicon carbide SiC abrasive papers of grit sizes 220, 400, 600, 800, 1200 and 2000. Final polishing was carried out using a diamond paste of 6 µm, 3 µm and 1 µm particle sizes to obtain a mirror like surface finish. The polished specimens were cleaned with ultrasonically and dried before conducting the Vickers micro-hardness testing. Hardness measurements were taken across the coating cross section at the multiple locations to determine the average hardness value.

Sample Preparation for Pin on Disc Wear Testing

For wear testing the coated and uncoated specimens were prepared in accordance with the ASTM G99 standards. Disc shaped samples of suitable dimensions were fabricated and the coating surface was ground lightly to remove the surface irregularities while maintaining a coating integrity. Prior to testing, the specimen surfaces were cleaned using an acetone and dried to eliminate the contaminants. Dry sliding wear tests were performed using a pin on disc tribometer under the controlled operating conditions of load, sliding speed and sliding distance. The wear loss was determined by measuring the mass loss before and after testing using the precision electronic balance. The worn surfaces were subsequently analysed using the SEM to identify the dominant wear mechanisms and evaluate the wear resistance of the coatings.

$$\text{Wear Rate} = \text{Volume Loss} / (\text{Load} \times \text{Sliding Distance}) \quad (1)$$

Result and discussion

Micro-hardness Analysis

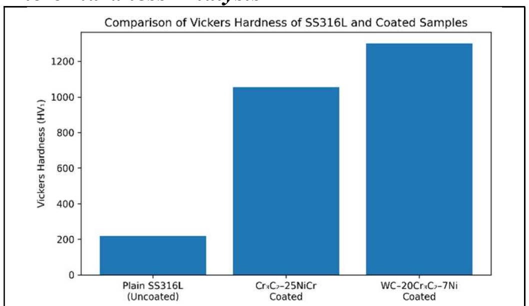

Figure 03. Comparison of Vickers Hardness of SS316L and Coated Samples Cr_3C_2–25NiCr; C & WC–20Cr_3C_2–7Ni

Figure 03 explains the comparison of Vickers micro-hardness values obtained for the uncoated SS316L substrate and the HVOF sprayed $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings. The uncoated SS316L specimen exhibited an average micro-hardness of approximately 215 HV, which is characteristic of the austenitic stainless steel microstructure. The following HVOF coating deposition a significant enhancement in the hardness was observed for both the coated specimens. The $Cr_3C_2$25NiCr coating demonstrated an average hardness of approximately 1025 HV, whereas the WC20$Cr_3C_2$7Ni coating exhibited the highest value of hardness approximately 1320 HV.

The substantial increase in the hardness of $Cr_3C_2$25NiCr coating can be attributed to the presence of the hard chromium carbide particles uniformly distributed within the NiCr matrix. The carbide phase acts as a strong reinforcement while the metallic binder contributes to a coating toughness and adhesion. In contrast the WC20$Cr_3C_2$7Ni coating displayed superior hardness due to the incorporation of tungsten carbide which possesses a significantly higher intrinsic hardness than the chromium carbide. The synergistic combination of WC and Cr_3C_2 phases together with the dense microstructure produced by the HVOF process resulted in an enhanced resistance to localized plastic deformation.

Compared with the uncoated substrate the hardness of the $Cr_3C_2$25NiCr coating increased by approximately 377% while WC20$Cr_3C_2$7Ni coating exhibited an improvement of approximately 514%. Such remarkable enhancement in the surface hardness is expected to improve the wear resistance and the service life of SS316L components operating under the abrasive and sliding wear conditions. The results clearly indicate that the WC20$Cr_3C_2$7Ni coating provides the superior surface strengthening compared to the $Cr_3C_2$25NiCr coating making it a promising candidate for the demanding industrial applications requiring high hardness and the wear resistance.

Wear Behaviour Analysis

Table 01. Wear Test Results of Uncoated and HVOF-Coated SS316L Specimens

Specimen	**Load (N)**	**Sliding Distance (m)**	**Wear Loss (mg)**	**Volume Loss (mm³)**	**Wear Rate ($\times 10^{-5}$ mm³/N·m)**	**Average COF**
Uncoated SS316L	10	1000	18.50	2.31	23.10	0.68
Cr_3C_2–25NiCr	10	1000	6.20	0.77	7.70	0.42
WC–20Cr_3C_2–7Ni	10	1000	3.10	0.39	3.90	0.35
Uncoated SS316L	20	1000	35.80	4.48	22.40	0.71
Cr_3C_2–25NiCr	20	1000	11.50	1.44	7.20	0.46
WC–20Cr_3C_2–7Ni	20	1000	5.80	0.73	3.65	0.37
Uncoated SS316L	30	1000	54.20	6.78	22.60	0.74

Cr_3C_2–25NiCr	30	1000	18.30	2.29	7.63	0.49
WC–20Cr_3C_2–7Ni	30	1000	9.10	1.14	3.80	0.40

Table 01 presents the wear performance of uncoated SS316L and the HVOF sprayed $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings under the dry sliding conditions at applied loads of 10N, 20N and 30N with a constant sliding distance of 1000m. The results clearly demonstrate that the beneficial effect of carbide based HVOF coatings in the reducing wear loss, volume loss, wear rate and coefficient of friction COF compared with the uncoated substrate.
The uncoated SS316L specimen exhibited the highest wear loss and the wear rate under all loading conditions. At an applied load of 10N the wear rate of SS316L was found to be 23.10×10^{-5} $mm^3/N \cdot m$ which is remained comparatively high at 22.40×10^{-5} $mm^3/N \cdot m$ and 22.60×10^{-5} $mm^3/N \cdot m$ for loads of 20N and 30N respectively. The high wear rate is attributed to the relatively low hardness of the austenitic stainless steel substrate which makes it more susceptible to the plastic deformation and the material removal during sliding contact. Furthermore, the coefficient of friction increased from 0.68 to 0.74 with an increasing load indicating the greater surface interaction and frictional resistance.
The $Cr_3C_2$25NiCr coated specimens exhibited the significantly improved wear resistance compared with the uncoated substrate. The wear rates were reduced to 7.70×10^{-5}, 7.20×10^{-5} and 7.63×10^{-5} $mm^3/N \cdot m$ at the loads of 10 N, 20 N and 30 N respectively. This improvement can be attributed to the presence of hard chromium carbide particles embedded within the NiCr matrix, which effectively resist the abrasive and adhesive wear. The relatively lower coefficient of friction values i.e. 0.42 to 0.49 further indicate an enhanced the tribological performance and reduced surface damage during sliding.
Among all tested materials the WC20$Cr_3C_2$7Ni coating exhibited the best wear performance. The wear rate was limited to only 3.90×10^{-5} $mm^3/N \cdot m$ at 10N decreasing slightly to 3.65×10^{-5} $mm^3/N \cdot m$ at 20N and remaining at 3.80×10^{-5} $mm^3/N \cdot m$ at 30N. The corresponding coefficients of friction ranged between 0.35 and 0.40 representing the lowest values among the all specimens. The superior wear resistance of this coating is primarily due to the presence of the tungsten carbide particles which possess exceptionally high hardness and excellent resistance to the microcutting, abrasion and plastic deformation. In addition, the dense microstructure and strong inter-particle bonding achieved through the HVOF process contribute to an improved coating integrity and durability.
A comparative assessment indicates that the $Cr_3C_2$25NiCr coating reduced the wear rate by approximately 67% compared with the uncoated SS316L. Whereas the WC20$Cr_3C_2$7Ni coating achieved a wear rate reduction of approximately 83%. These findings establish the direct correlation between coating hardness and wear resistance. Where the harder WC containing coating exhibited superior tribological performance. The results also confirm that the HVOF sprayed carbide coatings effectively enhance the service life of the SS316L components operating under the severe sliding wear conditions.

Effect of Applied Load on Wear Rate

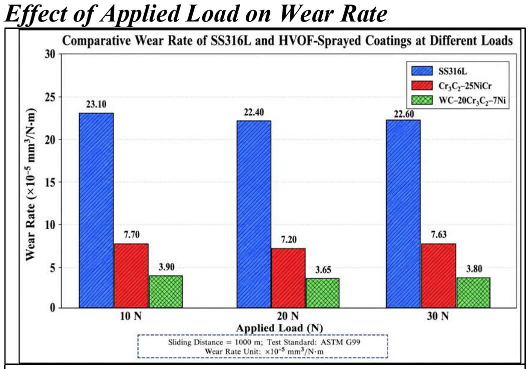

Figure 04. Comparative bar chart showing the wear rate of uncoated SS316L, Cr_3C_2–25NiCr coated SS316L, and WC–20Cr_3C_2–7Ni coated SS316L at applied loads of 10 N, 20 N, and 30 N under a constant sliding distance of 1000 m.

Figure 04 presents a comparative bar chart illustrating the wear rates of the uncoated SS316L, $Cr_3C_2$25NiCr coated SS316L and WC20$Cr_3C_2$7Ni coated SS316L under the applied loads of 10N, 20N, and 30N at a constant sliding distance of 1000m. The graphical representation is clearly demonstrating that the significant influence of HVOF sprayed carbide coatings on the tribological performance of SS316L stainless steel.
The uncoated SS316L specimen exhibited the highest wear rate under all testing conditions with the values ranging from 22.40×10^{-5} to 23.10×10^{-5} $mm^3/N \cdot m$. The consistently high wear rate is primarily attributed to the relatively low hardness of the austenitic stainless steel substrate which promotes severe plastic deformation and material removal during the sliding contact. Furthermore, the wear rate of the substrate remained considerably higher than those of the coated specimens indicating the limited capability of SS316L to withstand abrasive wear under an increasing load conditions.
The $Cr_3C_2$25NiCr coating substantially improved the wear resistance of the substrate, reducing the wear rate to approximately 7.20 to 7.70×10^{-5} $mm^3/N \cdot m$. The enhanced performance can be attributed to the presence of the hard chromium

carbide particles dispersed within the NiCr matrix. The carbide phase effectively resists the microcutting and abrasive wear while the NiCr binder improves the coating toughness and adhesion. The wear rate remained relatively stable with the increasing load suggesting excellent coating integrity and resistance to crack propagation during the sliding.

Among all investigated materials the WC20$Cr_3C_2$7Ni coating exhibited the lowest wear rate at every applied load. The wear rate varied only between the 3.65×10^{-5} and 3.90×10^{-5} $mm^3/N{\cdot}m$ indicating the superior wear resistance and excellent the load bearing capability. The outstanding performance of this coating is mainly due to high hardness of tungsten carbide particles and the dense microstructure produced by the HVOF spraying process. The combination of the WC and Cr_3C_2 phases provides effective resistance against abrasion, micro-ploughing and the surface deformation thereby minimizing material loss during the sliding.

It is also evident from Figure 04 that the wear rate of all the specimens remained nearly constant despite increasing the load from 10N to 30N. This behaviour suggests that the coatings maintained their structural stability and an adhesion strength throughout the testing range. The WC20$Cr_3C_2$7Ni coating consistently outperformed the $Cr_3C_2$25NiCr coating confirming that the tungsten carbide reinforcement contributes significantly to the wear resistance enhancement.

SEM Analysis Before and After Wear

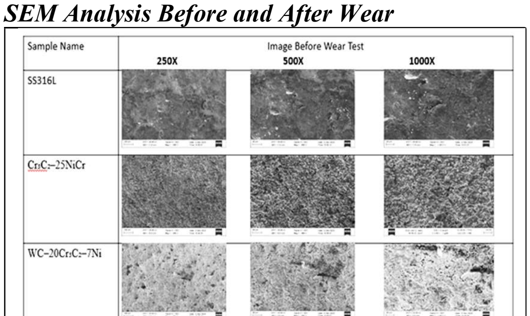

Figure 05. SEM Analysis – Before Wear of uncoated SS316L, Cr_3C_2–25NiCr coated SS316L, and WC–20Cr_3C_2–7Ni coated SS316L at applied loads of 10 N, 20 N, and 30 N under a constant sliding distance of 1000 m.

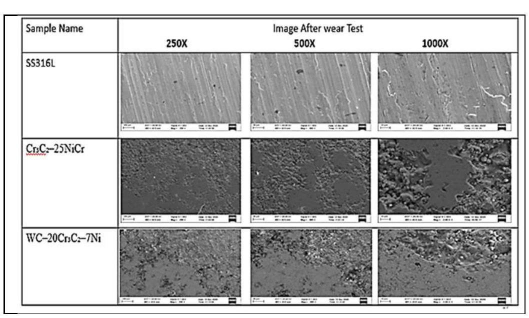

Figure 06. SEM Analysis – After Wear of uncoated SS316L, Cr_3C_2–25NiCr coated SS316L, and WC–20Cr_3C_2–7Ni coated SS316L at applied loads of 10 N, 20 N, and 30 N under a constant sliding distance of 1000 m.

Figures 05 and 06 shows the scanning electron microscopy images of the uncoated SS316L substrate and the HVOF sprayed $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings before and after the wear testing respectively. The comparative analysis of these micrographs provides valuable insights into the influence of a coating composition on wear resistance and the surface degradation mechanisms.

Prior to wear testing i.e. Figure 05 the uncoated SS316L surface exhibited the relatively smooth and the homogeneous morphology characteristic of an austenitic stainless steel. In contrast coated specimens displayed the dense and uniformly distributed carbide phases embedded within their respective metallic binder matrices. The $Cr_3C_2$25NiCr coating revealed a compact microstructure with the well dispersed chromium carbide particles and the minimal porosity indicating effective deposition through the HVOF process. Similarly, the WC20$Cr_3C_2$7Ni coating exhibited a highly dense microstructure with the uniformly distributed tungsten carbide and the chromium carbide phases. The absence of significant cracks voids or unmelted particles confirmed the excellent quality and adhesion of the both coatings to the SS316L substrate.

After wear testing i.e. Figure 06 shows the significant differences in surface damage were observed among the investigated specimens. The uncoated SS316L sample exhibited the severe wear scars characterized by the deep grooves, plastic deformation, material pull out and extensive surface damage. These features indicate that the predominance of abrasive and adhesive wear mechanisms during sliding contact. The relatively soft substrate underwent substantial material removal, resulting in the higher wear loss and wear rate values.

The $Cr_3C_2$25NiCr coated specimen showed considerably less surface deterioration as compared to the uncoated substrate. The worn surface exhibited the shallow grooves and the limited carbide pull out suggesting that the hard chromium carbide particles are effectively resisted the abrasive wear. Although localized the micro cracking and minor material removal were observed in an certain regions the coating largely maintained its structural integrity throughout the wear test. The NiCr binder phase contributed to improved toughness and prevented catastrophic coating failure under increasing load conditions.

Among all specimens the WC20$Cr_3C_2$7Ni coating exhibited the least amount of wear damage after testing. The SEM micrographs revealed only minor wear tracks and negligible surface deformation, indicating excellent resistance to abrasive and adhesive wear. The presence of the hard tungsten carbide particles significantly reduced micro-cutting and ploughing actions at the contact interface. Furthermore, the dense coating structure and strong interparticle bonding generated by the HVOF process minimized carbide detachment and the crack propagation. Consequently, the coating retained its surface integrity even under the highest applied load. A direct comparison between Figures 05 and 06 demonstrates that the extent of wear damage decreases with increasing a coating hardness. The uncoated SS316L specimen experienced severe material removal whereas the $Cr_3C_2$25NiCr coating provided moderate protection against wear. The WC20$Cr_3C_2$7Ni coating exhibited superior tribological performance due to its higher hardness and dense microstructure and enhanced load bearing capacity. These observations are in excellent agreement with the micro-hardness and wear rate results which showed that the WC20$Cr_3C_2$7Ni coating achieved the highest hardness and lowest wear rate among all investigated materials.

Conclusions

In this study, biomedical-grade SS316L stainless steel was successfully coated with $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni powders using the High Velocity Oxy Fuel thermal spray process. The influence of these coatings on microstructure, micro-hardness and tribological behaviour was systematically investigated to assess their suitability for the biomedical applications. Based on the experimental findings the following conclusions can be drawn:

1. The HVOF process successfully produced dense, uniform and the well adhered carbide coatings on SS316L with minimal porosity and the coating defects demonstrating the capability of HVOF technology to enhance the surface characteristics of biomedical metallic substrates.
2. Both coatings significantly improved the surface hardness of SS316L. The average micro-hardness increased from an approximately 215HV for the uncoated substrate to 1025HV for the $Cr_3C_2$25NiCr coating and 1320HV for the WC20$Cr_3C_2$7Ni coating. The substantial hardness enhancement is expected to improve the resistance against the surface deformation and material degradation in load bearing biomedical components.
3. The wear performance of SS316L was considerably improved after a coating deposition. The $Cr_3C_2$25NiCr coating reduced the wear rate by approximately 67%, while the WC20$Cr_3C_2$7Ni coating achieved an improvement of approximately 83% compared with the uncoated substrate. Such reductions in the wear are highly desirable for orthopaedic implants where continuous articulation can result in the material loss and implant failure.
4. Both coatings exhibited lower coefficients of friction than the uncoated SS316L indicating improved tribological behaviour. Reduced friction can minimize the surface damage and wear debris generation which is critical for an enhancing and implant longevity and reducing adverse biological reactions.
5. SEM observations before wear the testing revealed the dense carbide rich microstructures with strong coating substrate bonding while post wear analysis demonstrated significantly reduced wear damage in coated specimens compared with the uncoated SS316L. The coated surfaces effectively resisted abrasive and adhesive wear mechanisms commonly encountered the under sliding conditions.
6. Among the investigated coatings WC20$Cr_3C_2$7Ni exhibited superior performance in terms of hardness, wear resistance and surface integrity. The presence of the tungsten carbide and chromium carbide phases provided excellent protection against the material removal and surface degradation making this coating the most promising candidate for advanced biomedical applications.
7. The strong correlation observed between the hardness and wear resistance confirms that carbide based HVOF coatings can effectively improve the durability of biomedical grade SS316L. Enhanced wear resistance may contribute to the reducing the wear particle generation, major factor associated with inflammation, osteolysis and implant loosening in orthopaedic systems.
8. Overall, the results demonstrate that HVOF sprayed $Cr_3C_2$25NiCr and WC20$Cr_3C_2$7Ni coatings are significantly improve the surface performance of biomedical SS316L. The WC20$Cr_3C_2$7Ni coating, in particular, offers considerable potential for extending the service life and reliability of orthopaedic implants, surgical instruments, prosthetic components and other biomedical devices subjected to repetitive mechanical loading and the wear.

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