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Wet Sliding Wear Investigation of Ni-Based Coating for Piston Cylinder

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Abstract: This paper presents the investigation of sliding wear of nickel-based coatings for piston cylinder application. Wear and friction between cylinder walls and pistons is a critical issue in industries like power generation, aerospace, and nuclear plants, contributing significantly to engine losses. NiCrBSiFeC has been coated on steel by high velocity oxy fuel thermal process and investigated on tribometer for sliding wear as per ASTM G99 standard. The design of experiments was done by considering normal load, speed and track diameter as variable with three level. The wear tracks are analyzed using electro discharge spectrum (EDS) analysis and scanning electron microscope (SEM) images. The specific Mass Wear Rate (MWR) and coefficient of frictions are compared for coated and uncoated conditions. The results indicated the significant improvement in the wear life for the coated sample with mild abrasive and delaminated wear mechanism.

Keywords: Ni based coating; Wet sliding wear; Piston-Cylinder.

1. Introduction

In industries where harsh operating conditions are common place, the need for materials that can withstand extreme environments is paramount. While austenitic stainless steels are commonly utilized, they encounter significant challenges in settings such as nuclear reactors, medical implants, and chemical/food processing machinery due to their limited wear resistance. To address these shortcomings, surface modification techniques are employed to enhance their tribological properties, ensuring superior performance under extreme conditions [1]. One prominent method used in surface engineering for this purpose is thermal spraying [2,3]. Thermal spraying involves heating feedstock particles and projecting them onto a substrate, resulting in the formation of a robust lamellar microstructure that substantially improves the material’s resistance against wear, corrosion, and thermal degradation.

The piston and cylinder wear is very crucial for engine Performance as wear directly impact engine performance. Wear in pistons and cylinders can affect the overall reliability and durability of an engine. Excessive wear can lead to decreased power output, reduced fuel efficiency, and increased emissions, may lead to component failure, potentially resulting in costly repairs or even catastrophic engine damage. Understanding wear patterns can help optimize engine design and maintenance practices to ensure peak performance and also to develop materials and lubrication strategies to enhance component longevity and to implement cost-effective solutions to mitigate wear and prolong component life. The impact of cylinder liner surface topography on abrasive wear in a piston-cylinder assembly of Aircraft Engine revealing correlations between initial surface roughness and wear patterns [4].

The primary cause of diesel piston failure in transport utility vehicles such as carbon deposition and overheating have been analyzed using Failure Mode and Effect Analysis (FMEA), alongside Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometry (EDS) techniques and offer practical maintenance and prevention strategies based on thorough data analysis [5]. The tribological behavior of a cylinder liner and piston ring pair using the Taguchi design method, revealing that sliding velocity, applied load, and oil type primarily influence weight loss and friction, with the study emphasizing the importance of reducing friction and wear in engine components for enhanced fuel economy and performance [6]. A methodology combining numerical and experimental techniques has been proposed to analyze wear in internal combustion engine valves, determining wear coefficients for valve components and offering insights into wear mechanisms for design improvements [7]. The friction characteristics of microtextured surfaces, revealing significant friction reduction compared to untextured surfaces, influenced by texture depth, width, and density, with implications for tailored surface design in diverse applications [8].

The surface roughness, thermal performance, and material selection for the piston are the influencing factors in IC engine operation [9]. The Taguchi technique to optimize friction and wear parameters between a cylinder liner and piston ring pair revealed that the speed predominantly influences the coefficient of friction, while load primarily affects weight loss [10]. The non-uniform wear across different sectors of piston rings in internal combustion engines, indicative of varying lubrication regimes, thereby to enhance engine efficiency and durability the optimizing design and lubrication strategies are very important [11]. To ensure reliable engine operation and to avoid catastrophic failures, the factors such as material selection, design, operational conditions, lubrication, fatigue, and structural defects need to be investigated thoroughly [12]. The piston skirt-cylinder liner interface is need to be investigated for minimizing wear rates and enhancing service life in internal combustion engines [13].

Ni based alloy powder coating have gained popularity in surface engineering due to its exceptional wear and corrosion resistance, coupled with their relatively low cost. These coatings can be further strengthened by incorporating additional phases such as metal (e.g., Mo, Fe_2O_3) and ceramic (e.g., WC, TiN, Al_2O_3) particles, thereby enhancing their overall performance characteristics [14–16]. The widespread utilization of these coatings is evident across a wide array of industries, including turbines, coal-fired boilers, heat exchangers, tools, extruders, rolling mills, piston rods, and agriculture machinery. The application ensures heightened durability and improved performance, rendering them indispensable in challenging industrial environments where materials are subjected to extreme wear, corrosion, and thermal stress. Overall, these advancements in surface engineering play a crucial role in maintaining operational efficiency, prolonging equipment lifespan, and reducing maintenance costs across diverse industrial sectors. The thermal spray coatings has significant role in combating wear, erosion, and corrosion challenges across diverse industries, emphasizing their effectiveness, widespread applications [17]. The tribological performance of piston ring-cylinder liner contacts under bio-oil lubricated conditions, revealed distinct wear mechanisms and the superior performance of Ni-P-MoS2-GO coatings, offering promising prospects for the adoption of bio-oil as a lubricant in internal combustion engines [18]. The Laser Surface Texturing (LST) has the potential for enhancing mechanical system efficiency and durability in expanding the range of parameters associated with hydrodynamic lubrication, reducing friction coefficients, and improving tribological performance in oil-lubricated systems [19] .

The multistep induction cladding technique effectively enhances wear resistance of grey cast iron surfaces through element inter diffusion and chemical reactions, resulting in stable friction coefficients, increased microhardness at the interface, and dominant wear mechanisms of abrasion and oxidation [20]. The High Velocity Oxy Fuel (HVOF) process produced more protective coating than the (Atmospheric Plasma Spray) APS process for isothermal oxidation at 900 °C temperature after 1000 h [21]. The plasma sprayed coating predominantly exhibited fatigue as the primary wear mechanism, whereas the HVOF-sprayed and spray and fused coatings showcased a combination of adhesive, abrasive, and fatigue wear mechanisms [22]. The tribological behavior of a commercial semi-metallic friction material sliding against both uncoated and High-Velocity Oxygen Fuel (HVOF) coated cast iron discs at room temperature and 300°C, revealing distinct behaviors and the potential of HVOF coatings in enhancing braking efficiency and environmental sustainability [23]. The sliding wear behavior of HVOF sprayed WC-CrC-Ni coatings for automotive applications, highlighting their dense structure, minimal porosity, and enriched WC and Cr3C2 phases, leading to markedly improved wear resistance and reduced wear depth, with promising implications for enhancing the durability and performance of critical automotive components like gears, brake discs, and engine parts [24]. A comparative study on Ni-based coatings prepared via HVAF, HVOF, and APS methods for corrosion protection, emphasizing the influence of process parameters on microstructure and corrosion resistance, with HVAF-sprayed coatings showing superior characteristics and potential for enhanced corrosion resistance through optimized parameters, particularly in NiCr variants, thus highlighting the significance of meticulous parameter tuning for achieving dense coatings with superior corrosion protection [25]. The tribological behavior of Plasma and HVOF-sprayed Ni based coatings, emphasizing the multifaceted nature of wear resistance influenced by factors such as counter body materials, applied load, and sliding speed, highlighting the importance of hardness, hard phase characteristics, and the plasticity index-to-hardness ratio, with a focus on investigating dry sliding wear behavior and wear mechanisms, and employing ANOVA analysis to optimize coating parameters for improved wear performance [26]. The Ni-based composite coatings, reinforced with materials such as SiC, may be utilized to enhance mechanical and tribological properties through techniques like electroplating and electrodeposition indicating promising prospects for future industrial applications [27]. The dry sliding wear behavior of HVOF-sprayed NiCrBSiFe coating on SS316L, highlighting its exceptional attributes such as high density and minimal pore formation, along with remarkable mechanical properties including a hardness of 10.23 GPa and an elasticity modulus of 156.31 GPa, demonstrating commendable wear resistance properties across various test conditions, thus suggesting its promising potential for diverse industrial applications [3,28]. The particle behavior in HVOF spraying, highlighting the system's uniform heat input and acceleration, crucial for producing dense coatings in advanced applications [29].

From the research literature is has been observed that the thermal spray coatings are vital in addressing wear, erosion, and corrosion challenges in harsh industrial environments, particularly in enhancing the durability and performance of materials like austenitic stainless steels through surface modification techniques like HVOF spraying. Despite advancements in thermal spray coatings, further research is needed to optimize coating performance, explore innovative compositions, and understand wear mechanisms to ensure enhanced durability and protection of industrial components in extreme operating conditions.

2. Experimental and Methods

The study utilized stainless steel 316L as the substrate material, with a chemical composition including 0.018% of carbon, 1.3% of manganese, 0.36% of silicon, 16.62% of chromium, 2.07% of molybdenum, 0.0032% of phosphorus, 0.003% of sulfur, and 10.12% of nickel. Deposition was performed using NiCrSiBFe powder, obtained from PAC, Cincinnati, Ohio, comprising 14.5% chromium, 3.2% boron, 4.5% silicon, 4.5% iron, and 73.3% nickel. Particle size analysis revealed a mean size of 28.7 µm for the NiCrSiBFe powder [30]. Coatings were applied through high velocity oxy fuel (HVOF) methods, employing standard processing parameters. Evaluation of coating properties involved scanning electron microscope (SEM), Nano-indentation, and X-ray diffractometer analyses. Porosity of coatings was determined from SEM images using ImageJ software.

The experimental setup featured a pin/ball on disc tribometer by DUCOM instruments, Bengaluru, conforming to ASTM G99 standards for wear testing. The pin-on-disk apparatus monitored tangential frictional force and wear depth on specimens continuously, with data recorded via PC. Silicon nitride (Si3N4) with a hardness of 1580 HV served as the counter material, chosen for its chemical inertness aiding wear surface analysis. The input parameters for the experimentation corresponds to the piston cylinder applications are selected from the literature. The input parameters for the experimentation corresponding to piston cylinder applications are selected from the literature. The sliding velocity varies as from 0.07 to 1.5 m/s, the load acting varies from 5-100 N. Ni based alloy powder coated by HVOF method on the disc of 40 mm diameter has been used against Silicon Nitride counter material under drop lubrication using petrol adhesive. The sliding wear experiments were carried out in lab at room Temperature condition using following input parameters as mentioned in table 1.

Table 1. Input parameters for the sliding wear experiments

Normal load Range (N)	Track Diameter (mm)	Speed (RPM)
10, 50, 100	25, 30, 35	250, 375, 500

The Minitab software has been utilized to explore various combinations of load, track diameter, and speed. The L9 array was selected, incorporating three levels for each of the three variables. Each experiment was repeated three times, and the average values of wear and coefficient of friction were recorded for coated and uncoated disc. The ambient environment during the experiments was carefully controlled, maintaining a constant room temperature of 31°C with a relative humidity of 50 percent, ensuring consistent testing conditions. Six discs of coated and uncoated, each with a diameter of 40 mm, were meticulously prepared and employed in nine distinct experiments, varying the track diameter between 25, 30, and 35 mm to investigate the influence of this parameter on wear behavior. The mass change has been recorded for each experiment and MWR has been determined from the normal load, sliding distance and mass change for coated and uncoated sample.

A Scanning Electron Microscope (SEM) located at the MMMF Lab, IIT Bombay has been used for the wear track analysis. SEM imaging using The Zeiss Gemini SEM at MMMF Lab features dual-beam technology, high-resolution imaging, variable pressure mode, versatile detection modes including Energy- Dispersive X-ray Spectroscopy (EDS) for elemental analysis, advanced automation, and applications across various scientific and industrial domains. Imaged specimens included coated and uncoated samples, with images captured at multiple magnifications and tracks. This comprehensive approach allows detailed wear mechanism analysis and material composition assessment using EDS.

3. Results and discussion

A comprehensive visualization of the operating parameters alongside the corresponding coefficients of friction (COF) and MWRs is presented for each experimental trial, distinguishing between coated and uncoated specimens. This data-rich graphical representation offers invaluable insights into the performance characteristics under diverse experimental conditions, facilitating a nuanced understanding of the wear behavior exhibited by both the coated specimens and the uncoated counterparts.

The average coefficients of friction (COF) and MWRs from nine distinct experiments were meticulously tabulated and combined against corresponding values derived from both coated and uncoated specimens as shown in fig. 1. For the coated specimen, the average COF was computed at 0.10642, with a corresponding MWR of 3.995 x 10^{-7} gm/Nm. Conversely, the uncoated specimen exhibited a notably higher average COF of 0.27325, alongside a correspondingly elevated MWR of 8 x 10^{-7} gm/Nm. A discernible reduction in both COF and MWR is readily apparent in the coated specimen, indicative of its superior tribological performance compared to its uncoated counterpart. Notably, during the experimental trials, an observation of the acoustic environment revealed that the noise emanating from the uncoated specimen was substantially more pronounced compared to that generated by the coated specimen. This disparity in noise levels further underscores the enhanced performance and efficacy of the coated specimen in mitigating frictional forces and wear mechanisms. Hence, based on the comprehensive analyses conducted, it can be affirmed that the coated specimen exhibits superior tribological characteristics compared to its uncoated counterpart. These findings not only underscore the efficacy of the coating in reducing friction and wear but also hold significant implications for optimizing performance and longevity in diverse engineering applications.

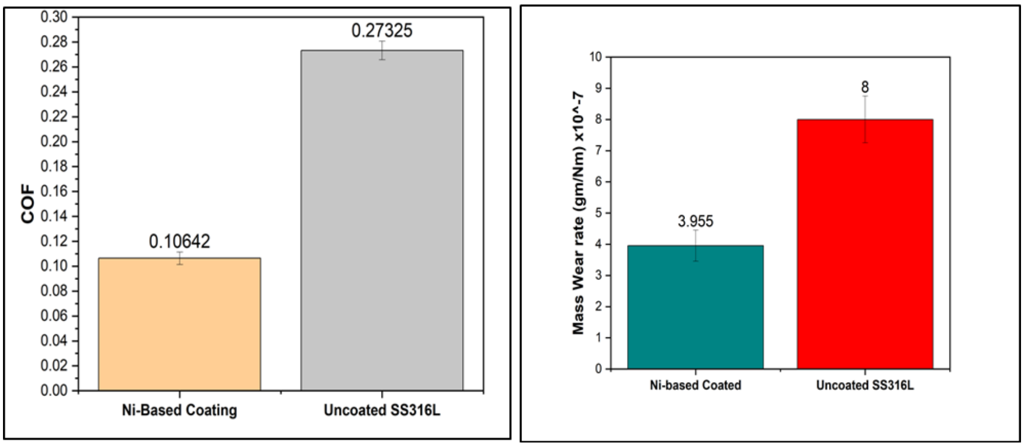

Figure 1. Comparison of Coated and Uncoated for COF and MWR

3.1 Design of experiments

The Design of Experiments (DOE) methodology is employed to efficiently gather conclusive information from a minimal number of experiments. To achieve this, the L9 orthogonal array, necessitating nine experimental runs, is appropriately selected. The assignment of factors and their interactions to the columns of the array is conducted following the triangular table method proposed by Taguchi. The Taguchi method, integral to this approach, prioritizes minimizing variance in the output response, even in the presence of noise inputs. Therefore, it is imperative for the Taguchi method to consider variability within trial conditions. This variability is effectively captured through the Signal-to-Noise (S/N) ratio, which serves as a means to convert experimental results into an evaluative characteristic value for optimal parameter analysis, instead of relying solely on the mean.

Table 2. Response table of mean S/N ratio

Level	Load (N)	Track Diameter (mm)	Speed (rpm)
1	-11.043	-8.084	-8.388
2	-6.264	-7.557	-7.744
3	-8.081	-9.747	-9.257
Delta	4.779	2.191	1.513
Rank	**1**	**2**	**3**

The core objective is to maximize the S/N ratio, thereby mitigating the impact of random noise factors that significantly affect process performance. In this study, S/N ratio analysis is conducted using mass wear rate as the performance index, with all associated calculations meticulously executed. The ranking as shown in table 2, indicates the significant impact of the normal load followed by track diameter and speed on the mass wear rate. The regression equations for the mass wear rate and frictional coefficient are obtained in terms of input variables as mentioned in equation 1 and 2.

$$MWR\left(\frac{gm}{N}.m\right) = (29.6 + 0.2727P - 0.707D - 0.1305N - 0.01059PD + 0.000141PN + 0.00392DN) \times 10^{-7} \tag{1}$$

$$COF = 0.441 + 0.00035P - 0.0093D - 0.00086N - 0.000045PD + 0.000028DN \tag{2}$$

where, P − Normal Load (N), D − Track Diameter (mm), N − Speed (RPM).

The equations are validated with the experimental results and the error has found to be less than 5%, therefore these equations can be applied to obtained the MWR and COF within the range of the input parameters.

3.2 SEM and EDS Analysis:

The wear track SEM image for coated specimen obtained by a Zeiss Gemini SEM 300 Scanning Electron Microscope are shown in fig. 2, fig. 3 and fig. 4 at different operating conditions. The images above reveal distinct wear patterns consisting of undulations, indicative of delamination wear, and scratches, characteristic of abrasive wear.

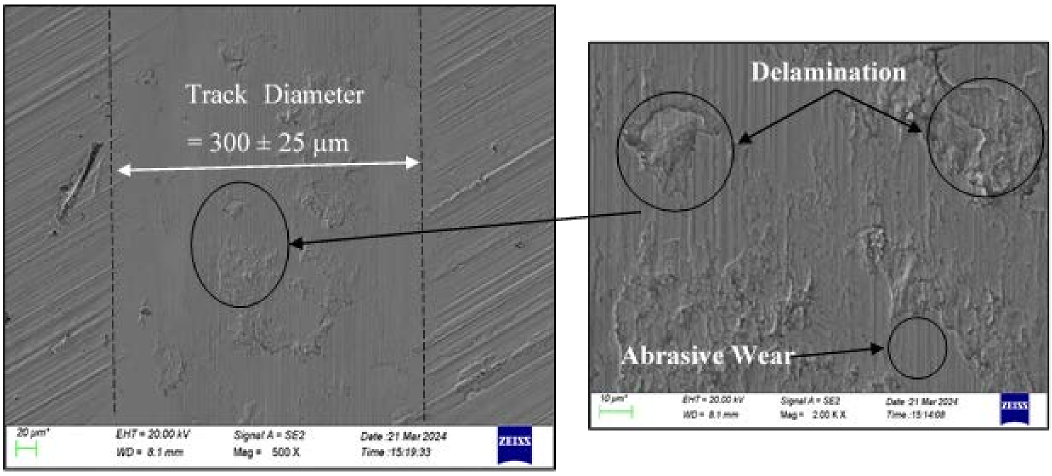

Figure 2. Coated specimen wear track morphology at 50 N load and 250 rpm

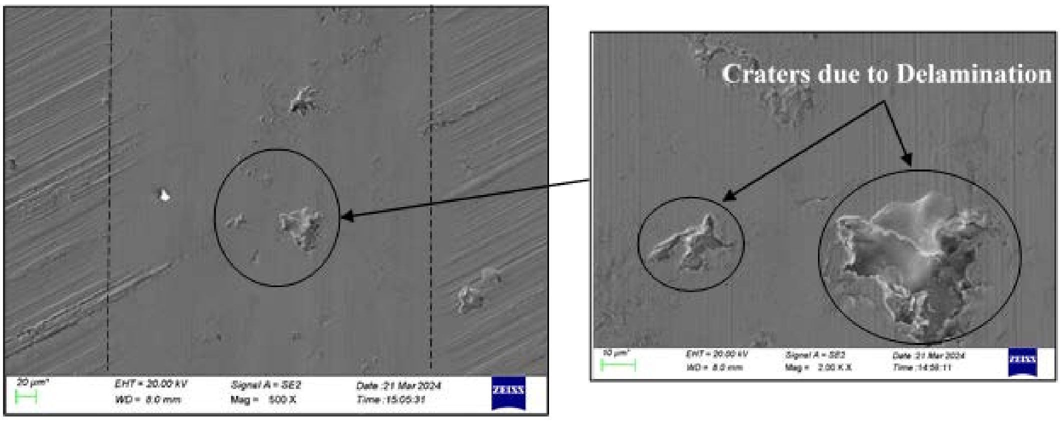

Figure 3. Coated specimen wear track morphology at 50 N load and 375 rpm

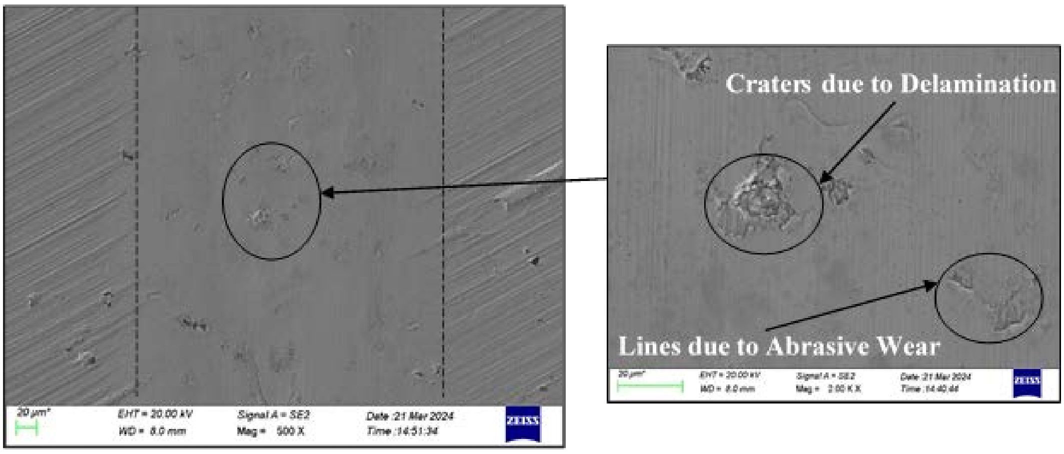

Figure 4. Coated specimen wear track morphology at 50 N load and 500 rpm

Fig. 5 shows the magnified image of wear track on the uncoated specimen. The wear mechanism observed is a combination of abrasive and adhesive wear where it might have occurred due to insufficient lubrication or where surfaces may have experienced high levels of pressure and friction.

Fig. 6 shows the results of EDS analysis of wear track obtained at 50 N normal load and 500 RPM. The different colour contrast represents the distribution of different elements like Nickel, Chromium, Silicon, Boron, and Iron. The weight percentage of each element at different instant during EDS are shown in the spectrum graph. The element Nickel is found to be the most abundant with 81.9 % wt. followed by Chromium with 11.9 %. The peaks for Nickel and other elements are at different instants due to different energy levels during the electron transitions within the atoms.

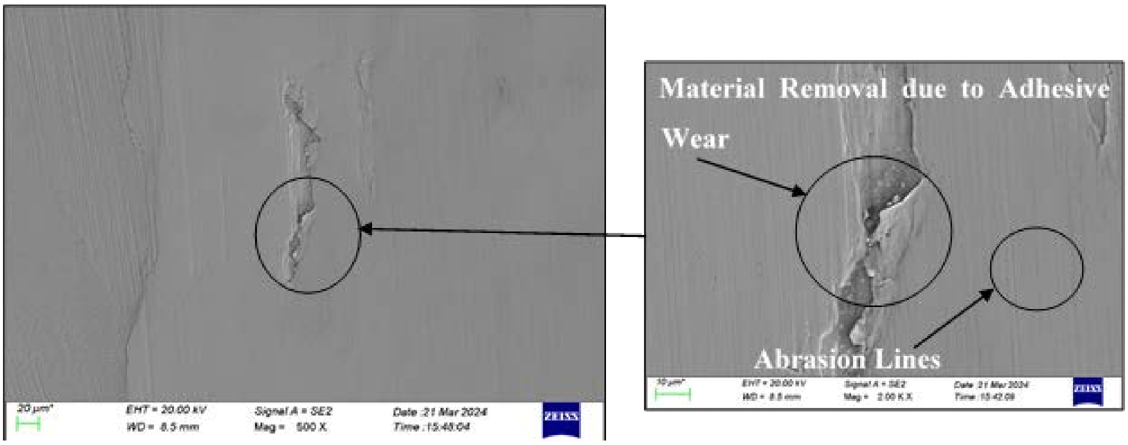

Figure 5. Uncoated specimen wear track morphology at 100 N load and 500 rpm

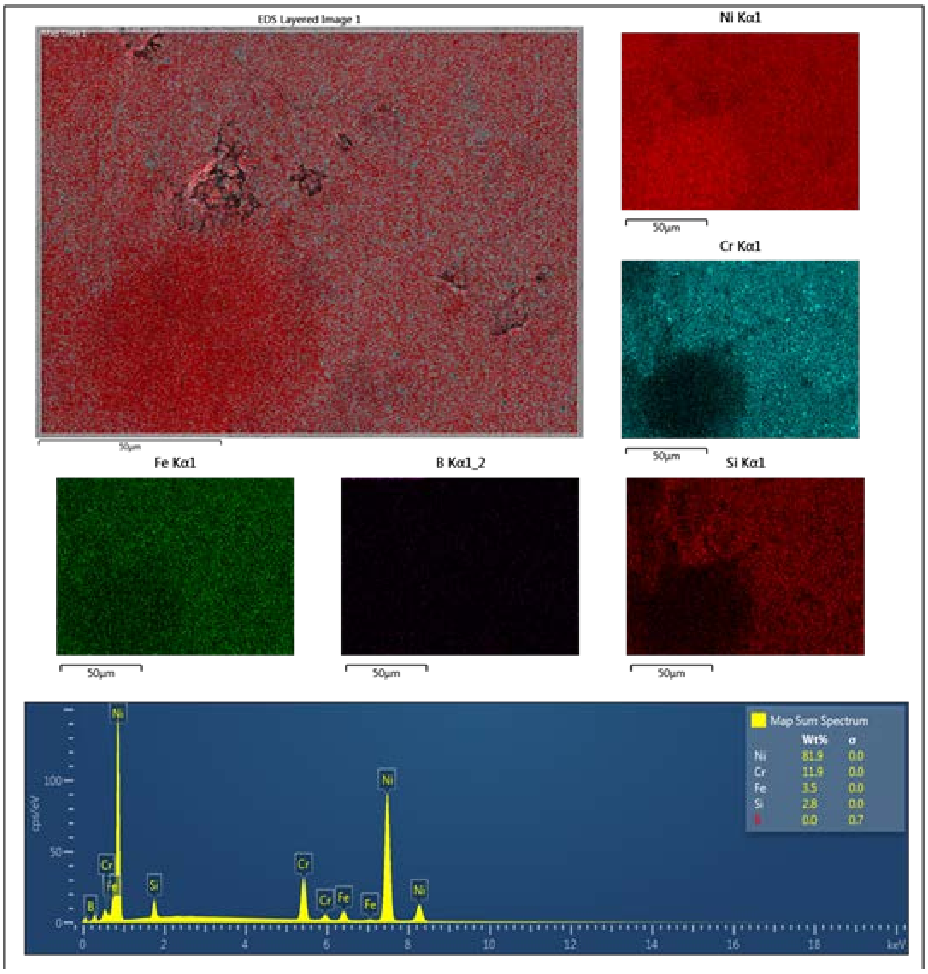

Figure 6. EDS graph for coated wear track obtained at 50 N and 500 rpm.

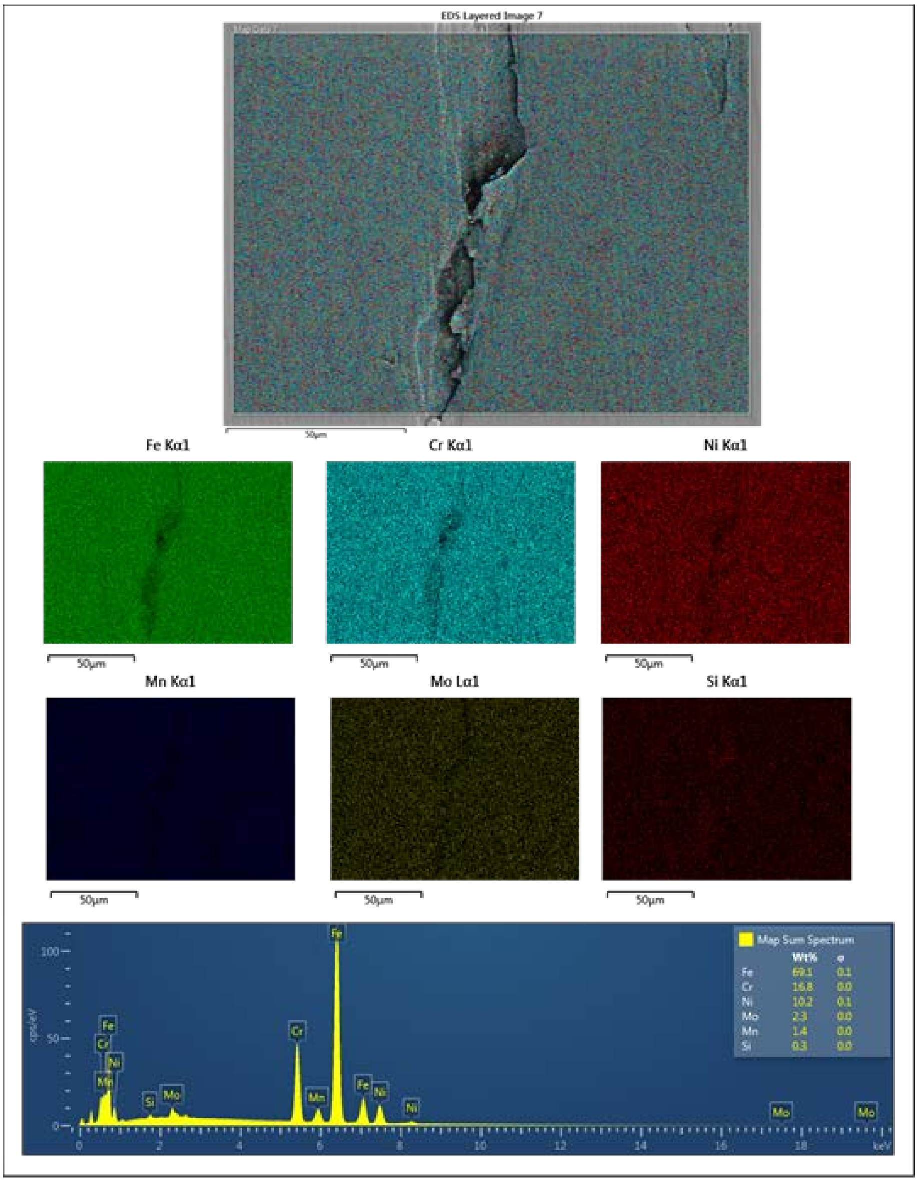

Figure 7: EDS graph for uncoated wear track obtained at 100 N and 500 rpm.

Fig. 7 shows the EDS analysis of wear track obtained at 100 N load at 500 RPM on uncoated specimen of SS316L. The different colour contrast represents the distribution of different elements like Iron, Chromium, Nickel, Molybdenum, Manganese and Silicon. The spectrum shows the percentage weight of each element at different instant during EDS. The element Fe is found to be the most abundant with 69.1 % wt. followed by Chromium with 16.8 % and Nickel at 10.2 % wt. and little amounts of Mo, Mn and Si.

4. Conclusion

Nickel based coatings said to be better in terms of sliding wear performance as less mass wear rate has observed due to the excellent properties provided by the NiCrBSiFeC coating and the overall advantages of HVOF thermal spraying technique. The wear rate of the coated sample is 50% less than uncoated sample and the wear mechanism on coated specimen was observed as mild abrasion. Therefore, recommended the Ni-based coating for life improvement. Regression Equations for MWR and COF which are applicable in range of the conducted experiment parameters within 5% error. The ranking by DOE indicates that Load is the most significant factor compared to speed and track diameter. The use of Ni-based coating in piston-cylinder application will ensure reduced sliding wear and hence an improvement in life and reliability of the systems.

5. References

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