# Enhancing wear and erosion resistance of partially oxidized NiCrBSiFeC coating by plasma spray on MDN431 substrate

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**Abstract.** This study investigates the enhancement of wear and erosion resistance through partial oxidization of NiCrBSiFeC alloy powders applied as coatings on MDN431 steel. Using a flame spray process, alloy powders were sprayed into water under controlled parameters to produce partially oxidized powders with approximately 50% oxide layer and 50% metallic core, balancing hardness and ductility. These powders were deposited onto MDN431 steel via plasma spray to form coatings, which were characterized for microstructure, hardness, and phase composition. Wear and erosion tests, conducted from room temperature to 600°C, revealed superior performance of the coatings. At 600°C, 2 m/s, and 30 N load, the NiCrBSiFeC coating exhibited six times higher wear resistance than the MDN431 substrate. However, erosion tests at 600°C showed higher weight loss in coatings compared to the substrate, attributed to alumina particle embedment. The formation of oxide phases in the coating significantly enhanced its high-temperature wear and erosion resistance.

## 1 Introduction

Wear and erosion is an important process of degradation of engineering materials, especially in processes in which the components are exposed to relative motion or impacts of abrasive particles. Procedures to reduce the effects include the application of protective coatings to base materials to increase their surface hardness and wear and erosion resistance. Ample literature has been done to demonstrate the effectiveness of thermal spray coating in enhancing wear and erosion resistance in a number of industrial uses [1]. A wide variety of coating methods and substances such as alloy and composite powders have been devised in order to advance these qualities [2]. One of the challenges in coating design is to balance hard and ductile in the same coating. Hard coats are strongly wear-resistant, but they might not be bonded or tough, and will delaminate off the substrate. In contrast, the softer coatings can be easily attached, but they are not able to resist abrasive wear. NiCrBSiFeC alloy metallurgy have been extensively credited to enhance wear resistance, including in the case of aluminum castings in turbines to prevent particle erosion and increase service life by

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covering the turbine blade with NiCrBSiFeC alloys [3]. Also, NiCr alloy over coatings have been shown to be versatile in improving tribological behavior and also as oxidation resistant across a wide substrate range [4]

The recent developments in coating technology have been centered on composite and hybrid coating to maximize on mechanical properties. But, a little work has been done on partial oxidation of alloy powders, which may be used at the same time to increase hardness and retain ductility by regulating the oxide layer thickness on powder grains [5]. New studies have explored new ways of powder treatment and deposition in order to enhance coating microstructures and interparticle bonding. As an example, post-deposition deformation processing has been reported to increase ductility in cold-sprayed coating by disclosing oxide films and facilitating metallurgical bonding [6]. Likewise, mechanically alloyed materials in conjunction with the cold spray techniques have enhanced wear tendency but maintained coating toughness [7]. Ni-based alloys have also been considered in laser cladding to achieve graded mechanical properties in the production of a coating, which works well in reducing the brittleness and improving microhardness [8].

Although these improvements have been made, it still is possible to establish a major opportunity to achieve coating technologies that would be high in hardness, ductile, and thermal stability by innovative means e.g. controlled partial oxidation and advanced processing of sprays. In this study, the influence of partial oxidation on NiCrBSiFeC alloy powders, which were prepared through a flame spray and deposed using plasma spray, is studied and aims at improving wear and erosion protection of the coated surface on MDN431 substrates. The study will help in explaining how the formation of oxide layers contributes to attaining a balance between hardness and ductility hence enhancing the functionality of coatings in high wear and high temperature conditions.

## 2 Materials and methods

### 2.1 Substrate and Coating Materials

MDN431 (weight %: Fe-78.95 Cr-17 Ni-2.5 Si-0.7 Mn-0.7 C-0.15) steel was used as a base material. NiCrBSiFeC (weight %: Ni-71.97 Cr-15.3 B-3.1 Si-4.8 Fe-4.2C-0.6 Co-0.03) alloy powders were selected as the coating material. NiCrBSiFeC alloy powder after converting into partially oxidized powders were utilized for deposition of the coating.

### 2.2 Preparation of the feedstock powders

Figure 1 depicts the process of transforming the alloy powders to prepare feedstock powders. Partially oxidized NiCrBSiFeC powders were prepared using a flame spray process. The alloy powders were poured into a chamber of coating gun and powders were deposited on the water to induce partial oxidization. The process parameters used for Plasma Spray and flame spray process are detailed in Table 1. These powders consisting of an outer oxide layer (harder than the original material) and an inner metallic core with properties similarly to the original alloy. The depth of the oxide layer was influenced by the spraying temperature and the standoff distance. Higher temperatures and shorter distances increased the deposition rate, resulting in a thicker oxide layer. The quenching time in water was maintained at 20 minutes, which had minimal impact on the oxide layer thickness [9].

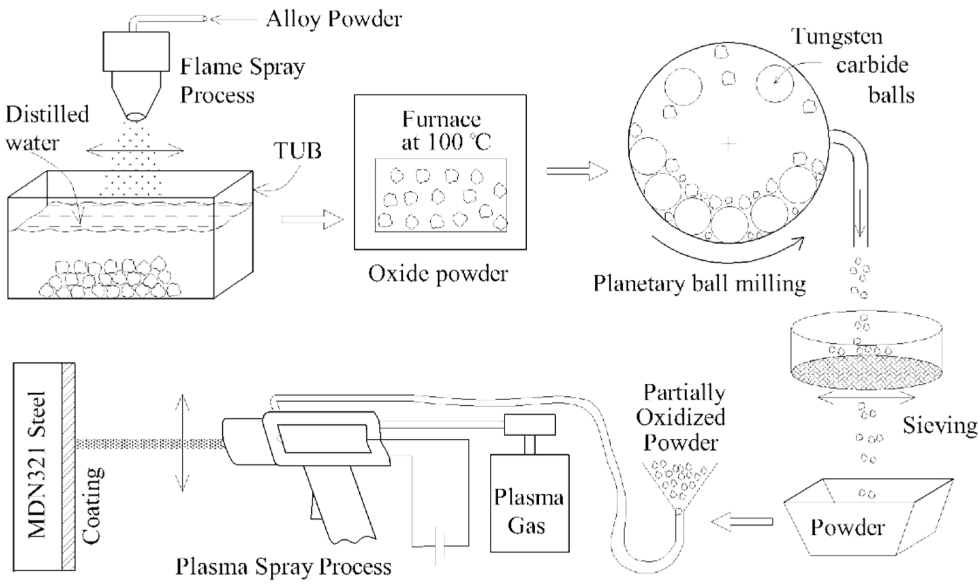


**Fig. 1.** Various steps involved in deposition of the coating on substrate.

**Table 1.** Process parameters of coating processes.

| **Plasma Spray Process** | | **Flame Spray Process** | |
|---|---|---|---|
| Standoff distance | 110 – 130 mm | Standoff Distance | 110 – 130 mm |
| Hydrogen | Pressure: 0.35 MPa<br>Flow: 7 L/min | $O_2$Pressure | 60 bar |
| Argon | Pressure: 0.7 MPa<br>Flow: 40 L/min | Air Pressure | 6 bar |
| Powder feed | 60 g/min | Dissolved Acetylene | 50 bar |

## 2.3 Coating deposition

The feedstock powders were deposited onto the MDN431 substrate using a plasma spray process. This process, operating at temperatures up to 20,000°C, melted the partially oxidized powders. The external oxide shell was harder, so to some extent limited the melting of the metallic core, forming a coating with increased hardness provided by the oxide layer and increased strength provided by the core material. This mixture led to high mechanical properties than untreated alloy powder coating. High plasma spray parameters were fine tuned to achieve consistency in the deposition of the coating and keeping the hardness-ductility balance intact. Average coating thickness of 250 µm is achieved.

## 2.4 Coating characterization

Vickers microhardness testing was performed on cross-sections of the coatings to measure hardness. Coating adhesion strength was evaluated using a pull-off test, where two counter blocks were adhered to both sides of the sample and tested using a Universal Tensile Testing Machine. Coating density was determined using a pycnometer, with the coating material removed from the substrate via mechanical hammering and weighed.

### 2.5 Wear and erosion testing

A pin-on-disk tribometer was employed to evaluate the wear resistance of the samples under varying conditions (Figure 2a). Tests were conducted at applied loads of 10, 20, and 30 N, and at four different temperatures—room temperature, 200 °C, 400 °C, and 600 °C. The sliding speed and total sliding distance were maintained at 2 m/s and 3000 m, respectively. To determine erosion resistance, Solid Particle Erosion Tester was used at the same temperatures and impact angles (30°, 45°, 60°, 75° and 90°) with constant particle flow rate 2 g/min, 35 m/s erodent velocity and 15 minutes impact time. These tests compared the performance of coatings derived from partially oxidized powders against substrate material.

## 3 Results and discussion

### 3.1 Wear rate analysis

Point analysis on NiCrBSiFeC coatings revealed a significant increase in microhardness 800 HV, whereas MDN431 shows 250 HV. the formation of a dense coating structure with a distinct oxide layer formed on the partially oxidized powders. Higuera Hidalgo et al. [10] reported lower microhardness values for NiCrBSiFeC alloy powder. Hence increased hardness of the coating is due to partial oxidization. The coating also contributed to enhanced mechanical properties such as bond strength of 13 MPa without bond coat, density of 5.5 g/cc with 1.5% porosity.

Figures 2b and 2c, demonstrated that the wear rate of the MDN431 substrate was higher than NiCrBSiFeC coatings at all tested temperatures. Specifically, the NiCrBSiFeC coating exhibited a wear rate up to 6 times lower than the substrate. The reduction in wear rate with increasing temperature was ascribed to the development of an oxide film over the coating surface via sliding wear. This oxide layer acted as a lubricant, reducing friction and wear, as evidenced by the worn surface microstructures. The oxide layer had increased in strength at the higher temperature further lowering the wear rate by giving a smoother surface and lowering the frictional forces [11] on the other hand, the substrate material at higher temperatures softened and resulted in increased wear rate.

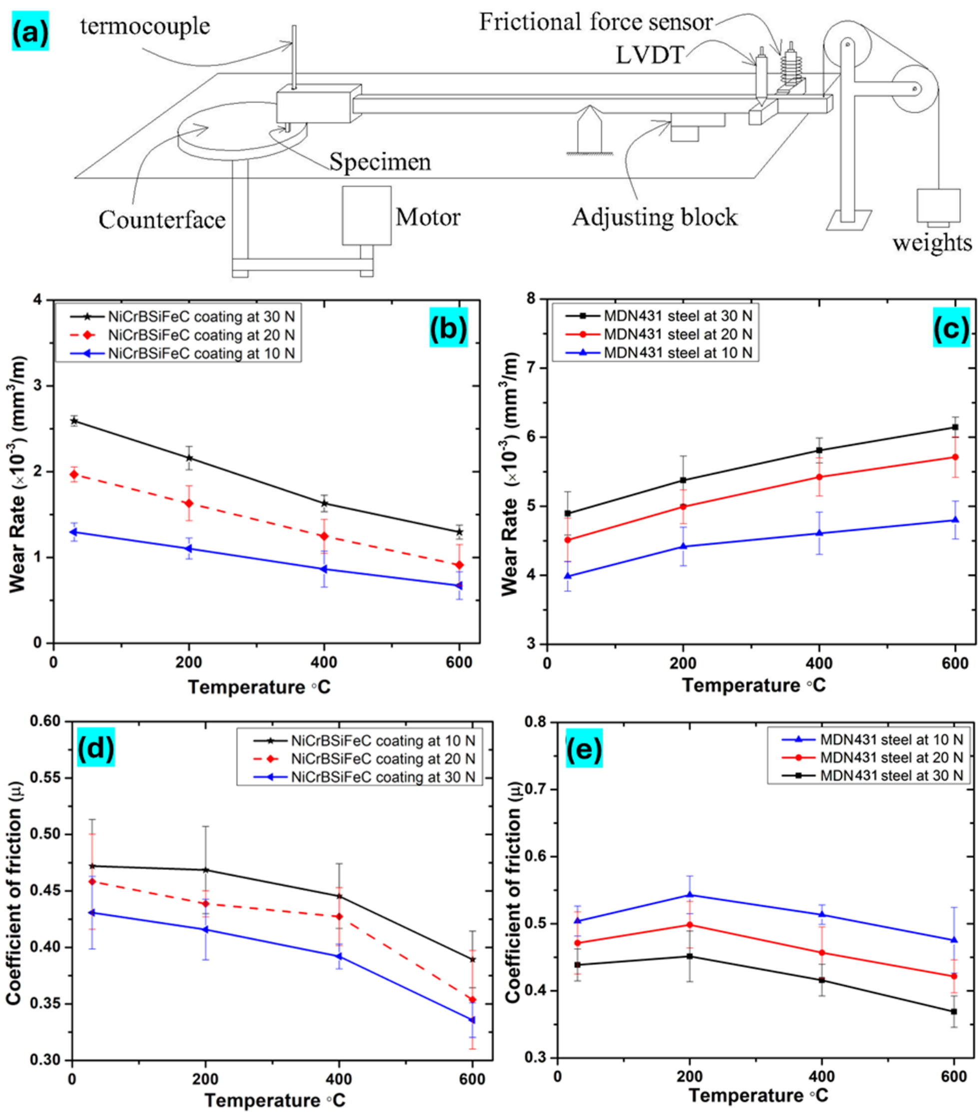


**Fig. 2.** (a) Schematic representation of experimental setup: Pin-on-disc tribometer; (b) wear rate and (d) Coefficient of friction (μ) of NiCrBSiFeC partially oxidized coatings (c) wear rate and (e) Coefficient of friction of MDN431 steel at different temperatures and loads.

The coefficient of friction (μ) was measured using a force transducer attached to the Pin-on-Disk Tribometer, Figure 2(d,e). The frictional force was recorded as the disk rotated, causing the fulcrum to shift due to friction, and μ was calculated as the ratio of frictional force to applied load. At higher loads (30 N), the coefficient of friction was lower compared to the 10 N load. This reduction was due to the flattening of surface asperities under higher loads, which decreased the frictional force relative to the applied load. A thin oxide layer developed on the coating surface due to the soft metallic core present in the partially oxidized powders, which helped lower the μ value, especially when the temperature increased. μ value for the coating and substrate was reduced with the temperature. This shows at higher temperature; material becomes soft and reduces the asperities strength during sliding [12].

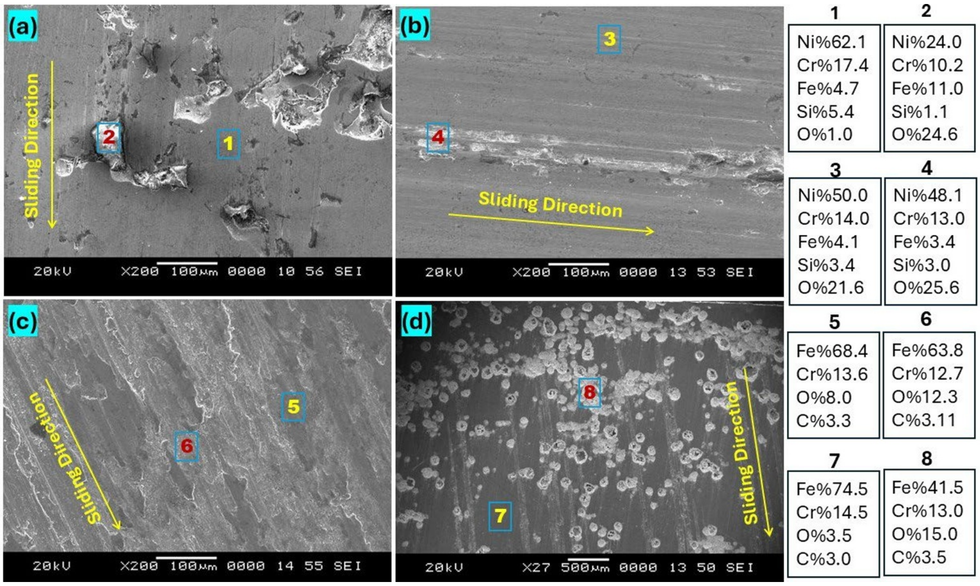


**Fig. 3.** Scanning Electron Microscope of worn-out surfaces of NiCrBSiFeC coating (a,b) and MDN431 steel (c,d); at Room temperature (a,c) and at 600 $^{O}$C (b,d) under the load of 30 N and 2 m/s sliding velocity.

Figure 3 presents worn-out surfaces of partially oxidized NiCrBSiFeC coating and MDN431 steel substrate. To analyze elemental variations, two points are selected in each image: white spots, indicative of oxide patches formed during sliding, and black spots, representing unmelted or burned regions from plasma spray deposition. Elemental analysis at the white spots indicates that they are rich in oxygen, while the black points represent unoxidized particles. However, at higher sliding temperatures, these black spots show a higher percentage of oxygen due to a thin oxide layer formation. To evaluate the wear-track development, the sliding direction is marked. Under room temperature, the coating of NiCrBSiFeC (Figure 3a) has many flaking pits because of hardness, in which sliding forces pull off the material and make the wear rate faster. These pits become smooth at 600°C (Figure 3b) where there is a formation of lubricious oxide layer which lessens friction and wear, since it acts as a solid lubricant, increasing wear resistance. On the other hand, the MDN431 substrate at room temperature (Figure 3c) experiences considerable loss of material because of its softness that causes poor wear resistance. By 600°C (Figure 3d), although the rate also decreases, the oxide scale is now detaching resulting in flaking pits and exposing fresh surfaces to wear. At each point also elemental analysis. Enhance this assertion on how oxides are formed at the higher temperatures.

The high wear resistance of the NiCrBSiFeC coating, especially at higher temperatures, may be explained by the fact that the partially oxidized powders have the unique structure. The hard oxide shell increases the hardness of the coating whereas the ductile metallic core provides the formation of a lubricating oxide film during a sliding wear. SEM and XRD showed the existence of strong oxide phases on the worn surfaces at increased temperatures (e.g. 600°C) and this lowered the frictional forces and wear rates. It is these oxide phases that were important in ensuring a smooth surface, friction reduction and also improving the wear resistance.

The decreasing coefficient of friction with increasing loads and temperature is an indication of the effectiveness of the partially oxidated coatings in high-wear conditions, including automobile and aerospace conditions. The reduced frictional forces are also imperative in decreasing the wear-rates and prolonging the component life, particularly in the high speed and high temperature regime where the uncoated substrates face a great deal of degradation through softening. The principle of partial oxidation came in handy to balance hardness and ductility, which makes such types of coatings very appropriate in industrial setups to need high wear resistance.

### 3.2 Erosion rate analysis

The erosion performance of NiCrBSiFeC partially oxidized coating and MDN431 steel substrate was investigated using a Solid Particle Erosion Tester (Figure 4a). The erosion rate, inferred from weight loss measurements, exhibited distinct trends for the coated and substrate samples (Figures 4b and 4c). Jian Guo Liu et al. [13] also considered weight loss measurement is directly related to erosion rate. The NiCrBSiFeC coating displayed higher erosion rates compared to the MDN431 substrate across all impact angles and temperatures. This variation is mainly explained by the fact that the alumina particles are embedded in the tested coating surface during testing in case of erosion. The embedment depth of the alumina particles is low at low angles of impact like 30$^{O}$ since the impact force is low. The bigger the impact angle, the stronger the impact force and thus it enhances larger embedding of alumina particles, especially at 90$^{O}$ which the impact force is at its highest. In coated samples, the probability of embedding alumina particles is some 50 percent at an impact angle of 45$^{O}$, and much less at 30$^{O}$.

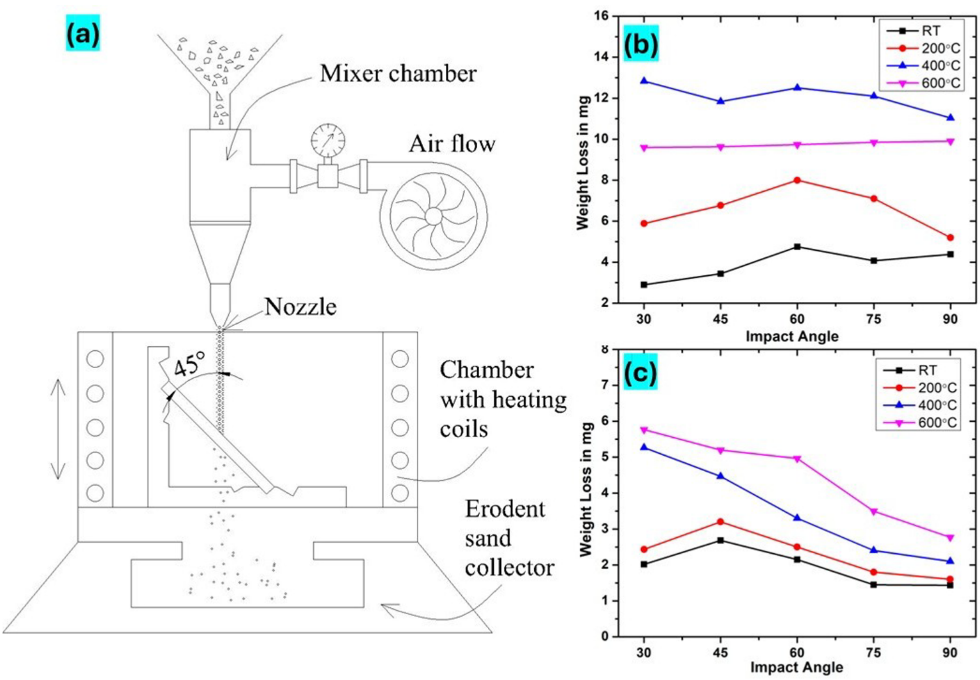


**Fig. 4.** (a) Schematic representation of Solid Particle Erosion Tester; Weight loss of (b) NiCrBSiFeC coated (c) MDN431 steel samples after 15 minutes of erosion with specified temperature and impact angle.

Conversely, the MDN431 substrate had a different erosion pattern. The erosion rate was greater at lower impact angles (e.g. 30$^{O}$) and lesser at higher impact angles (e.g. 90$^{O}$). This tendency implies that the increased the impact angle of alumina particles on the substrate surface, the less material will be lost as the protective layer will be formed. In the case of NiCrBSiFeC coating, the erosion rate also reduces with the impact angle, which implies that alumina particles do not embed in the substrate much. The behavior of erosion of both materials was very much affected by temperature. The rate of erosion was temperature dependent with the MDN431 substrate, and this might be attributed to the likelihood of an increased erosion rate of plastic and material softening at high temperatures (e.g. 600 $^{O}$C). On the contrary, the NiCrBSiFeC coating exhibited a rise in erosion rate to 400 $^{O}$C, then a decline at 600 $^{O}$C. This decrease in temperature is explained by the fact that the surface is hardened due to the impact of erodent particles itself and reinforces the coating, eliminating further losses of the material [14]. The substrate, however, experienced severe deformation at higher impact angles and temperatures, exacerbating erosion.

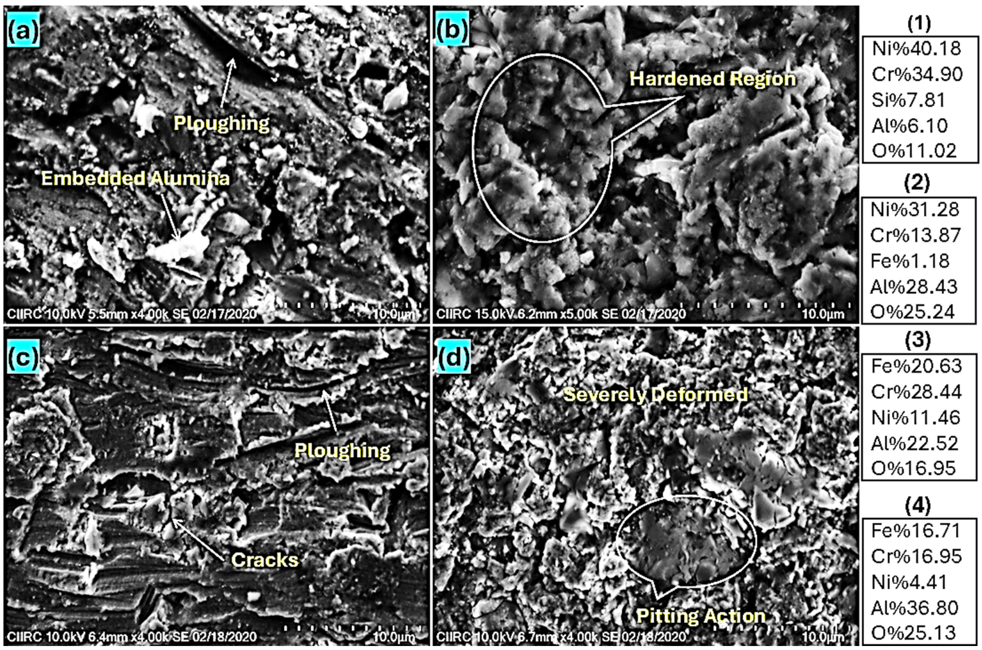


**Fig. 5.** Scanning Electron Microscopy of the eroded surfaces at 600°C NiCrBSiFeC coated (a,b) MDN431 steel (c,d) for impact angles of 30° (a,c) and 90° (b,d); (1, 2, 3 and 4) are EDAX surface morphology with a full-length spectrum on the eroded scar at the area of (a, b, c and d) respectively.

SEM images of the eroded surfaces at 600°C (Figure 5) reveal distinct morphological differences between the NiCrBSiFeC coating (Figure 5a, b) and MDN431 substrate (Figure5c, d) at 30° and 90° impact angles. EDAX analysis conducted on the eroded scars (Figure 5, spectra 1–4) indicates a higher aluminum content at 90° compared to 30°, confirming greater alumina particle embedment at higher impact angles. For the coating, the surface at 600°C appeared hardened, particularly at 90°, which correlates with the reduced erosion rate observed [15]. In contrast, the substrate exhibited severe deformation at 90°, consistent with higher material loss at elevated temperatures and impact angles.

## 4 Conclusions

1. In the present research, NiCrBSiFeC alloy powders were converted to partially oxidized powders via flame spray procedure after which the powders were deposited onto MDN431 substrates through plasma spray to form coatings.

2. The alloy powders and partially oxidized powders and the resulting coatings were well characterized in terms of microhardness, bond strength, density and surface roughness.
3. The performance of wear and erosion were investigated with the help of Pin-on-Disk Tribometer and Solid Particle Erosion Tester respectively.
4. The Pin-on-Disk Tribometer experiments showed that the rate of wear of the partially oxidized NiCrBSiFeC coatings was six times less than the substrate rate with increased performance at high temperatures.
5. Erosion test indicated that the erosion mechanism changed in high temperatures that was caused by the altered properties of the coatings through partial oxidation.
6. The NiCrBSiFeC coating had excellent mechanical properties hence it is very applicable in industry like boiler tubes coating and in aerospace parts.

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