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Solid particle erosion behavior of nichrome coated duplex stainless steel

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Abstract

One of the most serious concerns for the industry is material degradation, which leads to premature failure. Solid particle erosion (SPE) is a significant material degradation phenomenon. To be more specific, the erosion problem is made worse by the fluid inclusion of gravel and other contaminants. Despite being well studied and predicted, the process of solid particle erosion is still not properly known. Therefore, additional experimental research is still required to properly understand the erosion process and offer novel erosion resistance strategies. Employing coatings is the most effective technique to reduce/prevent solid particle erosion. The most commonly used methods to improve erosion resistance are proper material selection and the application of coatings. The erosion behaviour of atmospheric plasma-coated Nichrome (NiCr) on coated and uncoated duplex stainless steel (DSS2205) substrates were investigated. The erosion test is performed using an air-jet erosion tester with alumina as the erodent at velocities of 150, 175 and 200 m/s, impact angles of 30°,45° and 90°, and discharge rates of 2.5, 3.75 and 5 gm/min. This study discovered that the most influential factors of erosion are impact angle. When the impact angle is 90°, the velocity is 150 m/s, and the discharge rate is 5 gm/min, the erosion was minimal. Analysis of the surface microstructure reveals many erosion mechanisms linked to various incidence angles. The erosion mechanism changes from micro-ploughing to plastic deformation for low to high impact angles. Furthermore, metallographic examinations are used in conjunction with the experimental results. As per the experimental findings, coating bare substrates with NiCr can substantially increase erosion resistance. Moreover, NiCr coatings on bare substrates showed a 47% reduction in erosion wear, primarily as a result of their better toughness, higher density, improved micro-hardness, and lower porosity.

Keywords

Duplex steel, Nichrome, Thermal spray coating, Erosion.

1.Introduction

The objective of the oil and gas industries is to improve the equipment lifespan and reliability in order to reduce operational costs and safety risks. The tribological problem such erosion wear is a common problem which degrades the material property. Thus, a better understanding of erosion helps to enhance the efficiency and dependability of oil and gas machinery. The root causes of erosion have been the subject of in-depth study in order to develop effective preventive treatments [1]. The mechanism of the solid particle erosion (SPE) has not yet been clearly realized despite numerous attempts. With the current state of knowledge, it is impossible to comprehend the mechanism. Therefore, additional experimental research is still required to know the erosion process to create better components that are more erosion resistant. Erosion has a significant impact on many industrial uses, including pipelines and the oil and gas sector. Therefore, there is a need to create erosion-resistant materials and novel methods of protecting the material surface from erosion. Erosion by solid particles, sand, and other similar materials is a major phenomenon in material degradation, particularly in fluid carrying pipes. The particles moving at high speeds in the fluid will collide with the inner walls of the pipe causing erosion. Erosion is caused by material loss initiated by abrasive impacts on a regular and continuous

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basis, as well as by a micromechanical distortion or breakage process. The rate of wear is determined by the material, size, impact velocity, impact frequency, and angle of impingement [2].

Repeated surface contact with debris carried by flows in the pipeline industry results in significant erosion wear. Small, sharp, solid particles suspended in the flow will constantly hit the surface and erode it. In order to increase the service life and ensure the safe operation of oil and gas pipelines, a study into the features and mechanisms of erosion in the oil and gas industry is essential. Mechanical interaction occurs when the surface and the impacting abrasive particles come into contact, resulting in material loss [3].

Erosive wear has a very complex nature because rough, irregularly shaped solid particles of varying sizes move in different trajectories with varying velocities and angles, causing wear and injury [4]. One solution to the erosion problem is proper material selection. Duplex austenitic–ferrite stainless steels have been widely used in the oil and gas industry due to their superior erosion-corrosion performance and economic reasons, which have led to their selection as the substrate material [5]. In most cases, erosion studies were carried out at conventional standoff distances, with impact angle combinations between 15 and 90 degrees, impacting speeds from 20 and 150 m/s, with a mass flow rate within 5-8 g/min [6, 7]. However, hardly any studies have combined a discharge rate of less than 5 g/min, larger erosion duration of 30 minutes, and a speed in the range above 150 m/s, as in the case of oil rigs. The erosion test was therefore performed with the following parameters: constant standard distance of 15 mm, impact angle of 30-90°, impact velocity of 15-200 m/s, and discharge rate of 2. 5-5 gm/min.

Thermal spray coating method, which provides good surface resistance to erosion, is another method of preventing or minimizing erosion. Thermal spray coating has improved the erosion resistance up to 16 times [8]. The increased reliability of the development of various erosion and corrosion resistant property has increased the application and usage of thermal spray coating [9]. Thermal spray coating techniques, such as atmospheric plasma spraying (APS) processes, are commonly used because they are the most adaptable and can be used to cover a variety of composite materials and related mixtures [10]. It is a popular technique for coating surfaces with thicknesses ranging from a few microns to millimetres. APS coating entails spraying coating powder along with a plasma jet onto the surface, followed by a sudden deceleration that causes pressure accumulation and results in the flow of particles over the surface. These particles solidify on the surface, providing the substrate with the necessary coating. Several academic studies have described SPE experiments on a range of well-known metal and non-metal alloys. The numerous studies based on SPE examinations were found to have relatively little study on metal matrix composite coatings [11, 12]. Since powder metallurgy breakthroughs were few, the metal matrix composites were produced via the liquid approach [13].

This study aims to examine the erosion behaviour of duplex stainless steel (DSS2205) with powder metallurgy produced Nichrome (NiCr) coatings. In order to achieve the most effective coating against SPE behaviour, this study will thoroughly compare the APS coating with uncoated specimen. The erosion resistance of DSS2205 on atmospheric plasma sprayed with NiCr and uncoated DSS2205 under room temperature is compared. The experiments were done by varying the impact velocities, discharge rates, angles and the microstructural characterization was performed. The effects of operational parameters on the erosion mechanisms on coated and uncoated specimens were investigated. The ideal set of standards for enhancing equipment reliability and safety under challenging working conditions was also developed in order to be used for future applications.

This research concentrates on the primary factors that influence SPE. The influencing parameters include impact velocity, impact angle, and discharge rate. First, the parameters are explained, and then the experimental investigations that focused on them are discussed and compared in terms of their conclusions, ranges, and experimental consideration. Graphical displays that depict the typical trend of each parameter effect on erosion are compared. Finally, future perspectives and potential pathways are gathered as suggested guidelines for researchers based on the limitations of past experimental endeavors.

This paper is organized as follows. Literature review in section 2. Methods have been explored in section 3. Section 4 covered the results and analysis. Impacts have been discussed in section 5. Finally, it is concluded.

2.Literature review

Implementing preventative corrective steps to avoid machine component failure requires a thorough understanding of how metals and their alloys deteriorate under various environments. A thorough, in-depth, literate review was undertaken to identify the erosion mechanism and possible mitigation strategies for the components effective use. Numerous studies were conducted to determine the critical elements in erosion as well as the modern method that can be used commercially for prevention of material degradation due to erosion. An in-depth evaluation of the earlier studies will be provided in this section. Boggarapu et al. [14] state that erosion is a deteriorating process brought on by mechanically impacting particulates the exterior of a machine component. Corrosion, cavitation erosion, slurry erosion are many other processes, which are the types of erosion. Zhang et al. concluded that SPE is one of the common wear types that occur in a progressive loss of component material as a consequence of the striking of solid particles[15].

SPE causes surface damage to a component quickly, which lowers the structural integrity of the machine parts [15]. The mechanical surface degradation further compromises the component survival [16]. So, a thorough literature review for SPE is carried out. The article offers useful details about erosion processes and how they apply to diverse materials. The use of these procedures by researchers and industries will also be made clear. The results of this analysis can be applied in a variety of sectors, and practitioners and researchers will benefit from a thorough compilation of pertinent material. The SPE types are influenced by the component material structural and mechanical characteristics as well as the angle at which the erosion particles impact it [17]. The direction that the particles move in relation to the component surface is known as impact angle. Ductile erosion is defined as having the highest rate of erosion at a lower impinging angle. Due to the component ductile nature, material is removed from its surface through a micro-cutting and ploughing process that produces craters. On the other hand, brittle erosion occurs when the erosion rate rises as the impact angle rises, reaching its maximum at the typical impact angle [18]. Moving particles remove material in the shape of bits with an uninterrupted impact and cause fractures on the surface [19].

The erosion method is also influenced by additional elements, such as the erosion particles impact velocity, the temperature of the working atmosphere, and the erodent materials form, size, and density [20]. Jindal et al. noted that 59% of the publications they evaluated used steel as a base with varying alloying elements [21]. Cheniti et al. recognized the significance of giving a protective treatment to the component surface in effort to expand the lifespan of operating components that are susceptible to severe erosion damage during operations [22]. In earlier investigations, erosion-resistant coatings were created using coatings made of a range of materials [23]. Babu et al. [24] describe various methods for depositing materials using a variety of surface modification techniques, highlighted the importance of thermal spray technologies in the development of coatings. These benefits, especially the ability to cover large scale structures, thermal spraying is now widely employed in the hydro turbine industry. Pejchal et al. identified APS one of the common deposition processes that provides protection against erosive, abrasive, corrosion, high temperatures, and chemical attack [25]. Swain et al. claimed that it is the most appropriate method since it can deposit a variety of materials [26]. Due to this technique versatility, Swain et al. found that it has been used extensively in a variety of industries, including aerospace, automotive, nuclear, and many more. The literature has extensively covered the relationship between variables and characteristics. Hence, careful parameter management can ensure the desired outcome [27]. Aramian et al. concluded that NiCr coating is extensively employed in surface protection and part repair due to its superior characteristics, mechanical qualities, and machining capabilities [28]. NiCr coating provided good oxidation resistance and micro hardness that was 65.9% higher than that of bare steel [29]. Li et al. observed that the coatings microstructure was denser and had a stronger bond with the substrate [30].

An evaluation of the literature shows that NiCr coatings can endure erosion wear under mining environments. The current study, which examined the erosion wear of NiCr composite powders coated to DSS2205 substrate using the APS technique. Shahapurkar et al. claims that erosion has a significant impact on component performance. Therefore, it is crucial to do research on the behaviour and material removal techniques. Cutting, impact, and fatigue are just a few of the intricate processes that go into the SPE. Studies based on erosion behaviour must be carefully evaluated because they are highly complex in order to better understand material behaviour in erosive environments [31].

The characteristics of solid particles, impingement, and target materials, such as hardness and microstructure, all have an impact on erosion wear [32]. The elements that have the biggest effects have been thoroughly researched by numerous authors. Zhang et al. propose that the impacting angle has a substantial influence on the mechanism's erosion [33]. Presby et al. [34] and Panakarajupally et al. [35] research outcome has identified the role of particle speed in erosion rate. Sharma et al. examined at how concentration and particle interface influenced erosion rate and concluded that both factors had a large effect [36]. Kuruvila et al. conducted erosion research of solid particles utilizing the parameters based on the above-mentioned studies. They observed that erosion rate increases with increasing speed and reduces with increasing impacting angle and flow rates [37].

Though several researchers have investigated the erosion behavior of various coated steels, very few have found the optimum condition of the erosion parameters. The influence of various factors was not also much explored for effective erosion prevention. These key aspects were found to be the research gap, which helped to formulate the objectives for this work.

3.Materials and methods

3.1Coated DSS2205 sample preparation

Figure 1 shows the pictorial representation of the experimental study. Initially, the substrate was selected as DSS2205 based on the piping application. The specimen is then prepared to the required dimensions and APS coated with NiCr. The various input parameters were identified which influences/controls the erosion process. The ranges were selected and the experimental erosion tests were performed. To determine the influence of each parameter on the erosion, parametric analysis was performed. The results were later compared with those obtained from the uncoated DSS2205. Finally, an effective solution was derived which can prevent the erosion of DSS2205.

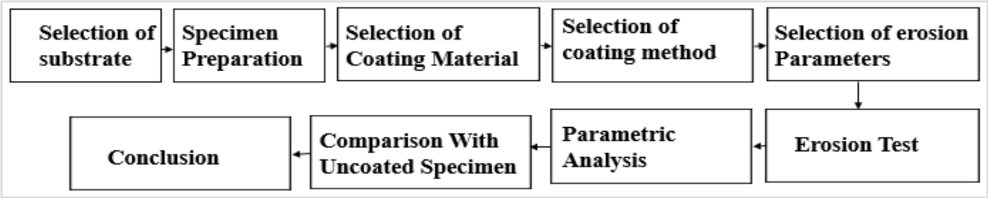


Figure 1 Pictorial representation of the experimental work

DSS2205 is one of the most commonly used stainless steel due to its excellent properties. The work piece material was delivered in sheet form with a thickness of 5mm, and samples with dimensions of 25×25 mm were cut using an abrasive water jet. The elemental composition is shown in *Table 1*. *Table 2* shows the coating powder characteristics for the NiCr coating materials used on the DSS2205 substrate. The metallurgical microscope is used to characterize the microstructures of the coatings, as shown in *Figure 2*.

Table 1 Elemental composition of DSS2205

Element	Composition by wt.%
Iron (Fe)	69.32
Chromium (Cr)	23.0
Nickel (Ni)	4.5
Manganese (Mn)	2.0
Silicon (Si)	1.0
Phosphorus (P)	0.03
Sulphur (S)	0.02
Carbon (C)	0.03
Nitrogen (N)	0.1

Table 2 Chemical composition of NiCr

Element	Composition by wt.%
Nickel (Ni)	72.3
Chromium (Cr)	23.2
Manganese (Mn)	1.1
Silicon (Si)	2.7
Carbon (C)	0.7

The APS coating method was used in the current research work on the DSS2205 substrate. Plasma spraying was chosen for the experiments due to its utility and benefits (the ability to coat both metallic and non-metallic materials). *Table 3* lists the APS spray parameters. A 50 µm average coating thickness was observed. *Figure 3* shows the optical image of the coating.

Table 3 Atmospheric plasma spray conditions

Parameters	Values
Current	451 A
Voltage	61-64 V
Plasma gas	$0.91x10^{-3}$ m^3/s

Parameters	Values
Secondary gas	0.12x10^{-3} m^3/s
Pressure: plasma gas	36 g/mm^2
Pressure: secondary gas	18 g/mm^2
Feed rate	121 g/min
Spray distance	101-149 mm
passes	11-16

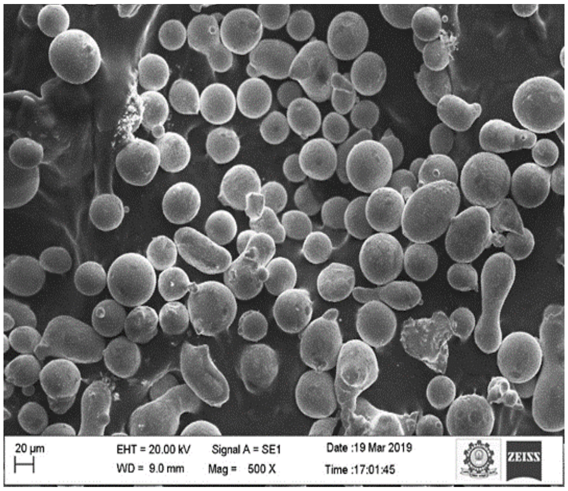


Figure 2 Initial morphology of NiCr

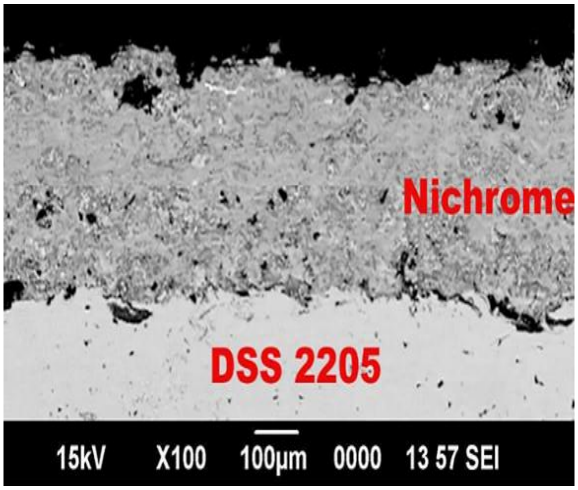


Figure 3 Plasma coating on the substrate

3.2Experimental setup

SPE tests were performed on NiCr coated specimens at selected incident angles and particle velocities in an atmospheric environment and at room temperature using a Ducom make erosion test rig TR-470 as shown in *Figure 4*. The erodent used in this research was a commercially available, angular-shaped alumina powder with a particle dimension of 50µm.

Erosion tends to be nonlinear in terms of its variables, materials, and operating circumstances. The operating parameters must be combined properly to produce the optimal result. Different variables may have different effects on erosion depending on the working environment. American society for testing and materials G76 was followed while conducting the erosion tests. The erosion test conditions are listed in *Table 4*. The sample was dried, cleaned, and weighed using an electronic balance with 0.01 mg accuracy. Alumina was used as the erodent for exactly 30 minutes under specified conditions after the sample was mounted to the specimen holder of the test device. The air along abrasive mixture are driven out of the mixing chamber to impact the specimen's fixed surface using a 30 mm long and 3 mm wide tungsten carbide converging nozzle. The standoff distance is maintained at 10 mm. Feed rate and impact velocities are abrasive characteristics that are controlled by compressed air pressure. The weight loss was calculated after the sample was taken out, dried, and weighed. The mass loss to the quantity of erodent causing this was used to calculate the erosion rate (i.e. time x discharge rate). The aforementioned steps were repeated until a steady state is reached.

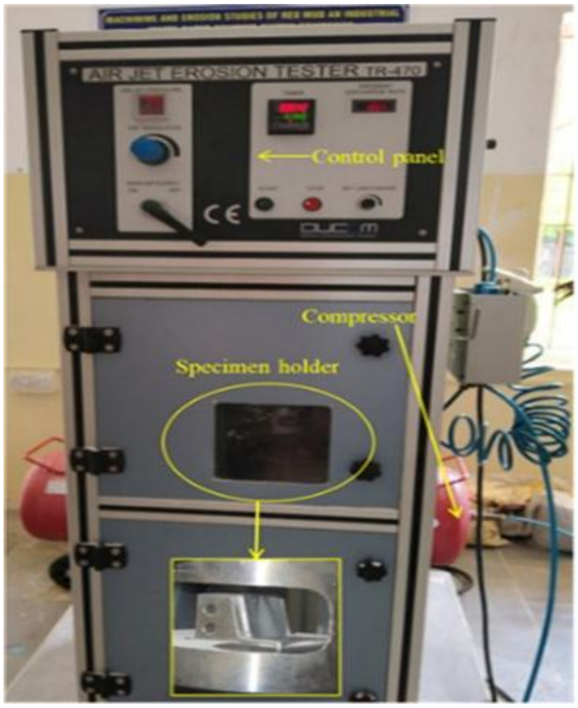


Figure 4 Erosion test rig

Table 4 Erosion process parameters

Factors	Range
Flow Velocity (m/s)	150, 175, 200
Discharge rate (gm/min)	2.5, 3.75, 5
Angle of Impact (°)	30, 45, 90
Time (min)	30

4.Results

4.1Coating characterization

The porosity of the coatings was assessed using a metallurgical microscope (QS-17 AT). The structural characterization of sprayed coatings was examined using scanning electron microscope (SEM). The cross sectioned surfaces of the specimens were measured for Vickers hardness using a Vickers hardness tester, model: VM-50, with a 250 g load. *Table 5* compares the properties of atmospheric plasma coatings to uncoated samples.

Table 5 Comparison of coating thickness, surface roughness and porosity

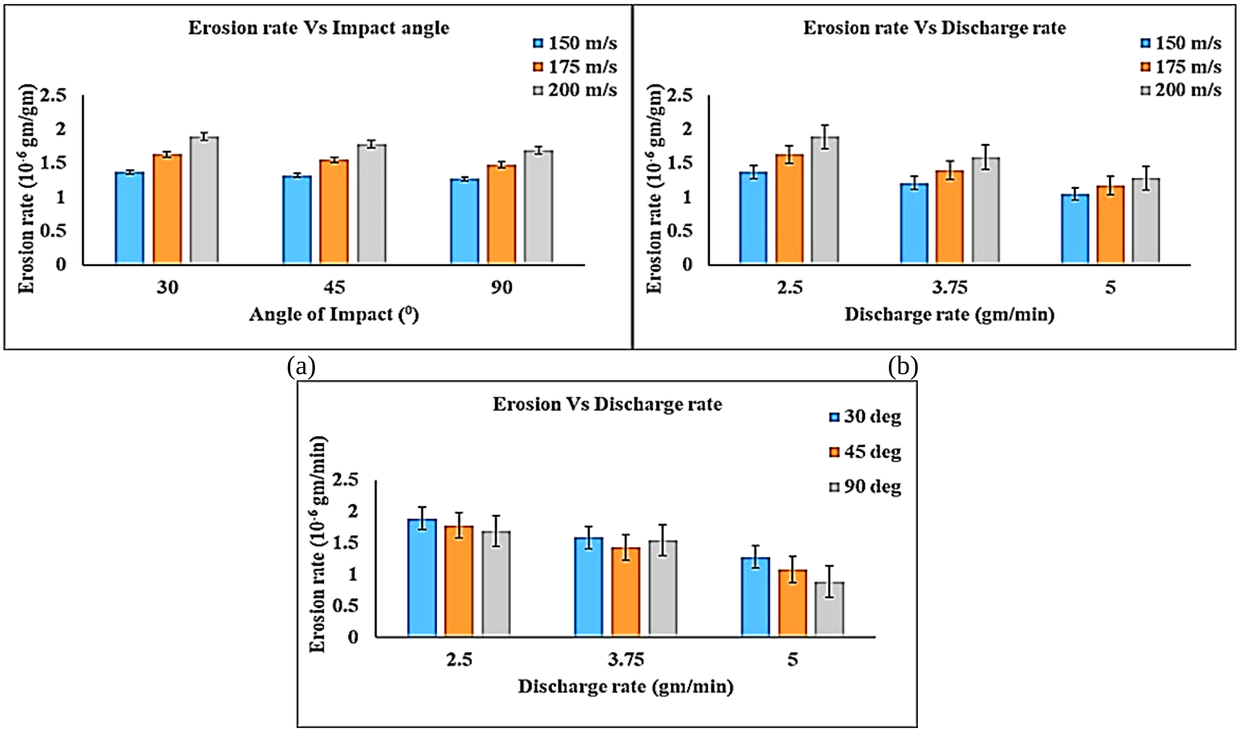
NiCr coating	Atmospheric plasma coating	Uncoated
Porosity (%)	2.1	6
Surface Roughness (μm)	5.5	6.9
Hardness (Hv)	423	359
Coating Thickness (μm)	50	-

4.2Erosion test

Erosion is a highly complex natural process that involves several variables. Identifying the mechanism is extremely difficult because these parameters behave differently depending on the environment. The experimental results are shown in *Table 6.* In the subsection, the effects of various factors influencing the results are explained. *Figure 5(a)* shows how the erosion rate varies with impact angle under conditions of ambient temperature while keeping the other elements as constant. The results of the data analysis reveal that erosion rates are lowest at high angles (90°) and largest at low impact angles (30°). As a result, erosion is a ductile process. This behaviour is due to the composites predominate brittleness or ductility of the NiCr coatings. Low angle particle strikes increase the magnitude of the tangential component velocity, which leads to plastic deformation and rapid surface erosion. The interface between the incoming particles and the particles rebounding back also reduces the force of the particles as the impact angle increases. The impact angle that had the greatest impact on erosion rate was found to at 30° [38]. At lower impact angles, where the striking particles produce a ploughing action, erosion is sharper whereas erosion at higher impact angles is through plastic deformation, where the majority of the kinetic energy is lost [39]. A significant number of particles firmly attached to the surface at high impact angles, adding weight. As a result, the surface becomes harder and more erosion-resistant.

Table 6 Erosion test results

Exp. No.	Velocity (m/s)	Discharge Rate (gm/min)	Angle of Impact (°)	Erosion (10^{-6} gm/gm)
1	150	2.5	30	1.37
2	150	2.5	60	1.32
3	150	2.5	90	1.27
4	150	3.75	30	1.21
5	150	3.75	60	1.13
6	150	3.75	90	1.05
7	150	5	30	1.05
8	150	5	60	0.94
9	150	5	90	0.83
10	175	2.5	30	1.63
11	175	2.5	60	1.55
12	175	2.5	90	1.48
13	175	3.75	30	1.40
14	175	3.75	60	1.28
15	175	3.75	90	1.17
16	175	5	30	1.17
17	175	5	60	1.01
18	175	5	90	0.86
19	200	2.5	30	1.89
20	200	2.5	60	1.78
21	200	2.5	90	1.69
22	200	3.75	30	1.59
23	200	3.75	60	1.43
24	200	3.75	90	1.29
25	200	5	30	1.28
26	200	5	60	1.08
27	200	5	90	0.89



(a) (b)

(c)

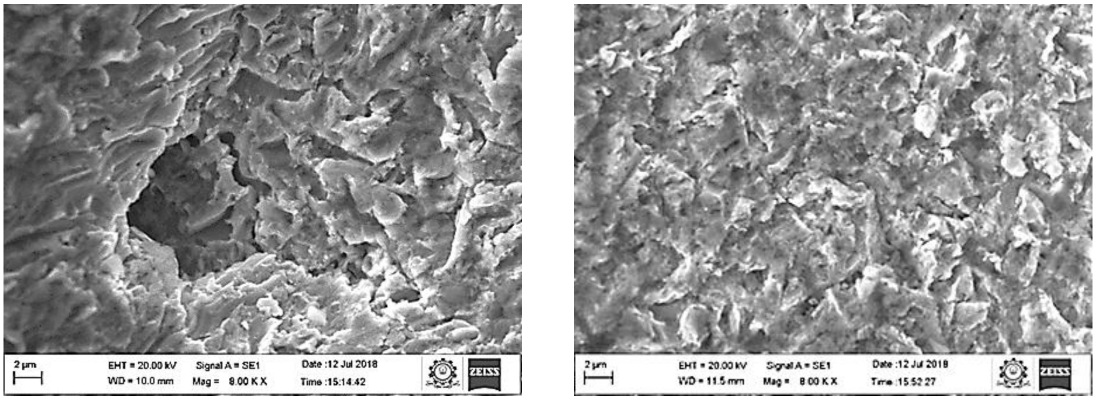
Figure 5 Erosion rate vs (a) impact angle, (b) flow velocity, (c) discharge rate

Figure 5(b) depicts the effect of flow velocity on the erosion rate of NiCr coated DSS2205 at various discharge rates under ambient conditions at a constant impact angle. The impact velocity of the impinging erodent has a considerable influence on erosion. The dependency is effectively described by a power law [40]. When the particle's velocity is increased, the kinetic energy increases. According to Wood and Speyer [41], particle fragmentation was shown to increase with speed, and erosion wear was found to be strongly correlated with initial kinetic energy. Erodent moving at higher velocities and kinetic energy results in greater loads for plastic deformation and destruction. Higher energy produces greater impact and more severe damages to the surfaces. Furthermore, a large number of particles attain critical energy, resulting in deformation and increased material removal over a localized area. Larger, faster particles tend to break upon impact and may rebound from the surface, causing radial damage. The increase in particle speed also causes a reduction in ploughing action, which results in an increase in elastic energy that exceeds the strain energy of the material. The highest erosion rate for all specimens was measured at the highest velocity (200 m/s), with a velocity exponent (n) of 2.016, confirming the ductile erosion wear behaviour in this experiment. Normally, n value for ductile erosion ranges between 2 and 3.

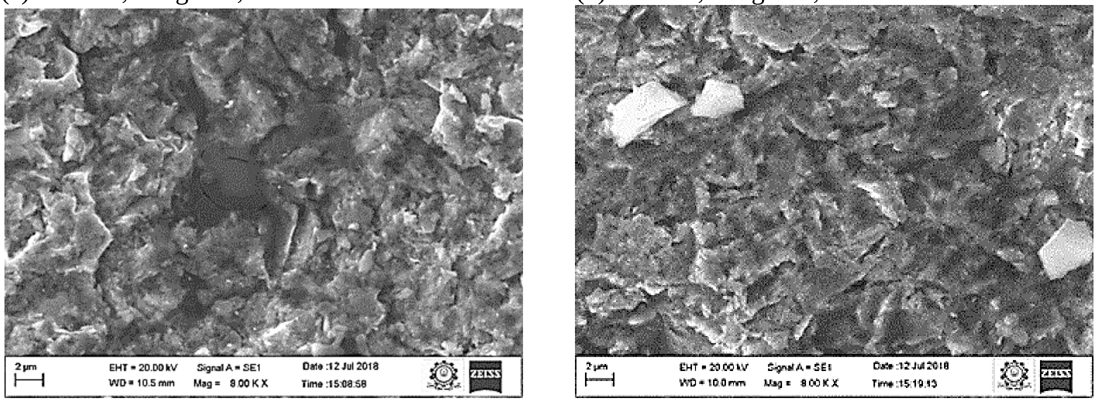
The influence of discharge rate of erosion is shown in *Figure 5(c)*. The erosion rate has decreased as abrasive particle concentration has increased. The particle guarding action is what actually reduces the erosion rate significantly. On the surface of the specimen, particles that are being eroded bounce back and collide with newly arriving particles. The particle trajectory becomes agitated and more disorganized as the discharge rates go up. The fluids' ability to transmit particles is constrained by the increasing discharge rate, which intensifies the contact between the fluid and particles as the discharge rate rises. The particles' paths, then become unstable as a result of the inability to transport them efficiently. As a result, the jet loses energy, weakening the erosion ability [42].

4.3Metallurgical analysis of eroded samples (coated specimens)

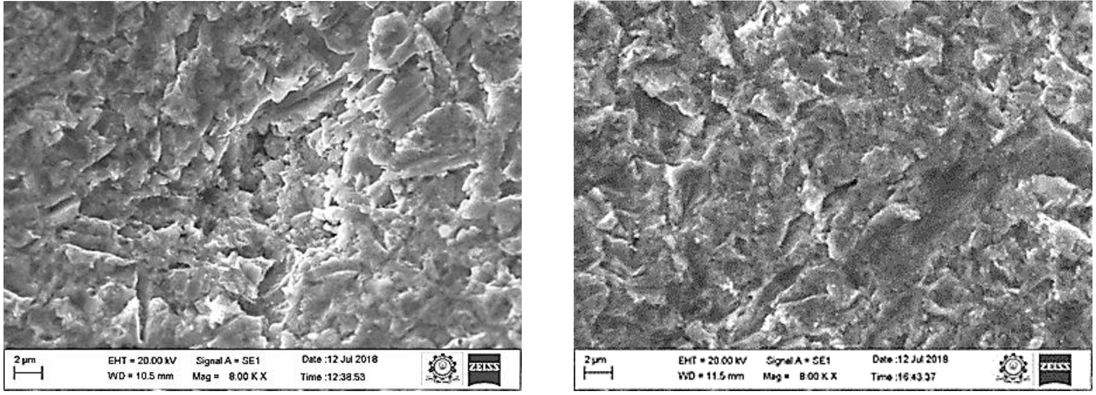
The degraded coatings underwent metallurgical analysis using SEM and energy-dispersive X-ray spectroscopy (EDAX). *Figure 6* shows the pits created when abrasive particles impacted with the coated DSS2205. The development of craters and lips demonstrated that a ploughing process is to account for degradation at a 30° impact angle. The creation of pits is accelerated when the impact angle is 90°, as stated by Hutchings and Levy [43]. Under the steady state situation, they discovered that the 3 levels coexist at various places throughout the exterior. Primary crater formation is caused by the striking particle, and a raised lip or mound is produced when material is projected or moved from the crater. In the second phase, further impacts on the moved element deform it, which can cause a horizontal shift of the material and around the ductile crack in severely strained areas. The dislodged part is finally put under such high strain that ductile fracture forces it to separate from the surface. While analysing the topography of the surface with maximum erosion at the velocity of 200 m/s and a 30° impact angle, the surface shows some grooves which are deeper initially, and the depths of the grooves are reduced, due to the reducing effect of micro cutting and plowing action of sharp and hard abrasive particles. At low impact angles and high velocities, erosion occurs by the failure of ridges around the cracks.



(a) 200 m/s, 2.5 g/min, 30° (b) 150 m/s, 2.5 g/min, 30°



(c) 200 m/s, 2.5 g/min, 90° (d) 200 m/s, 5 g/min, 90°



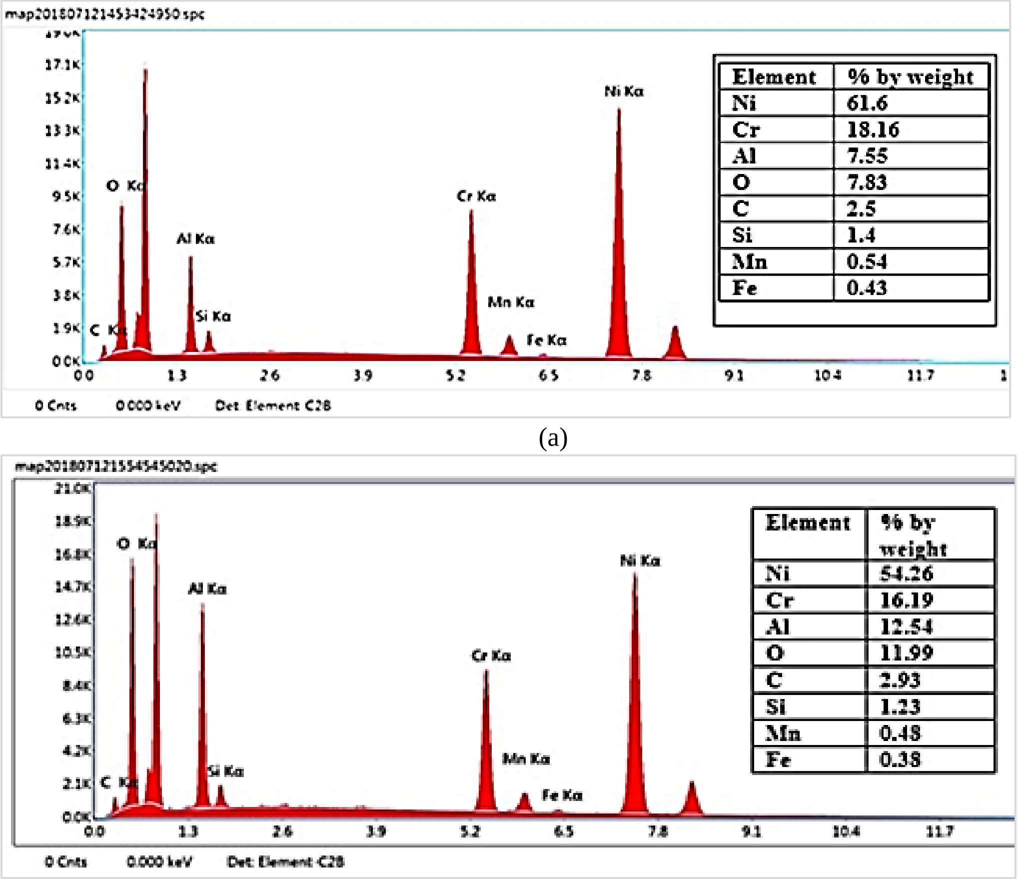
(e) 175 m/s, 2.5 g/min, 60° (f) 175 m/s, 2.5 g/min, 60°

Figure 6 SEM images of the coated surfaces subjected to erosion under various input conditions

The continuous impingement will result in work hardening which leads to brittle failure. The formation of work-hardened ridges can be observed at a 45° impact angle. Erosion occurs at low impact angles as a combination of plastic deformation and microcutting/plowing. Additionally, the increase in impact angle shows that plastic deformation outperforming other cutting processes. On the surface of a material, grooves emerge as a result of the movement of abrasive particles.

There is a strong possibility that the abrasives will penetrate deeply because they will be contacting the surface vertically at a 90° impact angle, which will result to a low metal removal rate. However, since the velocity is high, the abrasive particles may get scattered. It is more likely that some particles will be bouncing back from the surface. The continuous hitting of the abrasive particles over the surfaces can cause work hardening and leads to the development of cracks. The increased particle speed, the higher the energy level and it will be sufficient to penetrate the material against the hardness by causing the cracks. As a nutshell, the conditions that prevent erosion behaviour have been identified as 150 m/s velocity, 5 g/min flow rate, and 90° impact angle (optimum).

The EDAX analysis of the eroded coated DSS2205 surface is shown in *Figure 7*. The entire degraded surface consists of Cr, Ni, O, and Al. Al is becoming more prevalent at 90° impact, along with O, indicating that the base material has enveloped the erodent (alumina). The loss of cutting energy and abrasive mass produced by the incursion can be correlated with a decrease in erosion rate [44].



Element	% by weight
Ni	61.6
Cr	18.16
Al	7.55
O	7.83
C	2.5
Si	1.4
Mn	0.54
Fe	0.43

(a)

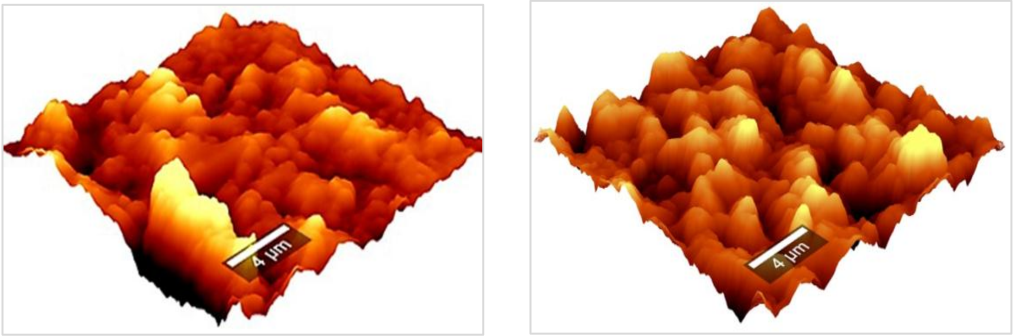
Element	% by weight
Ni	54.26
Cr	16.19
Al	12.54
O	11.99
C	2.93
Si	1.23
Mn	0.48
Fe	0.38

(b)

Figure 7 EDAX analysis of the eroded coated DSS 2205 surface a) 30° impact angle, (b) 90° impact angles

Atomic force microscopy (AFM) is used to evaluate the surface topography of the eroded surface while conducting the experiments with optimum conditions as shown in *Figure 8*. It is found that the average surface roughness is between 2 and 4 µm for coated surfaces, whereas, for the uncoated, it is much higher.

In our previous work the authors performed SPE on uncoated DSS2205 under similar conditions [45]. The experiments were repeated to compare the erosion rates of NiCr coated and uncoated DSS2205 specimens. Under similar experimental conditions, the results of these erosion rates are further analyzed to confirm that the erosion rate of the NiCr coated specimen is much lower than that of the uncoated specimen.



(a) (b)

Figure 8 AFM image of the eroded surface (a) coated, (b) uncoated

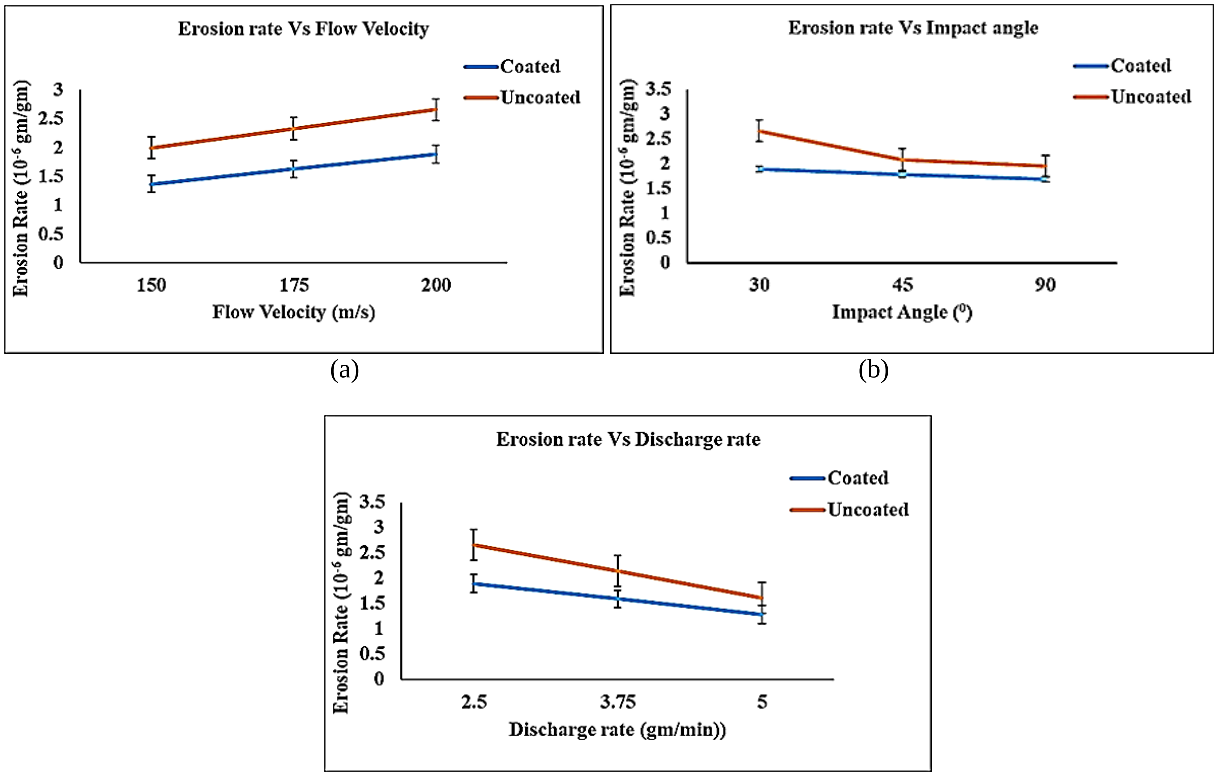
5.Discussion

5.1Comparison of erosion rate for coated and uncoated specimens

Figure 9(a) shows the change in flow velocity and erosion rate across different samples (coated and uncoated). All samples have higher erosion rates as flow velocity increases. As a result, higher speeds resulted in a greater erosion rate than lower speeds. The erosion rate caused by flow velocity was found to be highest in uncoated DSS2205 samples and lowest in NiCr coated samples. *Figure 9(b)* shows the erosion rate's relationship to impact angle for all samples (coated and uncoated). It has been shown that as the impact angle increases, the erosion rate of all samples—coated and uncoated—decreases. Additionally, uncoated DSS2205 samples show the highest rate of erosion when contrasted to coated samples. *Figure 9(c)* indicates the effect of the erodent discharge rate on all samples (coated and uncoated). It is discovered that as the erodent discharge increases from 2.5 to 5 gm/min, the erosion rate of all samples decreases. Comparing coated and uncoated DSS2205 samples, the erosion rate of the uncoated samples was always the highest.

The developed NiCr coatings had significantly better erosive behavior than the bare DSS2205 in all testing conditions. This could be due to the fact that NiCr coated samples are harder than bare samples. Since the NiCr coating is stronger it provides better erosion resistance than the uncoated DSS2205. According to Sheldon [46], the hardness has an inverse relationship with the amount of material lost per grams of erosion particles. Higher hardness provides greater resistance to abrasive penetration into surfaces, reducing crack initiation and propagation resulting better erosion resistance [47]. Another element that could affect a coating's erosion behavior is its surface roughness. Higher erosion rates are predicted because, when the surface is rougher, powder particles on the surface act as damage insertion sites and increase the amount of contact area between the material surface and the particles [48]. In addition to slowing erosion, reducing the initial surface roughness also delayed erosion. Superior erosion resistance was achieved by the coatings low porosity [49].

When comparing the data, it is obvious that the effect of erosion is minimal at lower velocities, but as the velocity increases, the erosion rate for uncoated material grows exponentially when compared to coated. The rise in velocity from 150 to 200 m/s resulted in 24.31% rise in erosion rate for coated specimens, compared to 34.8% for untreated specimens. Thus, the effect of velocity cannot be ignored. The erosion rate was reduced by just 5.8% in coated specimens, but by 34.8% in uncoated specimens. The porosity levels of the coatings can be compared to see how porosity influences degradation rates adversely. As a result, the NiCr coating performs better than the bare sample. According to Levy [50], increased porosity boosts the removal rate because erodent particles can more easily knock off parts from the exposed surface. Porosity also reduces the mechanical properties, which reduces the energy required to remove a surface [51]. The relative comparison of the porosity contents of the coatings on erosion rates indicates that porosity has a negative effect. As a result, the NiCr coating performs better than the uncoated specimens.



(a) (b)

(c)

Figure 9 Erosion rate for coated and uncoated samples (a) flow velocity, (b) impact angle, (c) discharge rate

Maximum signal-to-noise ratio (S/N) is required to provide ideal erosion conditions. Data means of S/N is shown in *Figure 10.* It is evident from this result that coating reduces the rate of erosion. The highest mean S/N levels are regarded as ideal levels. At an impact angle of 30°, a discharge rate of 5gm/min, and a flow velocity of 150 m/s, coated specimens reach their maximum value. The above results were confirmed by analysis of variance (ANOVA) (*Table 7*) and Ranking table (*Table 8*). A greater S/N denotes a higher degree of quality due to the decrease of noise, and the relevant process parameters remain untouched by changes in the surrounding environment or other noise-related factors. The S/N must be increased in order to reduce the impact of random noise components, which seriously impact process performance.

The response of the erosion rate was mathematically analysed using factorial design based on the experimental findings. Individual and combination process factors were shown to have a major influence. The coatings proposed had a significant impact on the maximum contribution of 50.62%. Individual and combination process factors were shown to have a significant impact. As previously stated, the material properties are responsible for the actual erosion mechanism on the coated alloy and the outcomes of the base metal, followed by the process parameters of impact angle (11.45%), particle flow velocity (3.2%) and discharge rate (17.96%). Furthermore, particle kinetics play a vital part in the erosion. When evaluating the interactions of the process parameters, the particle discharge rate had a maximum influence of 7.3% of the coating.

Similarly, the combination of particle velocity and flow rate has a 1.38% impact, and (ii) coating and impact angle have a 1.41% contribution. Similarly, the impact angle and flow velocity combination have a 0.32% impact, while discharge and angle of impact have a 0.1% impact (ii) coating and flow velocity contribute 1.2% of the total. Coating material, particle velocity, particle flow rate, impact angle, and discharge rate are all elements that influence the erosion rate. The results of the confirmation test in *Table 9* show that the S/N improvement from the original condition to the optimal condition was 49%. The SEM surface image reveals that the substrate surface has only minor surface damage. In addition, the coating is dense and has a low porosity in comparison to an uncoated surface.

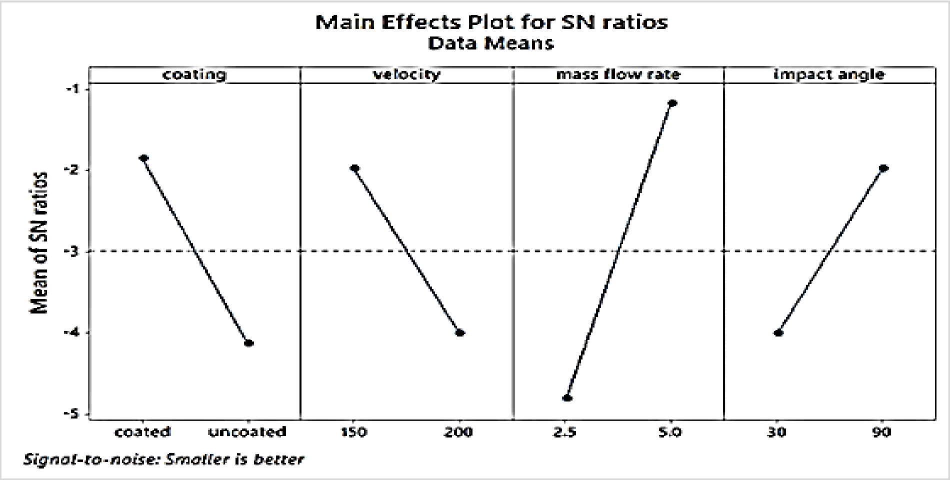


Figure 10 Main effects plot for S/N

Table 7 ANOVA table

Source	DOF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Coating	2	1.9327	0.96637	90.81	0.000	50.62
Velocity (m/s)	2	0.1246	0.06228	5.85	0.011	3.2
Angle of Impact (°)	2	0.4382	0.21912	20.59	0.000	11.45
Discharge Rate (gm/min)	2	0.6872	0.34361	32.29	0.000	17.96
AxB	1	0.0461	0.0461	7.34	0.0025	1.2
AxC	1	0.0542	0.0542	8.64	0.0011	1.41
AxD	1	0.2823	0.2823	44.95	0.0001	7.3
BxC	1	0.0119	0.0119	3.77	0.0615	0.3
BxD	1	0.0529	0.0529	16.85	0.0003	1.38
CxD	1	0.0046	0.0046	1.47	0.2341	0.1
Error	12	0.1915	0.0159	-	-	4.95
Total	26	3.862	-	-	-	-

DOF=Degrees of freedom, Adj SS= Adjusted sum of squares, Adj MS=Adjusted mean squares, F-Value: Division obtained by two mean squares, P-Value: Probability of obtaining an F-ratio

Table 8 Ranking table

Level	Coating	Velocity (m/s)	Angle of Impact (°)	Discharge rate (gm/min)
1	-3.6834	-0.6990	-2.6927	-3.0261
2	-2.1158	-1.7052	-1.5591	-1.4393
3	1.1247	-2.2702	-0.4226	-0.2091
Delta	4.8081	1.5712	2.2701	2.8170
Rank	1	4	3	2

Table 9 Results of confirmation test

Initial parameter level		Optimal parameter combination	
		Prediction	Experimentation
150m/s,60°, 5 gm/min	0.52103	0.940833	1.01220

NiCr have been successfully coated over DSS2205 using the atmospheric plasma coating process. Compared to coating procedures, this method is inexpensive and easily accessible. A relatively dense structured coating with an average thickness of 100μm and an average porosity of 2.1% has been generated using the specified spray conditions. The coating's lower porosity and stronger cohesive strength combined to produce a coating with 423 Hv hardness. The resistance to erosion was effectively enhanced by NiCr based coatings sprayed on DSS2205 by APS spraying. The greater micro hardness of NiCr based coatings may have been the primary factor in the better erosion resistance of DSS2205.Discharge rate and velocity were discovered to be the most important parameters in all coating situations throughout the experiment. While the erosion rate is proportional to velocity, it is inversely related to discharge rate and impact angle. Additionally, impact angle's effects, which have been shown to have less of a dominating effect, are also taken into account during the process. DSS2205 steel that has been coated shows lower steady state erosion rate when compared to uncoated under comparable test circumstances. The increased hardness ratio may have prevented Alumina particles from penetrating the surface, providing some protection against impacting particles.

5.2Limitations and recommendations

Although the findings are encouraging, this research could be expanded to include optimization techniques to gain a better understanding of how to identify acceptable process parameters and coating techniques. The above study could be expanded to examine the effects of other factors, such as the type of abrasive materials used and the coating procedures used to reduce erosion rate. Surface protective coatings are one method that has been shown to decrease the SPE mechanism; nevertheless, choosing the right thickness and production method are extremely important. The effects of standoff distance, temperature, coating thickness, and advanced coating fabrication techniques in terms of deposition rate, temperature, and surrounding pressure conditions are to be considered for further advancement in the field. However, the present study has only taken into account the effects of some elements like impact velocity, impact angle, and discharge rate.

Prevention of erosion provides major financial advantages in terms of ongoing operations and material savings. One approach is the creation of new alloys and coating techniques. The study's results will be useful in choosing the suitable procedures and materials for the system's design. It is recommended that NiCr based coatings produced through APS be employed as resistive coatings in the oil and gas industries in order to minimize the effects of the severe erosion problem in view of the above observations. A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

This study is to compare the erosion resistance of atmospheric plasma coated NiCr coating with an uncoated DSS2205 substrate. The effectiveness of coating as an erosion barrier has been accomplished through SPE tests on these samples. The experiment results contribute to the conclusions.

- Material loss increased as flow velocity increased, but uncoated specimens lost more material mass as compared to coated specimens for all impact angles and discharge rates for both coated and uncoated specimens. The inclusion of nickel and chromium had a positive impact on the production of oxide layers during erosion, resulting in a more durable surface for the coated specimen.
- APS coatings can provide denser microstructures, higher hardness, lower porosity, and a better surface finish than uncoated specimens. As a result, the APS coatings are found to outperform the uncoated specimens under all wear conditions studied.
- SEM images show that as the impact angle increases, the erosion rate decreases, indicating that a material loss at lower angles is produced by plastic deformation and micro-forging. However, increases in impact angle normally result in higher abrasive embedment with very little material loss, but increases in flow velocity typically increase metal surface erosion through micro-cutting.
- The ANOVA results showed that coating contributed significantly to the erosion wear rate of NiCr coated specimens, with a percentage contribution of 20.25% of erosion and 11.3% for impact angle. Similarly, the particle impact angle had a maximum influence of 12.39% on the coating, according to the analysis of variance data, which was higher than the individual contributions of the parameters. Similarly, interaction of particle velocity and flow rate has a 13.24% influence, while the interaction of coating and flow rate has a 10.79% impact.

The APS coated NiCr on the DSS2205 substrate revealed outstanding characteristics. The above study could be expanded to examine the effects of other factors, such as the type of abrasive materials used and the coating procedures used to reduce erosion rate.

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None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Roshan Kuruvila: Conceptualization, investigation on challenges, data analysis, data acquisition and writing original draft. **S. Thirumalai Kumaran:** Interpretation of results, review, supervision, proofreading and the revision of the whole article. **M. Adam Khan:** Supervision, methodology and proofreading.

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Appendix I

S. No.	Abbreviation	Description
1	AFM	Atomic Force Microscopy
2	APS	Atmospheric Plasma Spraying
3	DSS	Duplex Stainless Steel
4	EDAX	Energy Dispersive X-ray Spectroscopy
5	NiCr	Nichrome
6	SEM	Scanning Electron Microscope
7	S/N	Signal-to-Noise Ratio
8	SPE	Solid Particle Erosion