Investigation of the Impact of HVOF Spraying Parameters on the Abrasion Resistance of Tungsten Carbide Coatings

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ABSTRACT

For components operating under high pressure and high values of friction conditions, rapid wear is a common issue. Surface treatment measures are often employed to enhance the working lifespan of such components by improving their resistance to abrasion. This paper utilizes the Taguchi experimental design method in conjunction with Analysis of Variance (ANOVA) to assess the impact of spraying parameters on the abrasion resistance of the coating when applying the HVOF method. The sprayed material is WC HMSP1060-00+60% 4070, primarily consisting of Nickel and Tungsten Carbide, whereas the material for manufacturing the pressing screws is 1045 steel. The investigated spraying parameters include the spray Flow Rate (F), Spray Distance (D), and Oxygen/Propane Ratio (R). The experimental results are analyzed to determine the most suitable spraying parameters to achieve the highest abrasion resistance, and thereby improve the working lifespan of the components.

Keywords-spraying parameters; friction; abrasion; HVOF method; working lifespan

I. INTRODUCTION

The High Velocity Oxygen Fuel (HVOF) method is a high-speed oxygen-fuel spraying technique with spraying velocities reaching from 1000 m/s to 1500 m/s. HVOF-coated layers exhibit a laminar structure with distinct properties, composition, and a structure distinct from the original material [1]. Essentially, the coating comprises metal plates, with dimensions ranging from 0.1 mm to 0.2 mm and a thickness from 0.005 mm to 0.01 mm, stacked on top of each other. The deformation of each metal plate varies, as it is separated by a thin layer of oxide with an approximate thickness of 0.001 mm. There are also variations in the metal plates under different conditions. Because the coating is formed under high-temperature, high-pressure, and intense mechanical conditions, it possesses unique characteristics, notably high hardness and excellent abrasion resistance [2]. The method of measuring the coating's abrasion resistance is based on its ability to withstand dry and sliding abrasion. Cylindrical test samples are coated with an HVOF-sprayed layer and placed in direct contact with the friction surface of a rotating disc covered with diamond abrasive paper, subjected to standard load to induce frictional force. Research on coating technologies to enhance hardness, functionality, and abrasion resistance contributes to improving product quality and economic efficiency. Authors in [3] reviewed major types of abrasive coatings, their wearing mechanisms, preparation methods, and properties, by comparing coating methods and selecting suitable coating materials. Authors in [4] studied the abrasion resistance of HVOF-sprayed coatings on SUS 400 stainless steel. They analyzed and compared the abrasion resistance of several coatings, with the statistical results indicating that WC-12Co coatings sprayed by the HVOF method exhibited higher abrasion resistance than the CrC-NiCr coatings. Additionally, the study highlighted the impact of spraying parameters on the abrasion resistance of the coating. In another study, [5], the authors emphasized that the spraying parameters affected the porosity and hardness of the coating, thereby influencing its abrasion resistance. The current research investigates and analyzes the influence of HVOF spraying parameters, such as spray F, D, and R on the abrasion resistance of the coating.

II. MATERIALS AND METHODS

A. Testing Samples

The base material used to manufacture the test specimen is 1045 steel. This steel grade is commonly employed in mechanical structures. The chemical composition of 1045 steel is presented in Table I [6].

TABLE I. THE CHEMICAL COMPOSITION OF 1045 STEEL

Steel grade	C (%)	Si (%)	Mn (%)	P (%) max	S (%) max	Cr (%)
1045	0.42/0.50	0.15/0.35	0.50/0.80	0.025	0.025	0.20/0.40

The test samples are coated with a layer of WC HMSP1060-00+60% 4070 powder, containing Nickel elements combined with Tungsten Carbide, which is known for its excellent friction and abrasion resistance, using HVOF spraying equipment, as shown in Figure 1. One of the parameters of HVOF is the spraying equipment that has a significant impact during the experimental process. Through the investigation performed, it was found that a small spray F results in a coating that is too thin, compromising the deposition efficiency when spraying from a distance. Conversely, spraying from a closer distance to ensure efficiency can lead to thermal effects. If the spray F is too high, it results in many non-melted particles, boundary cracking, and numerous non-melted regions. Therefore, to ensure a high-quality coating, a spray F where F = 15/50 g/min is recommended. The key parameters of the HVOF spraying system are F = 15/50 g/min, D = 0.15/0.5 m, R = 2/7, precision of powder feed rate (0.1 g/revolution), control-required pressure ranging from 0 Bar to 11 Bar, and adjustable pressure within ± 0.1 Bar [7, 8]. The physical properties of WC and Ni are presented in Table III. The test specimen after having undergone HVOF coating is illustrated in Figure 2.

TABLE II. THE CHEMICAL COMPOSITION OF THE WC HMSP1060-00+60% 4070 SPRAYING POWDER

Chemical composition	C (%)	Ni (%)	Fe (%)	Cr (%)	Si (%)	B (%)	WC (%)
Ratio	2.96	27.59	1.85	6.45	2	1.4	57.75

TABLE III. PHYSICAL PROPERTIES OF WC AND NI

No	Properties	WC	Ni
1	Melting temperature (°C)	2785/2830	1455
2	Module Young (GPa)	530/700	200
3	Density (g/cm^3)	15.6	8.9

Fig. 1. HVOF spray equipment.

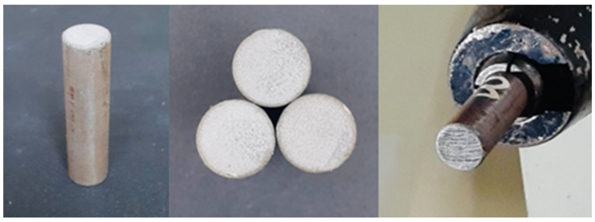

Fig. 2. The test sample after HVOF coating.

B. Testing Machine

The testing machine consists of a rotating friction disc around a fixed axis, as evidenced in Figure 3.

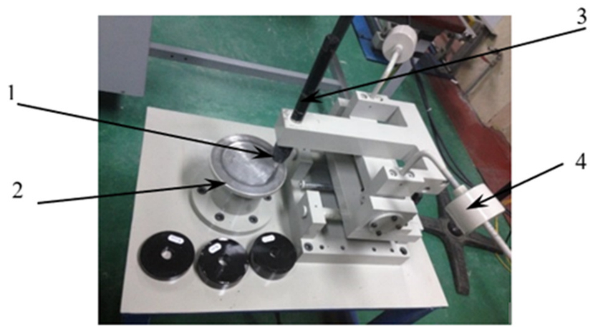

Fig. 3. The testing machine.

There are four key positions on the testing machine that require attention during the experiment. Position 1 involves a servo motor mounted to the rotating disc. The selected motor has a power output of 1 kW and a maximum rotational speed of 3000 RPM. Position 2 is the sample clamping position, capable of securing samples of up to 200 mm in length, with a clamping diameter ranging from 15 mm to 20 mm. Position 3 is the load application point, consisting of three load discs with masses of 1 kg, 2 kg, and 5 kg, respectively. Position 4 is the balancing point, which ensures that the sample remains aligned perpendicular to the disc. The test sample is mounted on the machine and subjected to an applied load to generate frictional force onto the rotating disc. During the experiment, the disc rotates, causing the contact surface between the sample and the rotating disc to wear down. The rotational speed of the rotating disc or the applied load can be adjusted throughout the experiment. The experiment is conducted to measure the change in the mass of the component undergoing abrasion over time.

C. Testing Method

The amount of abrasion is measured by the difference between the initial and post-wear masses. Based on the obtained abrasion values of the test samples, the abrasion intensity on the samples is calculated using (1) to compare the differences between the samples. The results serve as a basis for assessing the influence of each spraying parameter to determine the weight of impact. Additionally, this allows for comparing parameters and finding out which of the optimal ones is the most effective in improving the coating properties, particularly in terms of abrasion resistance.

$$I = \frac{\Delta m}{P.S} \quad (1)$$

where I is the abrasion intensity, P is the applied load, S is the length of the abrasion test path travelled by the test sample, and Δm is the weight loss degree of the sample before and after the abrasion test.

$$m = m_0 - m_1 \quad (2)$$

where m_0 and m_1 are the weights of the components before and after the abrasion test. The weight of the worn test sample is measured using an electronic scale, as shown in Figure 4.

Fig. 4. The electronic scale used to measure the weight of the test samples.

The abrasion rate of the coating caused by friction is determined by deploying the weight loss method, meaning it is calculated based on the amount of metal lost per unit time and unit area of the sample, using:

$$\rho = \frac{m_0 - m_1}{F.t} \quad (3)$$

where ρ is the abrasion rate of the coating, F is the surface area of the test sample, and t is the testing time.

If the value of Δm is too small, the measurement is prone to significant errors; in such cases, it may be necessary to conduct multiple tests to obtain an average value or extend the testing duration. The input parameters for the abrasion measurement process include the initial weight of the test sample m_0 (g), the number of revolutions of the motor n (rev/min), and the velocity of the measuring head v (m/s).

III. RESULTS AND DISCUSION

The results of measuring the mass of the samples before and after abrasion testing are provided in Table IV.

TABLE IV. MASS MEASURING RESULTS BEFORE AND AFTER ABRASION TESTING

No	F (cm^2)	t (h)	m_0 (g)	m_1 (g)
1	5.675	2.0	25.127	24.461
2	5.668	2.0	25.126	24.468
3	5.672	2.0	25.124	24.471
4	5.681	2.0	25.125	24.479
5	5.683	2.0	25.133	24.484
6	5.676	2.0	25.130	24.412
7	5.685	2.0	25.122	24.498
8	5.673	2.0	25.131	24.466
9	5.669	2.0	25.128	24.759

TABLE V. RESULTS OF MEASURING ABRASION RATE ACCORDING TO THE TAGUCHI L9 EXPERIMENTAL TABLE

No	F (g/min)	D (m)	R	ρ (g/cm^2.h) (1st)	ρ (g/cm^2.h) (2nd)	ρ (g/cm^2.h) (3rd)	$\bar{\rho}$ (g/cm^2.h)
1	25	0.2	4	0.585	0.588	0.588	0.587
2	25	0.25	5	0.572	0.578	0.590	0.580
3	25	0.3	6	0.579	0.571	0.578	0.576
4	30	0.2	5	0.559	0.575	0.573	0.569
5	30	0.25	6	0.572	0.571	0.571	0.571
6	30	0.3	4	0.633	0.629	0.634	0.632
7	35	0.2	6	0.550	0.552	0.545	0.549
8	35	0.25	4	0.585	0.585	0.587	0.586
9	35	0.3	5	0.327	0.320	0.328	0.325

The results of the abrasion rate test are designed according to the Taguchi L9 experimental table. The process parameters during HVOF spraying include F, D, and R. Each abrasion test is measured three times, and the average value of the measurements is considered. The abrasion rate measurement results are outlined in Table V. To analyze the influence of spray F, D, and R on ρ, the SN_i factor is utilized [9]:

$$SN_i = -10\log\left(\sum_{u=1}^{N_i} \frac{y_u^2}{N_i}\right) \quad (4)$$

where i = 1/9, u denotes the testing times (u = 1/3), and N_i is the number of trials for the experiment i (N_i = 3). The SN_i factors are displayed in Table VI.

TABLE VI. THE *SN* COEFFICIENTS CALCULATE THE RATE OF ABRASIVE WEAR

No	F (g/min)	D	R	ρ SN$_i$
1	25	0.2	4	4.627
2	25	0.25	5	4.731
3	25	0.3	6	4.791
4	30	0.2	5	4.897
5	30	0.25	6	4.862
6	30	0.3	4	3.986
7	35	0.2	6	5.208
8	35	0.25	4	4.647
9	35	0.3	5	9.762

The SN factor is calculated for each indicator and level as follows:

$$SN_{P1,1} = \frac{(SN_1+SN_2+SN_3)}{3} \qquad SN_{P1,2} = \frac{(SN_4+SN_5+SN_6)}{3}$$

$$SN_{P1,3} = \frac{(SN_7+SN_8+SN_9)}{3} \qquad SN_{P2,1} = \frac{(SN_1+SN_4+SN_7)}{3}$$

$$SN_{P2,2} = \frac{(SN_2+SN_5+SN_8)}{3} \qquad SN_{P2,3} = \frac{(SN_3+SN_6+SN_9)}{3}$$

$$SN_{P3,1} = \frac{(SN_1+SN_6+SN_8)}{3} \qquad SN_{P3,2} = \frac{(SN_2+SN_4+SN_9)}{3}$$

$$SN_{P3,3} = \frac{(SN_3+SN_5+SN_7)}{3}$$

The SN values for each parameter are presented in Table VII.

TABLE VII. SIGNAL FACTORS (SN) INDICATING THE DEGREE OF INFLUENCE OF THE EXPERIMENTAL PARAMETERS ON THE RATE OF ABRASIVE WEAR

Level	**ρ**		
	SN calculated for F	**SN calculated for D**	**SN calculated for R**
1	4.716	4.911	4.420
2	4.582	4.747	6.463
3	6.539	6.180	4.954
R	1.957	1.433	2.043

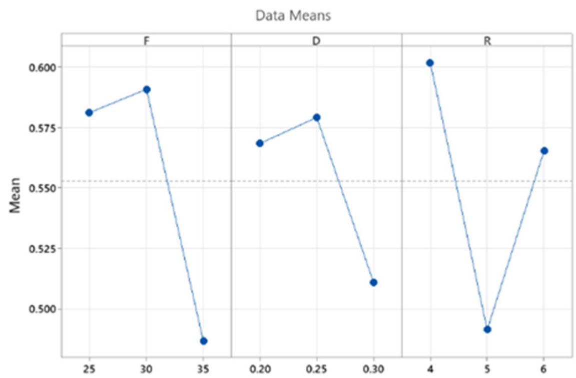

Fig. 5. Graph of the influence of each main parameter on the abrasion resistance of the coating.

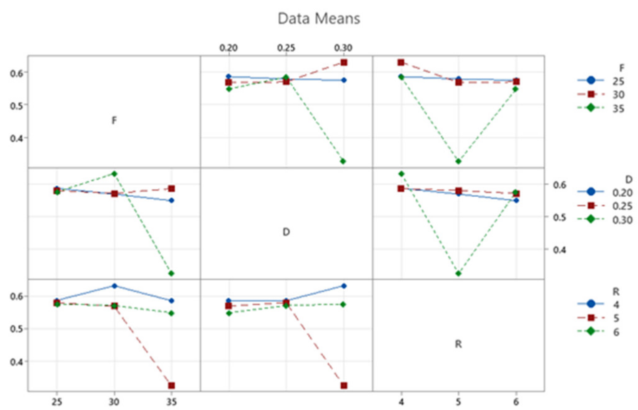

Fig. 6. Graph of the interactive effects of parameters on the abrasion resistance of the coating.

The results listed in Table VII indicate that the R has the greatest influence on the abrasion resistance of the coating, followed by the spray F and D, which have the least impact among the three parameters. Applying ANOVA analysis [10, 11] to assess the impact of each main parameter (F, D, R) and the interactive effects of the parameters on the abrasion resistance of the coating, the results were obtained and presented in Figures 5 and 6.

TABLE VIII. THE COEFFICIENTS IN THE REGRESSION EQUATION

Term	**Coefficients**	**VIF**
Constant	-3.175	
F	0.2096	533.00
D	19.51	698.00
R	-0.5828	418.00
F×F	-0.002273	433.00
D×D	-17.73	401.33
R×R	0.04583	401.33
F×D	-0.3707	246.67
F×R	0.002000	246.67

The coefficients in the regression equation and the analysis of variance are calculated as shown in Tables VIII and IX, respectively.

TABLE IX. THE COEFFICIENTS IN THE REGRESSION EQUATION

Source	**DF**	**Adj SS**	**Adj MS**
Regression	8	0.062324	0.007790
F	1	0.012368	0.012368
D	1	0.008183	0.008183
R	1	0.004876	0.004876
F×F	1	0.006460	0.006460
D×D	1	0.002948	0.002948
R×R	1	0.003151	0.003151
F×D	1	0.012881	0.012881
F×R	1	0.000150	0.000150
Error	0	0.000000	
Total	8	0.062324	

The mathematical equation representing the relationship between the wear rate of the coating and the spray process parameters is constructed and expressed as:

$$\rho = -3.175 + 0.2096F + 19.51D - 0.5828R - 0.0023F^2 - 17.73D^2 + 0.0458R^2 - 0.3707F{\times}D + 0.002F \times R \qquad (5)$$

The graphs representing each relationship between the parameters are illustrated in Figure 7.

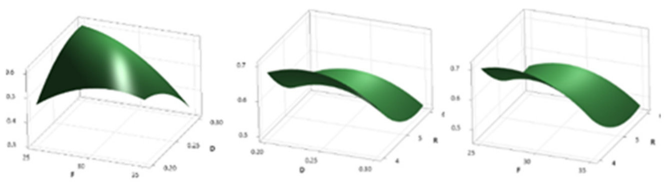

Fig. 7. The graphs represent the relationship between ρ and each pair of HVOF coating spray process parameters.

The data presented in Figures 5-7, and (5) reveal a type of correlation: increasing F from 25 g/min to 30 g/min results in elevated abrasion, whereas an increase from 30 g/min to 40 g/min leads to a reduction in abrasion. Similarly, elevating D from 0.2 m to 0.25 m correlates with increased abrasion, whereas an increase from 0.25 m to 0.3 m corresponds to decreased abrasion. For R, an increase from 4 to 5 results in reduced abrasion, whilst an increase from 5 to 6 leads to an increase in abrasion. A significant interaction is observed between F and D, a minor interaction between F and R, and no interaction between D and R. Optimizing the spray parameters, specifically, F3D3R2 (spray F = 35 g/min, D = 0.3 m, and R = 5), enhances the abrasive resistance of the HVOF-coated layer, contributing to extended working longevity and improved product quality for the lowest wear rate.

IV. CONCLUSIONS

This study investigated and subsequently analyzed the influence of spray process parameters, including spray Flow Rate (F), Spray Distance (D), and Oxygen/Propane Ratio (R), on the structure and hardness of the WC HMSP1060-00+60% 4070 coating on the surface of samples made of 1045 steel. The results revealed that R has the greatest impact on the wear rate of the coating, followed by spray F, with D having the least influence. The optimal values for the spray parameters are F = 35 g/min for the F, D = 0.35 m for D, and R = 5 for R, resulting in the lowest wear rate and consequently the highest abrasion resistance. These analyses will assist in selecting suitable spraying parameters, capable of achieving the lowest wear rate, thereby enhancing the abrasion resistance and improving the working lifespan of the High Velocity Oxygen Fuel (HVOF) coating under high loads and significant friction.

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