OPTIMIZATION OF HVOF SPRAY PARAMETERS FOR WC-CO-CR COATINGS ON AMMC (AL-RHA) FOR PUMP IMPELLER PROTECTION

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Varsha Pathak*, Delhi Technological University, India, **R S Mishra,** Delhi Technological University, India and **Ranganath MS**, Delhi Technological University, India

* Corresponding author. Varsha Pathak (Email): varshapathakdtu@gmail.com

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SUMMARY

Present study investigates the enhancement of pump impeller materials using aluminium matrix composites (AMCs), specifically focusing on Al 7075 Alloy strengthened with rice husk ash (RHA) for enhanced durability and resistance to corrosion. It employs Thermal spraying using high-velocity oxygen-fuel (HVOF) to apply WC-Co-Cr powder, emphasizing low porosity, high adherence, and superior wear and corrosion resistance. By optimizing HVOF spray parameters using Taguchi L25 Orthogonal array, the research aims to minimize porosity and maximize hardness, addressing challenges in material dispersion, sustainability, and process control. The objective is to develop predictive models for the microhardness and porosity characteristics of WC–10Co–4Cr coating powder utilized through HVOF on AMMC substrates. AMMC substrates. Spray distance, carrier gas flow rate, powder feed rate, oxygen flow rate, and LPG flow rate are examined, with spray distance exerting the most significant influence on porosity, followed by powder feed rate and other parameters. This study contributes to improving coating characteristics crucial for industrial applications.

KEYWORDS

Aluminium matrix composites, Rice husk ash (RHA), High-velocity oxy-fuel (HVOF), Taguchi L25 orthogonal array

NOMENCLATURE

Lpm	Litre per minute
Gpm	Gram per minute
RHA	Rice husk ash
HVOF	High velocity oxyfuel coating
AMMC	Aluminium metal matrix composite
MMC	Metal matrix composite
OFR	Oxygen flow rate
LFR	LPG flow rate
SD	Spray distance
CGFR	Carrier gas flow rate
P	Parameter
R	rank
L	level
Range	Max-Min

1. INTRODUCTION

Pump impellers represent critical components in fluid handling systems, requiring materials that offer high durability, corrosion resistance, and mechanical strength. Metal matrix composites (MMCs) emerge as promising solutions for enhancing the performance and longevity of pump impellers across various industries. By incorporating reinforcement materials such as metals, ceramics, or organic compounds, MMCs offer improved wear, fatigue, and thermal properties compared to base materials [1-3]. Among MMCs, aluminium matrix composites (AMCs) are highly regarded for their balance of attributes, encompassing a strong weight-to-strength ratio and resistance to wear and precise thermal expansion coefficients. Aluminium alloys, such as Al-7075, exemplify the versatility and effectiveness of AMCs for manufacturing pump impellers because of their low weight, robust stiffness, and superior mechanical qualities, coupled with excellent resistance to corrosion [4-6]. Stir casting is a key method for efficiently producing high-performance MMCs, although achieving uniform reinforcement distribution remains a challenge [2,5,11]. Furthermore, agricultural residues like rice husk (RH) present opportunities for sustainable material development. RH, with its renewable energy potential and value-added byproducts, offers a viable source for composite materials. Specifically, the Al-3.7%Cu-1.4%Mg/1.5%wtRice husk ash (RHA) nanoparticles composite, produced using modified stir casting, demonstrates promising strength and corrosion resistance for pump impeller applications [1,7]. Aluminium alloys require protection from corrosion, often achieved through treatments like plasma electrolytic oxidation or HVOF thermal spraying. HVOF stands out for creating coatings that are hard, dense, and minimally oxidized, offering better protection than plasma spraying. This method's effectiveness is due to its use of high-velocity flames and the efficient combination of particle kinetic and thermal energies, resulting in coatings with superior hardness, adhesion, and resistance to corrosion and wear [15-18]. The WC-Co-Cr coatings, implemented via HVOF technology, are renowned for their efficacy in safeguarding machinery from wear and corrosion. This method's high kinetic energy results in coatings that are dense, offering enhanced mechanical characteristics like hardness and toughness, resistance to erosion and abrasion. The low porosity content (about 1%) and minimal oxidation of these cermet coatings, compared to those produced by other thermal spray methods, are attributed to HVOF's high velocity and relatively low flame temperature [8-10,13,21]. The effectiveness of WC-Co-Cr coatings is significantly affected through the mechanical characteristics they possess and microstructural properties, including Hardness, porosity, and the presence of cracks and impurities are dictated by the dimensions, quantity, and arrangement of WC phases, along with composition and dispersion belonging to the Co binder phase and the metallurgical bonding between WC, Co and Cr. Additionally, the residual stress state within the coatings plays a crucial role in their tribo-mechanical properties. Advanced coating techniques enable the creation of WC-12Co coatings with fine structures, near-net shapes, and very low porosity [13,17,20]. The HVOF coating technique's effectiveness depends on various operational parameters that influence coating formation, microstructure, and mechanical properties. Understanding and controlling these parameters are crucial for achieving optimal thickness, minimizing porosity, ensuring adhesion and cohesion among layers, and preserving mechanical properties. Imperfections like pores and cracks affect coating performance, emphasizing the need for parameter optimization. Variables For example, the distance of spraying, flow rates, and powder feed rate ascertain coating quality, making process control challenging. Research focuses on optimizing deposition processes to enhance coating properties and reproducibility [14,18,19]. Researchers globally use Taguchi optimization technique to model thermal spraying processes, identifying key parameters for enhanced coating properties. Through DOE, researchers integrate a scientific approach into HVOF spraying, enhancing understanding and control of coating processes [20,22,26]. The areas needing further exploration within materials and coating technologies for pump impellers and machinery components involve difficulties in ensuring even dispersion of reinforcements in MMCs, maximizing the utilization of sustainable materials such as rice husk, deeper comprehension of HVOF coating efficacy, and refining optimization techniques like Taguchi to enhance control and repeatability. Bridging these gaps promises to yield more effective and environmentally friendly solutions for fluid handling systems and machinery components. The goal of the study is to fine-tune HVOF spray parameters to achieve optimal coating outcomes, establishing empirical connections to forecast minimal porosity and maximal hardness. Furthermore, the optimization approach integrates essential HVOF spray variable that is the rate of oxygen flow, The flow rate of LPG, spray distance, powder feed rate, and carrier gas flow rate—for comprehensive enhancement. Limited research has been conducted to explore the connection amid HVOF spraying conditions with the characteristics of coating that emerges like porosity and hardness. Therefore, this study aims to establish empirical formulas that can predict the degree of porosity and the hardness exhibited by WC–10Co–4Cr coatings applied through HVOF spraying. on AMMC (Aluminium-Rice Husk Ash) substrates. To achieve the optimal coating hardness and minimize porosity, a L25 orthogonal array designed by Taguchi was employed to fine-tune the HVOF spraying parameters.

2. METHODOLOGY EMPLOYED

2.1 MATERIALS

The utilization of Al 7075 as a matrix and rice husk ash (RHA) as a reinforcement in creating aluminium matrix composites (AMMCs) is strategically chosen to harness the superior mechanical properties of Al 7075, such as high durability and resilience, while capitalizing on the sustainability and cost-effectiveness of RHA. RHA, an eco-friendly and economical by-product of rice processing, not only addresses environmental concerns by repurposing agricultural waste but also enhances the composite's properties, including wear resistance, thermal stability, and hardness [23-24]. This combination aims to produce lightweight, high-performance, and cost-efficient materials suited for demanding applications for pump impeller protection. As shown in figure 1, AMMC was prepared through the use of stir casting set up.

2.2 SPRAY PROCESS AND METHODOLOGY

For the application of coatings on the Al-RHA aluminium matrix composites, the selected material was a commercially sourced 86WC-10Co-4Cr cermet powder. The deposition process employed was the HVOF (High Velocity Oxygen Fuel) technique, utilizing a Diamond Jet 2700 Sulzer Metco spraying device. The procedure incorporated nitrogen as the carrier gas and hydrogen as the combustion fuel to ensure the effective application of the cermet coating onto the composite surface. For each coating condition, the thickness was meticulously measured using a digital micrometre, revealing a variation in the coating thickness that ranged from 300 μm to 400 μm.

2.3 POROSITY TEST AND MICROHARDNESS MEASUREMENT

For porosity specimens were prepared by polishing with emery sheets. Examining porosity in a WC-Co-Cr coated substrate was done using the AXIOVERT A1 metallurgical microscope by Carl Zeiss, with magnifications ranging from 100x to 1000x. This procedure involved preparing and assessing the sample to detect and measure porosity.

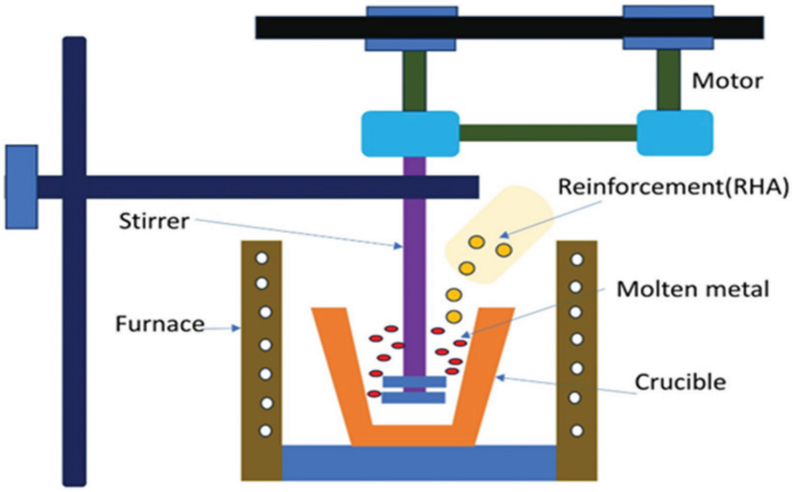

Figure 1. Schematic figure of stir casting set up

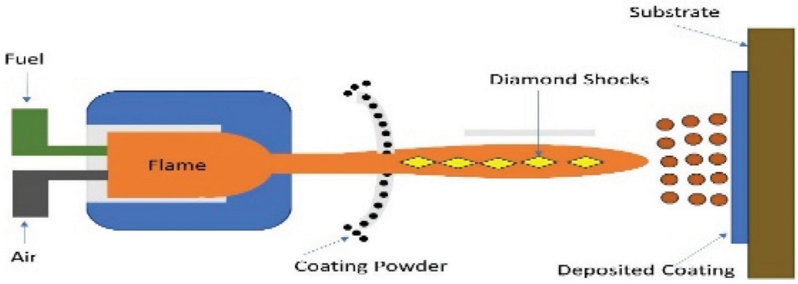

Figure 2. Schematic figure of HVOF coating deposition

The coated specimens were subjected to microhardness testing. Porosity and hardness are critical attributes of coatings for applications involving wear and corrosion resistance, significantly affecting the components' lifespan. In the procedure of HVOF spraying, factors like the rate of oxygen flow, the flow rate of LPG, the rate at which powder is fed, and the distance of spraying play crucial roles in deciding the ultimate characteristics of the coatings. The adjustments in these spraying parameters can markedly impact the properties of the coatings, including their porosity and hardness. Specifically, in WC-Co-Cr coatings, the WC (Tungsten Carbide) particles are primarily responsible for enhancing the coating's hardness [20,27,38]. Achieving low porosity in coatings is crucial for enhancing their abrasion resistance. A reduction in porosity and micro-cracks within the coating typically results in a rise in hardness. Furthermore, the microhardness of a coating is highly responsive to its porosity level, with lower porosity often resulting in greater microhardness. Essentially, porosity exerts a significant impact on the microhardness of coatings [28-30].

2.4 DESIGN OF EXPERIMENTS BY TAGUCHI

Numerous studies highlight the significant impact of spray conditions on the microscopic arrangement and functionality of carbide coatings. The optimization of process parameters in thermal spraying is crucial due to its complexity and the effect of parameter combinations on coating quality. By optimizing spray conditions through specialized Tools and statistical techniques experimental design (DoE), enhancements in both the economic efficiency (increased deposition rates) and the mechanical characteristics of materials. (improved microhardness and reduced porosity) of the spray process can be realized. Such optimization also contributes to the rise in microhardness observed in finely structured

Table 1. HVOF coating variables and their values

No.	P	L1	L2	L3	L4	L5
1.	OFR lpm	242	246.0	250.0	254	258.0
2.	LFR lpm	52.0	56.0	60.0	64.0	68.0
3.	PFR gpm	30.0	34.0	38.0	42.0	46.0
4.	SD mm	220	224.0	228.0	232	236.0
5.	CGFR lpm	13.0	14.0	15.0	16.0	17.0

coatings. The impact of different spraying techniques and parameters on coating improvements varies across different types of coatings [13,33,36,39]. For getting high microhardness and low porosity value, HVOF spray parameters oxygen flow rate [35], spray distance [32], LPG flow rate, powder feed rate, carrier gas flow rate was chosen [20,31]. In previous research, it was found that the properties of WC-Cr_3C_2-12Ni HVOF coatings, including microhardness was affected by the rate of oxygen flow as well as proportion of Cr_3C_2. The study also highlighted that notable improvements in hardness could be achieved by employing a shorter stand-off distance and a lower fuel flow rate in the HVOF spraying process [37,40]. in accordance with the information presented in the table 1, five values were taken for all the five variables.

3. RESULT AND DISCUSSION

As shown in table 2, experimental values of porosity and microhardness are mentioned respectively for all the 25 runs.

Table 2. Experimental values of porosity and microhardness.

No.	OFR lpm	LFR lpm	PFR gpm	SD mm	CGFR lpm	P vol%	MH HV 0.3
1.	242	52	30	220	13	2.84	840.00
2.	242	56	34	224	14	1.89	1117.20
3.	242	60	38	228	15	1.90	999.60
4.	242	64	42	232	16	1.65	1269.45
5.	242	68	46	236	17	3.36	840.00
6.	246	52	34	228	16	2.96	908.25
7.	246	56	38	232	17	1.69	1183.35
8.	246	60	42	236	13	1.85	1253.70
9.	246	64	46	220	14	3.11	897.75
10.	246	68	30	224	15	1.33	1342.95
11.	250	52	38	236	14	2.83	899.85
12.	250	56	42	220	15	2.09	1264.20
13.	250	60	46	224	16	3.56	779.10
14.	250	64	30	228	17	3.23	779.10
15.	250	68	34	232	13	3.32	790.65
16.	254	52	42	224	17	2.75	1074.15
17.	254	56	46	228	13	3.25	801.15
18.	254	60	30	232	14	1.20	1245.30
19.	254	64	34	236	15	3.25	773.85
20.	254	68	38	220	16	2.09	1065.75
21.	258	52	46	232	15	1.80	1219.05
22.	258	56	30	236	16	3.26	924.00
23.	258	60	34	220	17	2.09	1116.15
24.	258	64	38	224	13	3.24	934.50
25.	258	68	42	228	14	1.55	1286.25

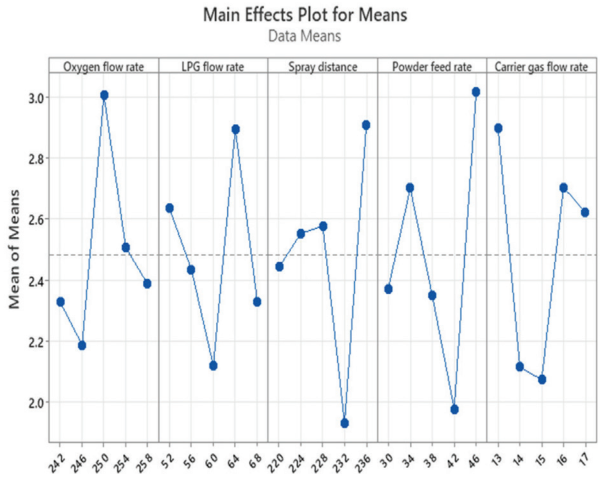

Figure 3. Graph illustrating the relationship between HVOF spray parameters and porosity mean values (Main effect plot for means)

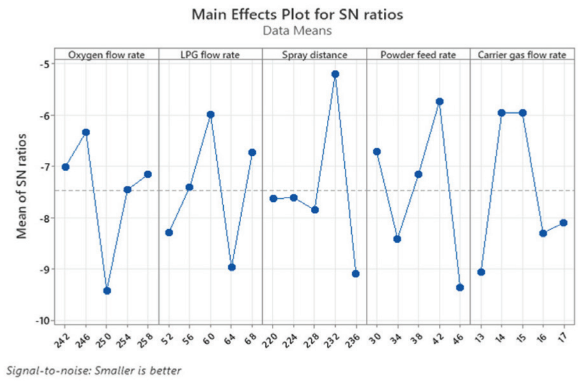

Figure 4. A main effect plot depicting the relationship between HVOF spray parameters and Signal-to-Noise ratios concerning porosity

3.1 RESULT AND DISCUSSION FOR MINIMUM POROSITY

In Taguchi analysis, the objective is to minimize porosity in the developed coating by optimizing the process using the “Smaller the better” quality criterion. Figure 3 illustrates how porosity correlates with various HVOF spraying variables for instance, the rate of oxygen flow, powder feed rate, spraying distance, carrier gas flow rate, and LPG flow rate, utilizing the Taguchi method. The mean value is depicted by the horizontal mark line.

Examining the outcomes of figure 3 and figure 4, it was deduced that for the WC-Co-Cr coatings deposited, the lowest porosity occurred at an oxygen flow rate of 246 lpm. Additionally, the minimum porosity was observed at a spraying distance of 232 mm, with the powder feed rate set at 4.2 gpm and the carrier gas flow rate at 15 lpm. Moreover, the lowest porosity was achieved with an LPG flow rate of 56 lpm.

Table 3. S/N ratio response regarding porosity

P	Mean S/N Ratio (db.)						
	L1	L2	L3	L4	L5	Range	R
OFR	-7.09	-6.33	-9.41	-7.45	-7.16	3.08	4
LFR	-8.28	-7.39	-5.98	-8.96	-6.72	-2.98	5
SD	-7.62	-7.60	-7.84	-5.23	-9.08	-3.87	1
PFR	-6.71	-8.40	-7.15	-5.74	-9.35	3.61	2
CGFR	-9.05	-5.96	-5.96	-8.29	-8.02	3.09	3

Table 3 indicates that among the parameters examined, spray distance exhibits the most significant influence on porosity, followed by powder feed rate, carrier gas flow rate, oxygen flow rate, and LPG flow rate, in descending order of impact.

Figure 5 depicts a contour map illustrating the relationship between coating porosity and two influential parameters: oxygen flow rate with LPG flow rate. It also showcases the ideal conditions for oxygen flow rate and LPG flow

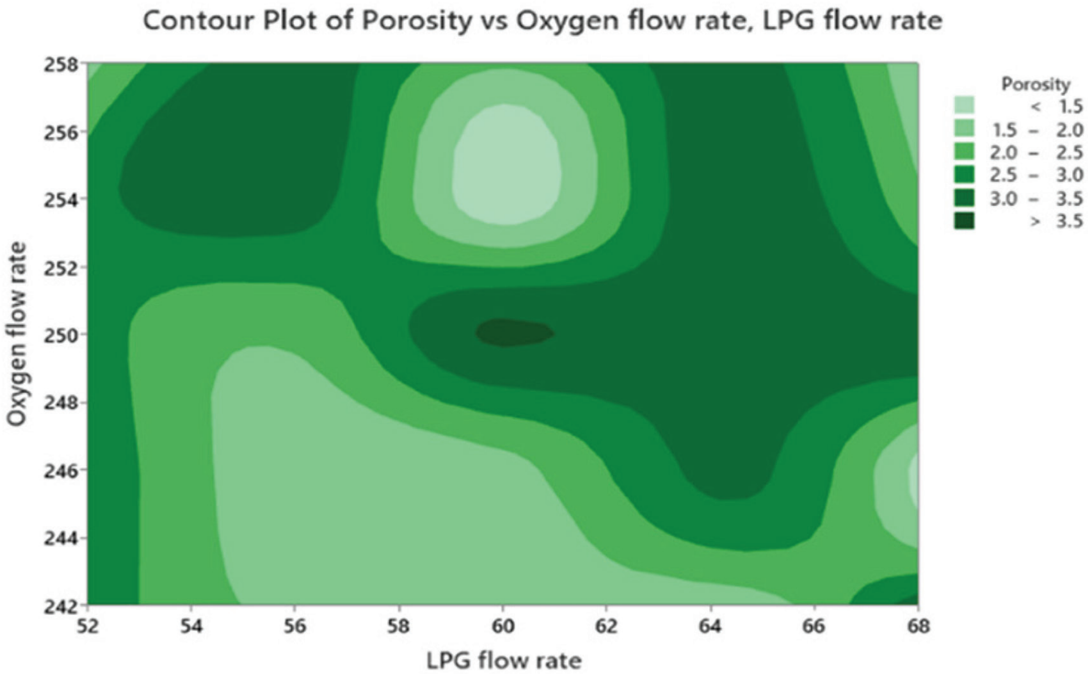

Figure 5. A contour map illustrating the variation of porosity percentage in the developed coating concerning changes in both the oxygen flow rate & LPG flow rate

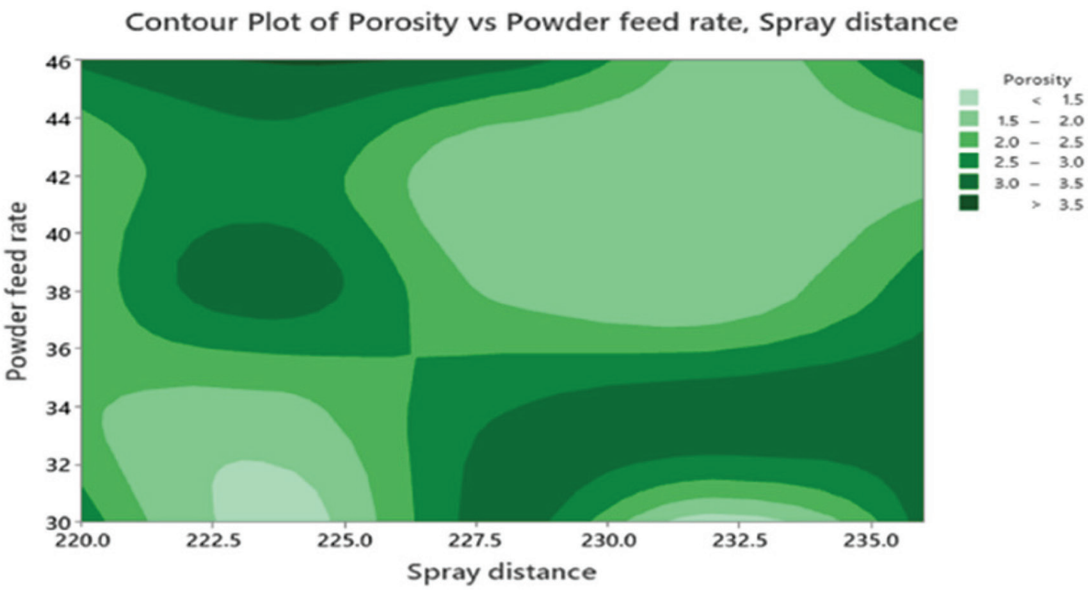

Figure 6. A contour map illustrating the variation of porosity percentage in the developed coating concerning Alterations in both the powder feed rate and the spray distance

rate based on porosity levels. To achieve a low degree of porosity, it is advisable to utilize a higher oxygen flow rate (above 252 lpm) along with a moderate LPG flow rate (ranging between 59 lpm to 62 lpm).

Table 4. Displaying the S/N ratio response for microhardness

P	Mean S/N Ratio (db.)						
	L1	**L2**	**L3**	**L4**	**L5**	**Max-min**	**R**
OFR	60.00	60.84	58.95	59.79	60.72	1.89	2
LFR	59.81	60.37	60.53	59.23	60.35	1.30	5
SD	60.22	60.28	59.45	61.02	59.32	1.70	3
PFR	60.02	59.36	60.10	61.78	59.04	2.74	1
CGFR	59.18	60.64	60.82	59.79	59.87	1.64	4

Figure 6 depicts a contour map illustrating the correlation between coating porosity and two influential variables: powder feed rate & Spray distance. It also showcases the ideal conditions for powder feed rate with Spray distance based on porosity levels. To achieve a low degree of porosity, it is advisable to utilize low powder feed rate (below 32 gpm) along with a moderate spray distance (ranging from 222.5 mm to 225 mm).

3.2 RESULT AND DISCUSSION FOR MAXIMUM HARDNESS

In Taguchi analysis, the aim is to achieve maximum microhardness in the coating through optimization, utilizing the "higher the better" quality criterion.

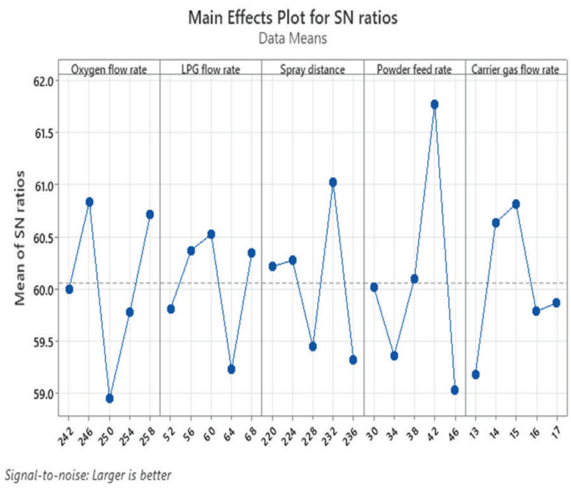

Figure 7. A main effect plot depicting the connection between HVOF spray parameters and Signal-to-Noise ratios regarding microhardness

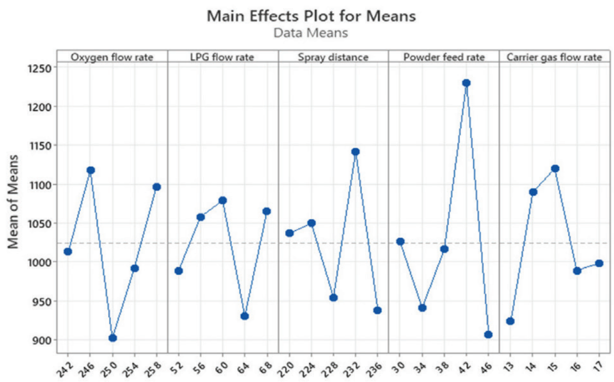

Figure 8. A main effect plot illustrating the relationship associated with HVOF spray variables and means concerning microhardness

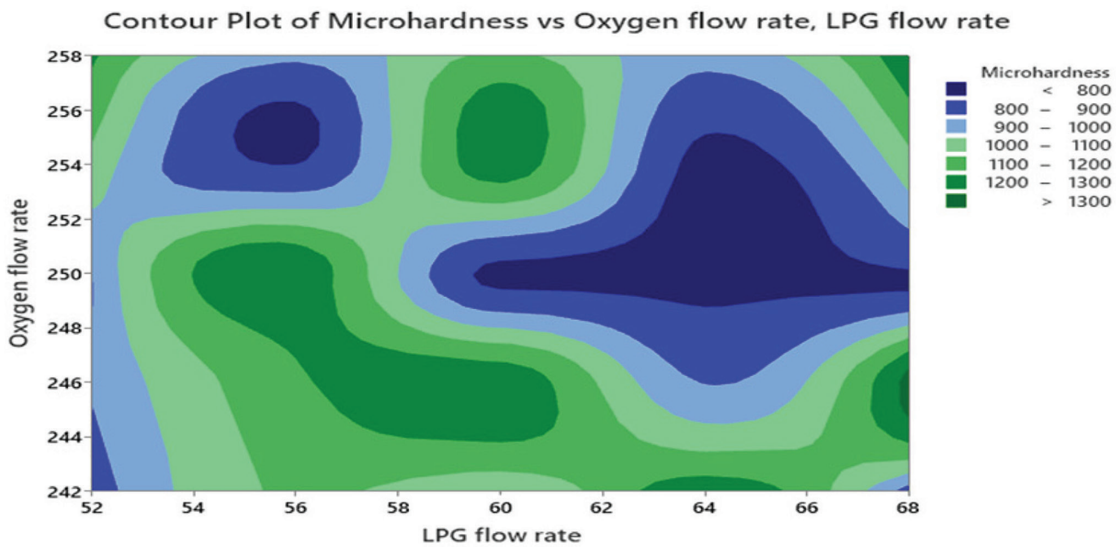

Figure 9. A contour map illustrating the variation of porosity percentage in the developed coating concerning changes in both the oxygen flow rate & LPG flow rate

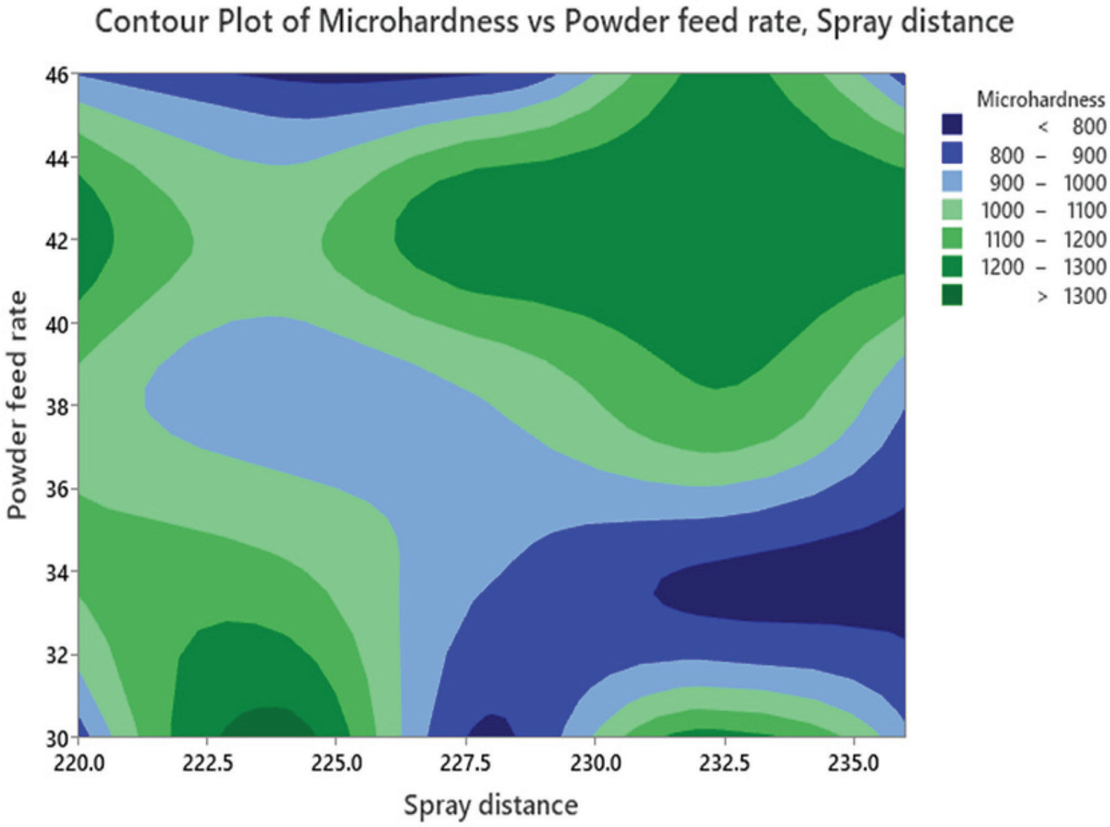

Figure 10. A contour map illustrating the variation of porosity percentage in the developed coating concerning variations in both the powder feed rate & spray distance

Table 4 illustrates that the powder feed rate emerges as the most significant variable for achieving maximum hardness, followed by the oxygen flow rate, spray distance, carrier gas flow rate, and finally, the LPG flow rate.

Examining the outcomes of figure 7 and figure 8, it was deduced that for the WC-Co-Cr coatings deposited, the highest microhardness occurred at an oxygen flow rate of 246 lpm. Additionally, the maximum microhardness was observed at a spraying distance of 232 mm, with the powder feed rate set at 4.2 gpm and the carrier gas flow rate at 15 lpm. Moreover, the Higher microhardness was achieved with an LPG flow rate of 60 lpm.

Figure 9 depicts a contour map illustrating the relationship between coating microhardness and two influential variables: oxygen flow rate & LPG flow rate. It also showcases the ideal conditions for oxygen flow rate and LPG flow rate based on microhardness levels. To achieve a high degree of microhardness, it is advisable to utilize a higher oxygen flow rate (above 248 lpm) along with a short LPG flow rate (within range from 54 lpm to 58 lpm) and higher LPG flow rate within range from 60 lpm to 68 lpm.

Figure 10 depicts a contour map illustrating the Association between coating microhardness and two influential parameters: powder feed rate & Spray distance. It also showcases the ideal conditions for powder feed rate and Spray distance based on microhardness levels. To achieve a high degree of microhardness, it is advisable to utilize low powder feed rate (below 34 gpm) or very high powder feed rate above 46 gpm along with a higher spray distance (more than 231 mm).

4. CONCLUSION

The analysis of the experimental results reveals important insights into the factors influencing both porosity and microhardness in WC-Co-Cr coatings. For achieving a high degree of microhardness, optimal conditions involve utilizing either a low or very high powder feed rate along with a higher spray distance. Furthermore, higher oxygen flow rates paired with short LPG flow rates or moderately high LPG flow rates contribute to increased microhardness. Conversely, to minimize porosity, it is recommended to utilize low powder feed rates with moderate spray distances, along with higher oxygen flow rates and moderate LPG flow rates. Specifically, the lowest porosity was observed at an oxygen flow rate of 246 lpm, with the minimum observed at a spraying distance of 232 mm, a powder feed rate of 4.2 gpm, and a carrier gas flow rate of 15 lpm. The lowest porosity was further achieved with an LPG flow rate of 56 lpm. Among the parameters studied, spray distance emerges as the most influential factor affecting porosity, followed by powder feed rate, carrier gas flow rate, oxygen flow rate, and LPG flow rate, in descending order of significance. Conversely, the powder feed rate is the most influential parameter for achieving maximum microhardness, followed by the oxygen flow rate, spray distance, carrier gas flow rate, and LPG flow rate. In conclusion, optimizing HVOF spraying parameters is crucial for enhancing the properties of WC-Co-Cr coatings, with specific combinations yielding superior microhardness and minimal porosity, contributing to improved performance and durability in various industrial applications.

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