APPLICATION OF THERMAL SPRAY TECHNOLOGY IN THE REFURBISHMENT OF AUTOMOTIVE CAMSHAFT COMPONENTS

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ABSTRACT

This paper presents the research results on the application of High-Velocity Oxy-Fuel (HVOF) thermal spray technology for the refurbishment of automotive camshaft components manufactured from 40Cr steel using WC-12Co cermet coatings, as an environmentally friendly alternative to conventional hard chromium electroplating. The study employs the Taguchi experimental design method based on an L9 orthogonal array to evaluate the effects of key process parameters, including powder feed rate (m), rotational speed of the workpiece (n) and spray gun traverse distance (S), on the adhesion strength of the coating. The results indicate that the maximum adhesion strength of 72.8MPa was achieved under the optimal process conditions (m = 32g/min, n = 100rpm, S = 8mm/rev). Microstructural analysis using SEM confirms that the coating exhibits a dense lamellar structure with low porosity (< 1%), where the dominant bonding mechanism is mechanical interlocking combined with metallurgical diffusion at the coating-substrate interface. The study demonstrates the high feasibility of HVOF spraying technology in enhancing the service life and functional performance of refurbished camshafts, meeting the stringent requirements of the automotive industry.

Keywords: *HVOF thermal spraying, WC-12Co, automotive camshaft, 40Cr steel, adhesion strength, process optimization.*

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1. INTRODUCTION

In automotive engines, the camshaft is a critical component of the valve train mechanism, responsible for precisely controlling the opening and closing of valves in accordance with the engine operating cycle. The quality and geometric accuracy of the camshaft directly affect the intake and exhaust processes, engine power, fuel consumption, and overall durability of the engine [1, 2]. During service, the cam lobe surface operates under high contact loads, repeated sliding friction against the follower, is subjected to high Hertzian contact stresses, and is exposed to a complex lubricating environment [3]. Numerous studies have shown that deterioration of lubrication quality or the presence of abrasive particles in the oil can rapidly increase wear rates and contact fatigue of the cam surface [4]. Therefore, the camshaft is considered one of the components most susceptible to damage during the service life of an automotive engine [5].

Common failure modes of camshafts include wear leading to a reduction in cam lobe height and profile deviation, pitting and spalling due to contact fatigue, as well as degradation of geometric accuracy caused by non-uniform wear [6, 7]. These failures result in valve timing deviations, increased vibration and noise, thereby reducing engine performance and reliability [2, 8]. In practice, complete replacement of the camshaft is often costly and increases the amount of mechanical waste, which is not consistent with the trend toward efficient resource utilization and sustainable development in the modern automotive industry [9].

Currently, conventional repair methods such as hardfacing welding and hard chromium plating are still applied for camshaft restoration. However, hardfacing welding often induces significant thermal distortion, forms undesirable heat-affected zone microstructures, and degrades the mechanical properties of the substrate, especially for components operating under high contact loads [10]. Meanwhile, hard chromium plating suffers from limitations in adhesion, the formation of microcracks in the plated layer, and, most critically, serious environmental pollution issues associated with the use of toxic Cr^{6+}-containing solutions [11]. These drawbacks have driven the research and development of more advanced surface restoration technologies.

Thermal spray technology is considered an effective solution for the repair and remanufacturing of mechanical components due to its ability to produce thick functional coatings, good control of the heat-affected zone, and flexibility in coating material selection [12]. In particular, high-velocity oxy-fuel (HVOF) spraying enables the deposition of coatings with high density, low porosity, strong adhesion, and superior wear resistance, and is regarded as an environmentally friendly alternative to hard chromium plating in many industrial applications [13, 14]. On this basis, this paper focuses on investigating the applicability of HVOF spraying technology for the restoration and remanufacturing of automotive camshafts, aiming to evaluate coating quality and the technical-economic effectiveness of the solution under practical application conditions.

2. LITERATURE REVIEW

2.1. Wear mechanisms of automotive camshafts

The wear mechanisms of automotive camshafts mainly arise from repeated sliding friction and high contact loads between the cam lobes and the followers, causing surface deformation and progressive wear over time. Experimental studies on camshafts indicate that surface wear and contact fatigue are the dominant mechanisms, in which fatigue cracks initiated under repeated Hertzian stresses lead to pitting and spalling on the cam lobes [15]. In addition, inadequate lubrication conditions increase direct contact between surface asperities, thereby intensifying frictional wear [16]. Factors such as lubricant composition, additives, and operating conditions also have a significant influence on the wear rate and characteristics of camshafts [15].

2.2. HVOF spraying technology

High-velocity oxy-fuel (HVOF) spraying is an advanced thermal spray technique widely used to enhance the surface performance of mechanical components subjected to wear and heavy loads. In the HVOF process, a mixture of oxygen and fuel is combusted in a reaction chamber to generate a high-pressure, high-velocity gas jet, which heats and accelerates coating powder particles toward the component surface at very high velocities. As a result, dense coatings with low porosity and superior adhesion compared to conventional spraying methods are formed [17]. Studies have shown that HVOF coatings exhibit outstanding wear resistance, corrosion resistance, and load-bearing capability due to the effective combination of thermal energy and high kinetic energy of the sprayed particles, which reduces defects and improves durability under severe service conditions [17]. Control of spraying parameters such as oxygen flow rate, spray distance, and particle velocity is critical to coating quality, including hardness, adhesion strength, and wear-resistant performance [18].

3. MATERIALS, EQUIPMENT, AND RESEARCH METHODS

3.1. Materials

Substrate material: The substrate material used in this study is 40Cr steel, whose mechanical properties and chemical composition are presented in Table 1 and Table 2.

Table 1. Chemical composition of 40Cr steel (Unit: %)

Steel grade	C	Si	Mn	Cr	Ni	Other ingredients
40Cr	0.36~0.44	< 0.4	< 0.80	0.8~1.1	≤ 0.3	-

Table 2. Mechanical properties of 40Cr steel

Steel grade	Heat treatment state	Mechanical properties			HB hardness
		σ_k (MPa)	σ_{ch} (MPa)	δ (%)	
40Cr	Normalization	980	785	9	217

The test specimens were fabricated according to the cam lobe profile, as shown in Figure 1. A total of nine specimens were prepared in this study.

Coating material: The coating material used in the experimental process was WC-12Co alloy powder supplied by PAC Powder Alloy (USA). The powder had a spherical morphology with particle sizes ranging from 5 to 45µm. Its composition consisted of 88% tungsten carbide (WC) and 12% cobalt (Co), providing high wear resistance.

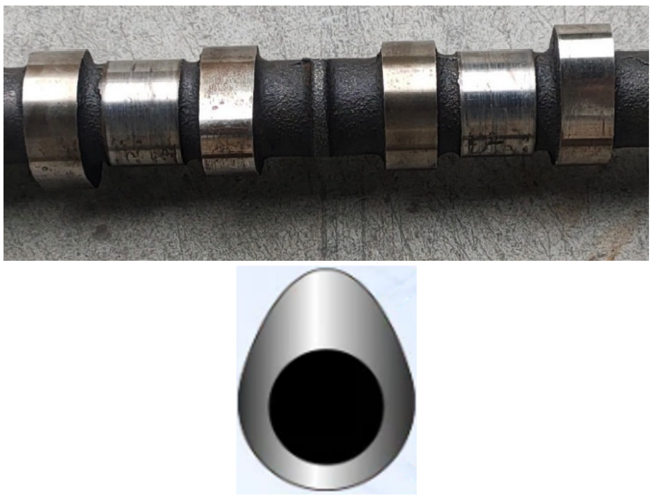


Figure 1. Cam lobe

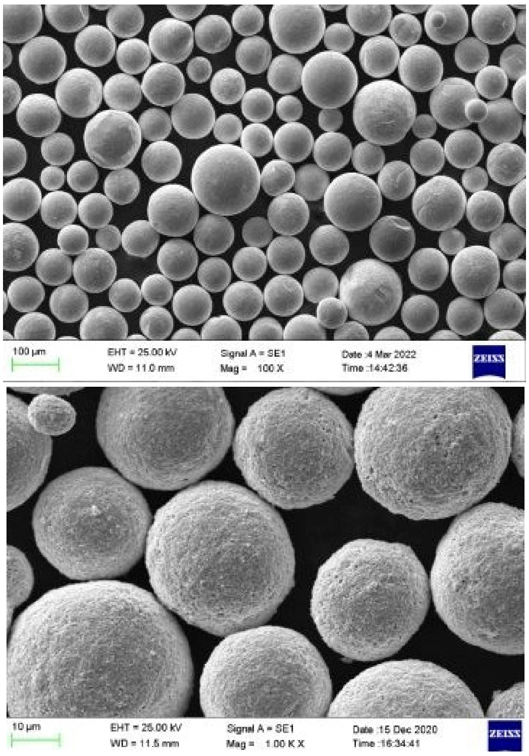


Figure 2. WC-12Co spray powder

3.2. Equipment

The equipment used in the experimental spraying process was an HVOF system Model MP-2100 Manual HVOF Control Panel supplied by Metallizing Equipment Co. Pvt. Ltd., Jodhpur, India. The spraying system comprised:

- Gas supply system (oxygen, propane, and compressed air);
- Powder feeder PF-3350;
- MP-2100 flow control panel;
- HVOF spray gun HP-2700-M;
- Auxiliary equipment.

The technical specifications of the HVOF spraying system are presented in Table 3 and were maintained constant throughout the spraying process.

Table 3. Technical specifications of the HVOF spraying system

Exp. number	Gas	Flow (LPM)	Pressure (kg/cm^2)
1	Oxy	250 - 350	10.0
2	LPG/Propane	60 - 80	07.0
3	Compressed air	600 - 700	07.0

The selection of spraying parameters was based on theoretical analysis of the HVOF spraying process combined with the research results reported by previous authors [19-22], in peer-reviewed journals and scientific reports, in order to determine the appropriate parameter ranges for the experimental study. Accordingly, the spraying parameters considered included the powder feed rate (m), the rotational speed of the workpiece (n), and the traverse speed of the spray gun (S). Each parameter was investigated at three levels, and the corresponding values were arranged according to the Taguchi L9 orthogonal array. The experimental spraying matrix and the resulting adhesion strength values are presented in Table 4.

Table 4. Taguchi L9 orthogonal array

Exp. number	Spray parameters			Results
	m (g/min)	n (rpm)	S (mm/rev)	Adhesion (MPa)
1	30	62.1	4	62.1
2	30	71.6	6	71.6
3	30	69.5	8	69.5
4	32	66.6	6	66.6
5	32	72.8	8	72.8
6	32	66.9	4	66.9
7	34	61.6	8	61.6
8	34	64.7	6	64.7
9	34	62.3	4	62.3

3.3. Research Methods

Coating Microstructure Analysis by SEM: To evaluate the coating microstructure, a scanning electron microscope (SEM/EDX) Jeol 6490 JMS JED 2300 (Japan) was used (Figure 3) to capture cross-sectional SEM images of the coating at the interface between the coating and the substrate. The obtained images provided the basis for assessing the coating quality and the distribution of its constituent phases.

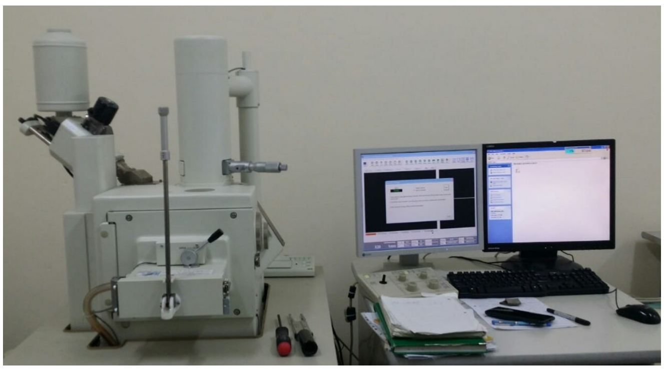


Figure 3. Jeol 6490 SEM/EDX/EDS imaging device

Coating Adhesion Strength: To ensure the accuracy of the experimental results, the fixture for the coating adhesion test specimens was designed as shown in Figure 4. A tensile-compression testing machine (MTS-809), combined with a computer system and dedicated software, was used to automatically generate the characteristic curve representing the applied tensile force, as illustrated in Figure 5.

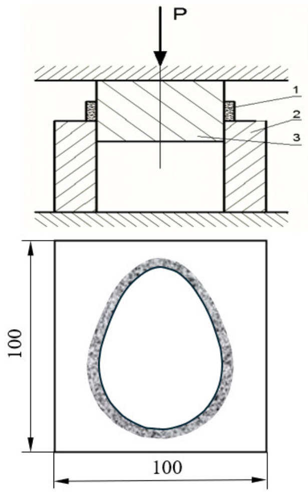


Figure 4. Test specimen fixture

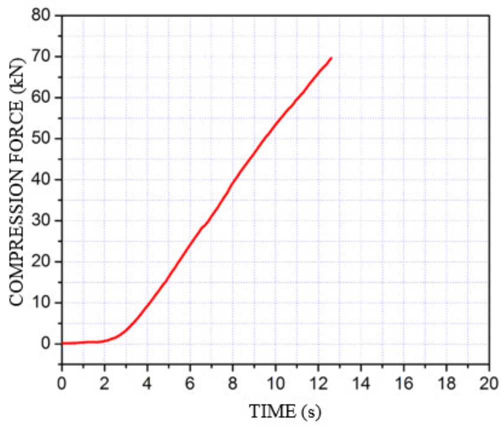


Figure 5. Graph showing tensile force values when measuring coating adhesion

4. RESULTS AND DISCUSSION

4.1. SEM Microstructural and Coating-Substrate Interface Analysis

SEM Microstructural Analysis: The microstructure of the WC-12Co coating deposited by HVOF spraying is characterized by a lamellar structure with overlapping splats. This structure is formed as a result of the high-velocity impact of molten or semimolten particles onto the substrate surface [23]. SEM images (Figure 6) show that the coating is bonded to the substrate surface primarily through mechanical interlocking, resulting in a dense interface with high adhesion strength. However, small sized impurities and pores are still present within the coating.

Owing to the extremely high particle velocity of the HVOF spray gun, the particles impact the substrate with high kinetic energy, undergo significant deformation and flatten to form thin splats that are tightly bonded to each other. This process leads to strong compaction of the coating, resulting in high density and very low porosity. However, a small number of partially melted particles may still remain, although their presence is significantly reduced compared with other thermal spray technologies.

Microstructural analysis shows that the superhard tungsten carbide (WC) particles are dispersed within and surrounded by the ductile cobalt (Co) metallic binder. The uniform distribution of these hard particles is a key factor governing the wear resistance of the coating [23]. Although these SEM images do not reveal secondary phases, XRD and EDS analyses commonly identify secondary carbide phases, such as W_2C or Co_6W_6C, which form as a result of WC decomposition during the thermal spraying process.

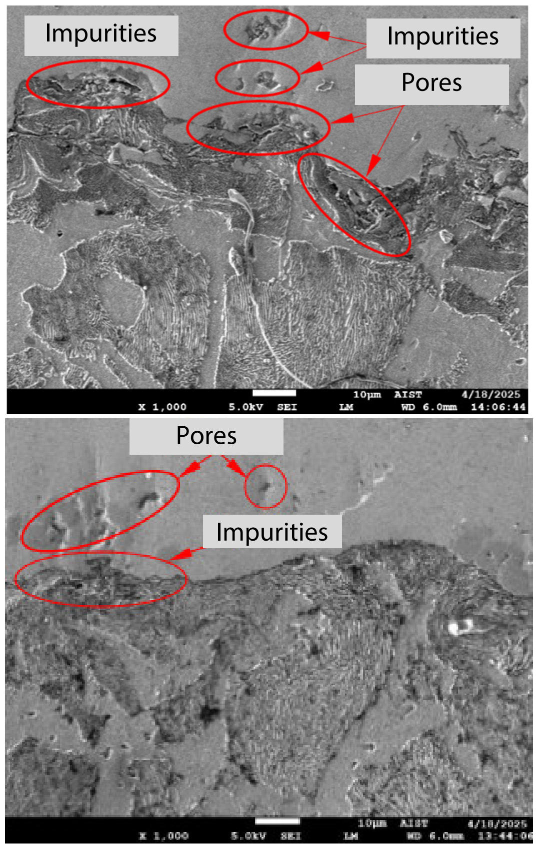


Figure 6. SEM microstructure of the WC-12Co alloy powder coating deposited by HVOF spraying

Coating-Substrate Interface: SEM images show that the transition zone (interface) between the WC-12Co coating and the substrate surface exhibits an irregular, uneven morphology resulting from the surface roughening process. This surface roughness is crucial for establishing a strong mechanical interlocking mechanism, which is the primary adhesion mechanism of thermally sprayed coatings. Molten particles impact the substrate at supersonic velocities, deform and fill the surface asperities. This strong anchoring confirms the extremely high impact kinetic energy, which is also a characteristic feature of HVOF coatings.

However, the interface region also reveals the presence of impurities and pores. These defects indicate that surface preparation and spraying parameters were not fully optimized. Such impurities, which may include oxides, unmelted powder particles, or debris, create localized weak points and reduce the effective contact area. They therefore serve as potential sources of crack initiation that can lead to coating delamination.

4.2. Effect of Coating Adhesion Strength

The adhesion strength of the WC-12Co alloy powder coating deposited on 40Cr steel by the HVOF spraying process was measured using an MTS 809 tensile–compression testing machine, supported by a computer and dedicated software. The experimental results are presented in Table 4.

Based on the data in Table 4, the adhesion strength of the WC-12Co coating deposited on 40Cr steel by HVOF spraying ranges from 61.6 to 72.8MPa. The variation in these values indicates that the adhesion strength is dependent on the spraying parameters. The maximum adhesion strength of the coating, σ_{lp} = 72.8MPa, was obtained at spraying parameters of m = 32g/min, n = 100rpm, and S = 8mm/rev.

To evaluate the effects of the technological parameters (m, n and S) on the adhesion strength of the coating, an orthogonal experimental regression method was employed to model the adhesion strength as a function of the three spraying parameters m, n and S. Using Matlab R2020b software, Equation (1) was established, along with 3D plots illustrating the relationship between adhesion strength and the spraying process parameters, as follows:

$$\sigma_{lp} = -0.82.m^2 - 0.0019.n^2 - 0.14.S^2 - 0.0037.n.S + 51.23.m + 0.44.n + 2.92.S - 761.07 \quad (1)$$

Where: σ_{lp} - Adhesion strength of the coating;

m - Powder feed rate (g/min);

n - Rotational speed of the workpiece (rpm);

S - Spray gun traverse speed (mm/rev).

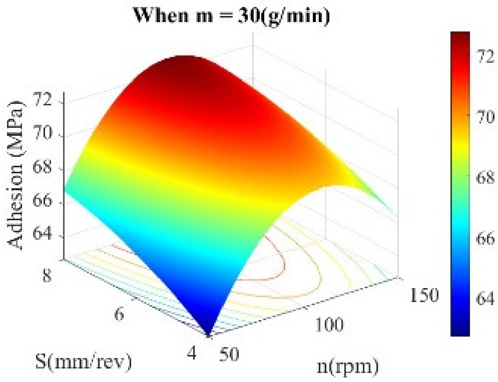
Based on the 3D plots shown in Figure 8 for specimens 1 to 9, a detailed analysis can be conducted to elucidate the influence patterns of the powder feed rate (m), workpiece rotational speed (n), and spray gun traverse speed (S) on the adhesion strength of the coating.

Influence of Powder Feed Rate (m): Observation of specimens 1, 2 and 3 indicates that the powder feed rate (m) plays a key role in controlling the thermo-dynamic balance of the spray jet. At the intermediate level of m = 32g/min, the adhesion strength reaches its maximum value (above 70MPa).

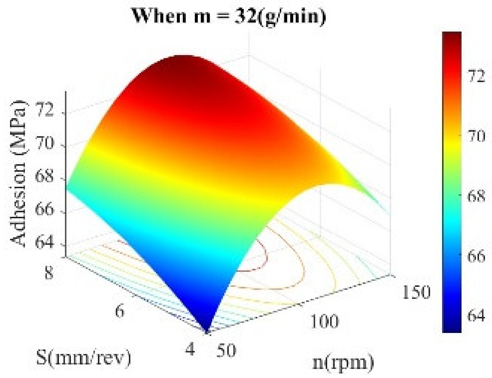
The underlying physical mechanism is related to the particle density within the flame jet. When m is too low (m = 30g/min), powder particles are prone to overheating, leading to the decomposition of the WC phase into W_2C and η phases (such as Co_3W_3C or Co_6W_6C), which increases residual stresses and reduces interfacial bonding capability. Conversely, when m is too high (m = 34g/min), the flame energy is dispersed among an excessive number of particles, reducing the temperature and impact velocity of individual particles. This limits the plastic deformation of particles upon impact with the 40Cr steel substrate, thereby significantly weakening the mechanical interlocking mechanism.

Influence of Rotational Speed (n) and Spray Gun Traverse Speed (S): The combination of the rotational speed (n) and the spray gun traverse speed (S) determines the scanning velocity of the spray gun over the camshaft surface, thereby affecting the overlap structure of the splats. The 3D plots show that optimal adhesion strength is generally achieved at intermediate values of both parameters (n = 100rpm and S = 6mm/rev). This behavior can be explained by the trade off between thermal contact time and coating density. If the rotational speed (n) and spray gun traverse speed (S) are too low, excessive localized thermal energy accumulates on the 40Cr steel substrate, causing non-uniform thermal expansion and the formation of microcracks due to thermal stresses.

If these parameters are too high, the residence time of powder particles in the thermal jet is shortened and the overlap between successive spray passes becomes insufficient, resulting in a non-uniform coating structure with high porosity, which reduces the effective contact area and, consequently, the adhesion strength.



Specimen 1



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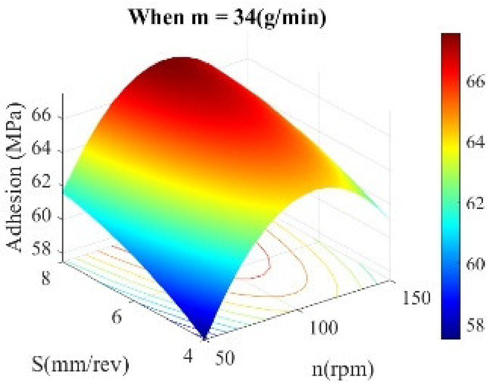
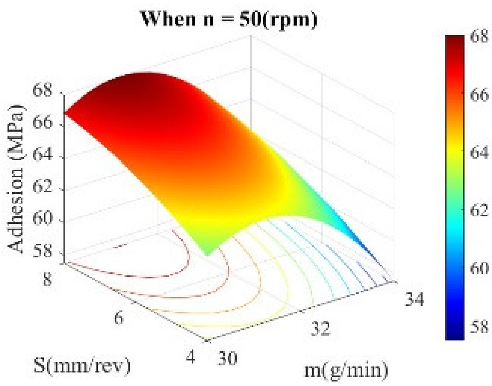


Specimen 3



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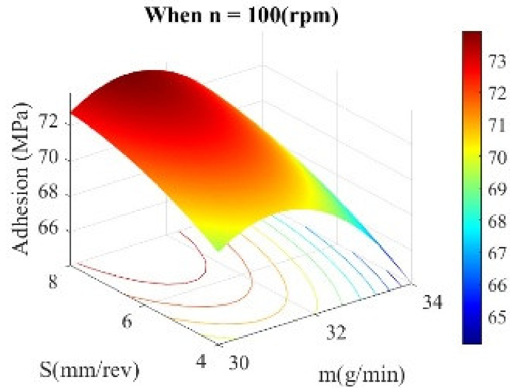
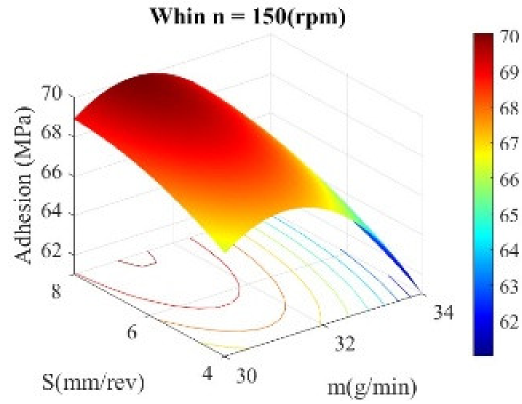


Specimen 5



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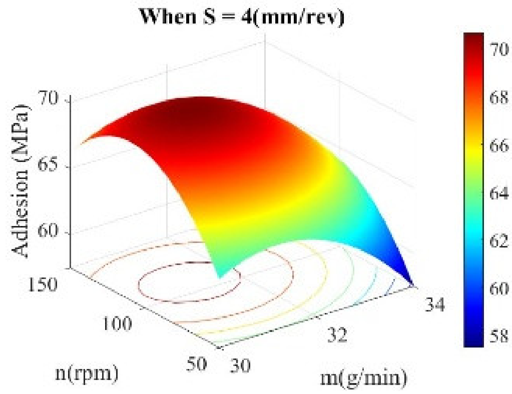
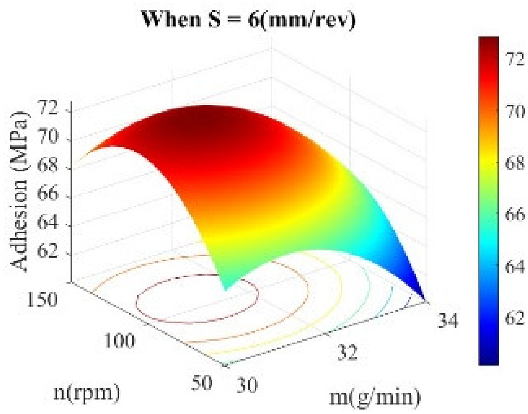
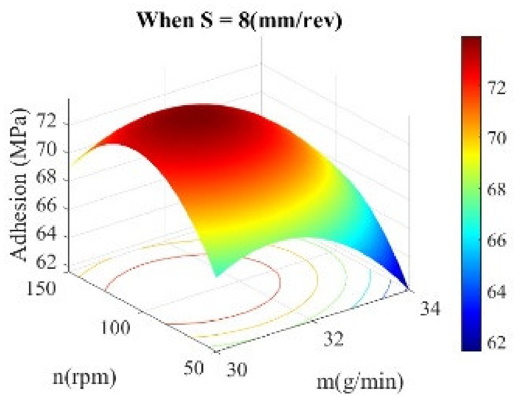


Specimen 7



Specimen 8



Specimen 9

Figure 7. 3D plots showing the relationship between coating adhesion strength and spraying parameters under constant conditions

4.3. Restoration Effectiveness

Thermal spray coating technology enables the restoration of the functional shape and dimensions of worn components, reconstructing dimensions close to the original prior to final machining in order to meet technical tolerances. For components such as camshafts, the coated surface is finished by grinding or turning to satisfy service requirements after restoration. This method is widely applied to extend component service life and to replace the need for new manufacturing or complete component replacement.

Figure 8. Details of the camshaft before and after HVOF injection

Numerous studies have shown that the service life of components restored by thermal spray coating can be comparable to, or even exceed, that of original components, owing to the significant improvement in wear and corrosion resistance of the surface.

From both economic and environmental perspectives, thermal spraying reduces repair costs compared with replacement, while also limiting material consumption and waste generation. Figure 8 illustrates the camshaft surface before and after HVOF spraying.

5. CONCLUSIONS

The study clarified the formation characteristics and quality of WC-12Co coatings deposited on 40Cr steel substrates using the HVOF spraying technology. The results show that the obtained coatings exhibit a dense microstructure with very low porosity, in which carbide particles are uniformly distributed within a ductile cobalt binder phase, satisfactorily meeting the service requirements of components subjected to high contact loads. The coating adhesion strength ranges from 61.6 to 72.8MPa, exceeding the technical requirements for cam lobe restoration applications.

The powder feed rate was identified as a key parameter influencing the thermo-dynamic state of the sprayed particles; an optimal value of m = 32g/min effectively limits carbide decomposition while ensuring sufficient impact kinetic energy. The combined effect of the workpiece rotational speed and the spray gun traverse rate governs splat overlap, directly affecting coating uniformity, density, and residual stress.

The coating-substrate bonding mechanism is formed through a combination of mechanical interlocking caused by particle impact at supersonic velocities and localized atomic diffusion at the interface. Optimization of the spraying parameters using a 3D response surface model demonstrates the feasibility of HVOF technology for automotive camshaft restoration and confirms it as an effective and environmentally friendly technical solution to replace conventional hard chromium plating.

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