

Article

Microstructure and Properties of Inconel 718/WC Composite Coating on Mold Copper Plate

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Abstract

In order to improve the high-temperature wear resistance of mold copper plates, this study used laser cladding technology to prepare a high-wear-resistant composite coating with Inconel 718 and WC (Tungsten carbide) particles. The phase composition, microstructure, microhardness, and tribological properties at 400 °C were systematically analyzed using X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), Vickers microhardness tester, and high temperature friction and wear tester. The results indicate that the Inconel 718/WC coating is free of pores and cracks and exhibits a metallurgical bond with the substrate. Its phases mainly consist of a γ -Ni solid solution and various hard carbide reinforcing phases, such as MC, M_3W_3C , and W_2C . The average microhardness of the coating reaches 851.7 HV_{0.5}, which is 11.5 times that of the substrate (74 HV_{0.5}). At 400 °C, the wear rate of the coating is $3.48 \times 10^{-4} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, only 35.7% of the substrate's wear rate. The dominant wear mechanism is abrasive wear, accompanied by oxidative wear. The outstanding performance of the coating is attributed to the combined effects of grain refinement strengthening, solid solution strengthening, and second-phase strengthening induced by the various hard carbides.

Keywords: laser cladding; Inconel 718; composite coatings; microstructure; high-temperature wear resistance



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1. Introduction

The mold, as the core component of the continuous casting system, directly affects the quality of the cast slab and production efficiency due to its high temperature working condition [1–3]. At present, Cr-Zr-Cu alloy mold copper plates are widely used due to their outstanding thermal conductivity. However, under extreme working conditions, such as high temperature and friction from the cast slab, the mold copper plate surface often suffers severe mechanical wear, which usually leads to failure. This affects the surface quality of the cast slab, even causes unplanned downtime for replacement, and economic losses [4].

Surface strengthening technology is considered to be one of the most effective solutions to extend component service life, including shot peening strengthening, vapor deposition, thermal spraying, and electroplating [5–8]. Among these, laser cladding technology uses

a high-energy laser beam to instantaneously melt high-performance material with the substrate surface, followed by rapid solidification. This process results in a coating that exhibits a metallurgical bond with the substrate and a fine-grained microstructure. It can significantly improve the wear resistance of the substrate surface [9,10]. Wherein, Inconel 718 alloy is widely used for protecting components due to its excellent strength, oxidation resistance, and good toughness at high temperature [11,12]. However, when harsh friction and wear environment appear at same time, the hardness and wear resistance of a single Inconel 718 coating are still insufficient to work at high temperatures.

To overcome the limitations of single coating, the preparation of metal matrix composite coatings by adding hard ceramic phases has been extensively studied as an effective way to enhance wear resistance [13–17]. Among them, WC (Tungsten carbide) is widely used as a reinforcing phase material due to its extremely high hardness, excellent thermal stability, and good wettability. Li et al. [18] prepared a WC composite coating by laser cladding. The main phases of this composite coating were $\text{Fe}_{0.64}\text{Ni}_{0.36}$, W_2C , M_7C_3 , and other reinforcing phases. Under the influence of WC particles, grain refinement strengthening and second-phase strengthening modified the composite coating, increasing its hardness and enhancing its wear resistance. Ding et al. [19] prepared WC/Fe composite coatings with different WC contents by laser cladding. The results showed that the grain refinement effect became more pronounced along with the increase in WC content. When the WC content was 30 wt.%, the coating achieved the best balance between impact resistance and sliding wear resistance. The impact damage mode was primarily spalling, while the sliding damage mode was mainly plowing. Han et al. [20] studied the microstructure evolution and tribological properties of nano WC particles. The results indicated that the wear resistance increased by 73.3%, which was attributed to the more significant grain refinement effect of nano-WC, resulting in a unique combination of dispersion strengthening and solid solution strengthening. In order to improve the wear resistance of 42CrMo steel, Qin et al. [21] fabricated an Inconel 718/WC composite coating on its surface using laser cladding. The results indicated that the coating consisted primarily of γ -(Ni, Fe), WC, and W_2C phases, with a microstructure dominated by planar and columnar crystals. The average hardness of the coating reached 784.3 $\text{HV}_{0.2}$, approximately 3.4 times that of the substrate. The wear mass loss of the coating was reduced by 76.19% compared to the substrate, with abrasive wear identified as the dominant wear mechanism.

Although many studies have reported on laser cladding Ni-based coating or WC-reinforced coatings [22–25], the microstructure and high temperature tribological properties of Inconel 718/WC composite coatings on the mold copper plates are lacking in the literature. Therefore, this study uses laser cladding technology to prepare an Inconel 718/WC composite coating on a Cr-Zr-Cu copper alloy surface. The strengthening mechanisms of the composite coating induced by the addition of WC particles are investigated by characterizing the microstructure, phase composition, microhardness, and high-temperature wear resistance.

2. Experimental Materials and Methods

2.1. Experimental Materials

Table 1 includes the chemical composition of the Cr-Zr-Cu copper alloy (Shanghai Hengdi Industry Co., Ltd., Shanghai, China) used for the laser cladding substrate. Before the experiment, the substrate was mechanically ground with sandpaper to remove the surface oxide layer, ultrasonically cleaned for 300 s, and finally dried by a hot air gun. Table 2 includes the chemical composition of the Inconel 718 alloy powder (45–55 μm , Henan Xintie Metal Materials Co., Ltd., Gongyi, China) used for the laser cladding coating. In order to prevent cracks, the 10 wt.% Co was mixed with WC particles. Then, the 80 wt.%

Inconel 718 alloy powder and 20 wt.% WC particles (0.3–0.6 μm , Shanghai Pantian Powder Material Co., Ltd., Shanghai, China) were dried and mixed by a ball mill (ball-to-powder ratio 2:1) for 2 h. The obtained composite powder was preplaced onto the Cr-Zr-Cu substrate surface to form a preplaced coating approximately 0.6 mm thick.

Table 1. Chemical composition of Cr-Zr-Cu copper alloy (wt.%) [26].

Cu	Cr	Zr
99.07	0.68	0.25

Table 2. Chemical composition of Inconel 718 alloy powder (wt.%) [26].

Element	C	Cr	Nb	Mo	Ti	Al	Co	Mn	Si	Ni	Fe
Amount	0.08	19	4.8	3	0.75	0.65	1.2	0.35	0.35	55	15.17

Figure 1 shows a schematic diagram of coating preparation by laser cladding. Before the laser cladding experiment, a layer of Inconel 718/WC alloy powder was preplaced on the substrate. Subsequently, the substrate was placed on a preheating device for 60 s. Based on previous studies [26], the laser cladding process parameters are listed in Table 3.

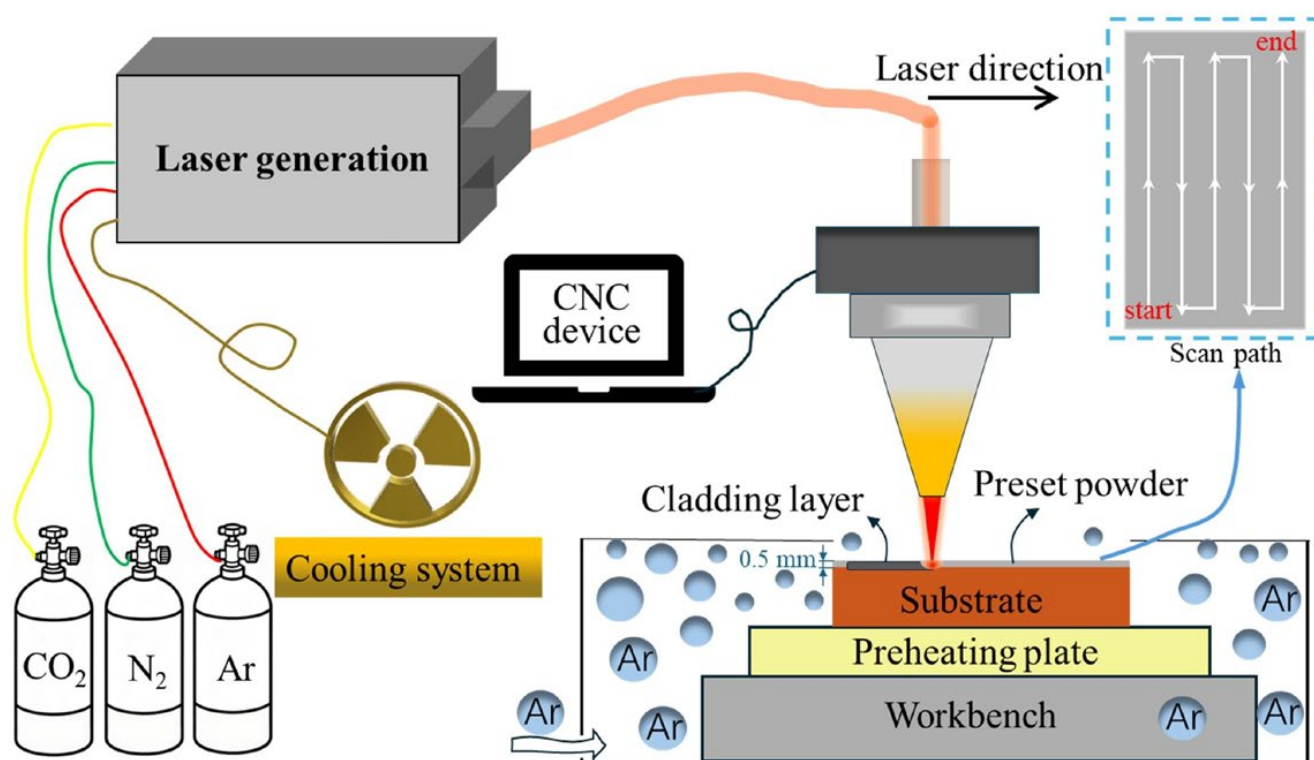


Figure 1. Schematic diagram of coating preparation by laser cladding [26].

Table 3. Process parameters of laser cladding.

Laser Power (W)	Scanning Speed (mm/min)	Spot Diameter (mm)	Overlap Rate (%)	Preheating Temperature ($^{\circ}\text{C}$)
1400	120	3	30	200

2.2. Experimental Methods

At first, cube specimens with dimensions of $10 \times 10 \times 10$ mm were prepared using wire cutting machine. These specimens were then progressively ground with silicon carbide papers of varying grit sizes and finally polished to a metallographic finish, according to the requirements of the analysis. The phase composition was detected by an X-ray diffractometer (TD-3500, Dandong Tongda Science and Technology Co., Ltd., Dandong, China). The coating cross-section was etched with a corrosive solution ($\text{HNO}_3:\text{HCl} = 1:3$) about 100 s. The microstructure and element distribution of the coating were observed by a scanning electron microscope (ZEISS Gemini SEM 300, Carl Zeiss Microscopy GmbH, Oberkochen, Germany). The microhardness across the coating cross-section was measured at different depths using a Vickers microhardness tester (HXD-1000TMC, Shanghai Optical Instrument Co., Ltd., Shanghai, China) under a load of 50 gf with a dwell time of 15 s. At each depth, three adjacent measurements were performed, and the average value was calculated. High-temperature wear tests were conducted using a reciprocating tribometer (MGW-02, Jinan Yihua Tribology Testing Technology Co., Ltd., Jinan, China) with a Si_3N_4 ball ($\Phi = 6.5$ mm) as the friction pair. The wear resistance of each sample was evaluated through three repeated tests, and the average value was calculated. The test parameters were set as follows: load 10 N, frequency 2 Hz, temperature 400°C , duration 20 min.

3. Results and Discussion

3.1. Phase Analysis

Figure 2 shows the XRD pattern of the Inconel 718/WC coating. The coating consists of the solid solution γ -Ni and carbides, such as MC, $\text{M}_3\text{W}_3\text{C}$, $\text{W}_{0.15}\text{Ni}_{0.85}$ and W_2C . Some hard phases like $\text{M}_3\text{W}_3\text{C}$ are formed in accordance with previous research [27]. The reactions occurring in the molten pool are represented by Equations (1)–(4). XRD analysis confirms that the coating is strengthened by the formation of multiple carbide phases. The identified phase composition and underlying reaction mechanisms provide a fundamental microstructural basis for the enhanced coating performance.



3.2. Microstructure and Element Distribution

Figure 3 shows the cross-sectional morphology and element distribution of the Inconel 718/WC composite coating. The coating thickness was measured at five equally spaced locations along the cross-section. The average of these measurements was calculated and determined to be approximately 5.8 mm. The coating cross-section is smooth, free of pores and cracks, indicating a sound coating structure. Some columnar compounds are distributed in the middle region of the coating, which grow in the direction perpendicular to the coating surface. The element distribution shows that Cu from the substrate has an obvious boundary, which is the same to elements like Ni, Cr, and W from the coating. It means that the severe dilution did not occur during the cladding process. The coating exhibits uniform thickness, a dense microstructure, and distinct elemental distribution boundaries. These characteristics confirm that the laser cladding process achieved excellent bonding with the substrate while effectively minimizing dilution effects.

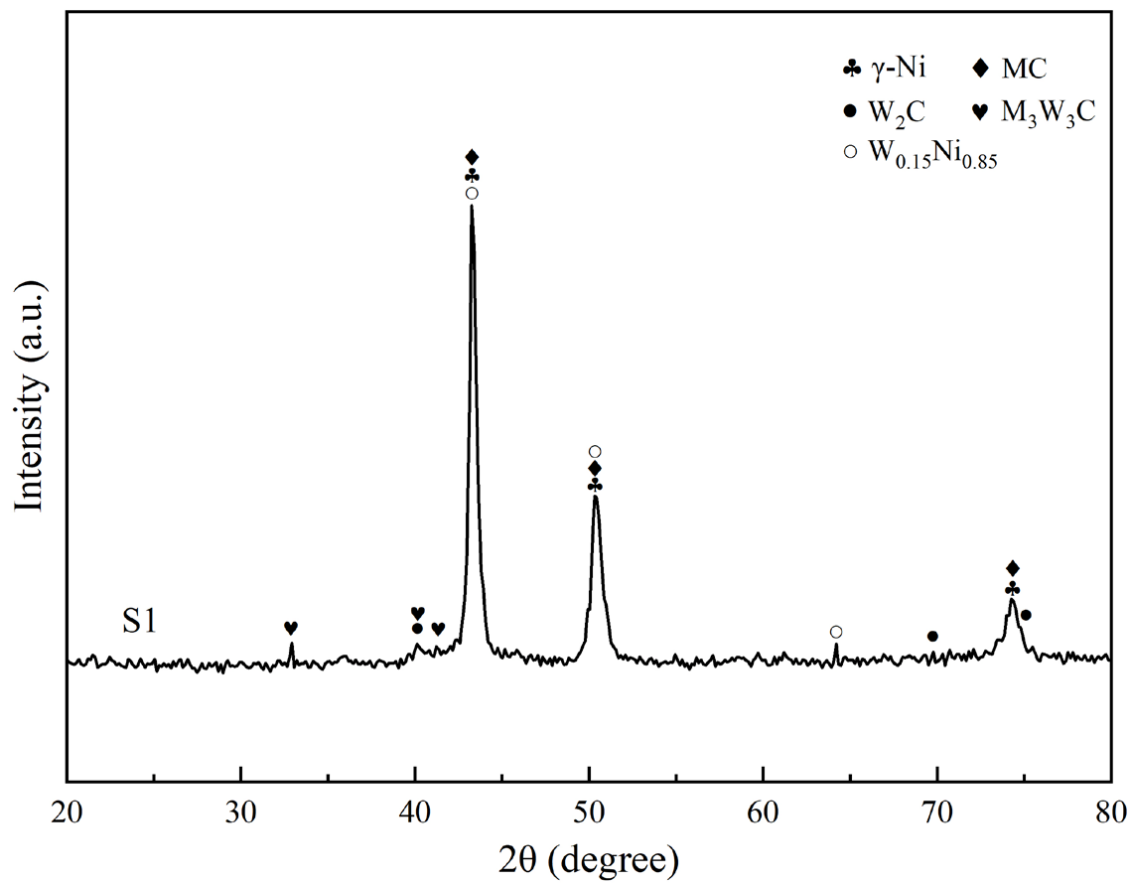


Figure 2. XRD pattern of the Inconel 718/WC coating.

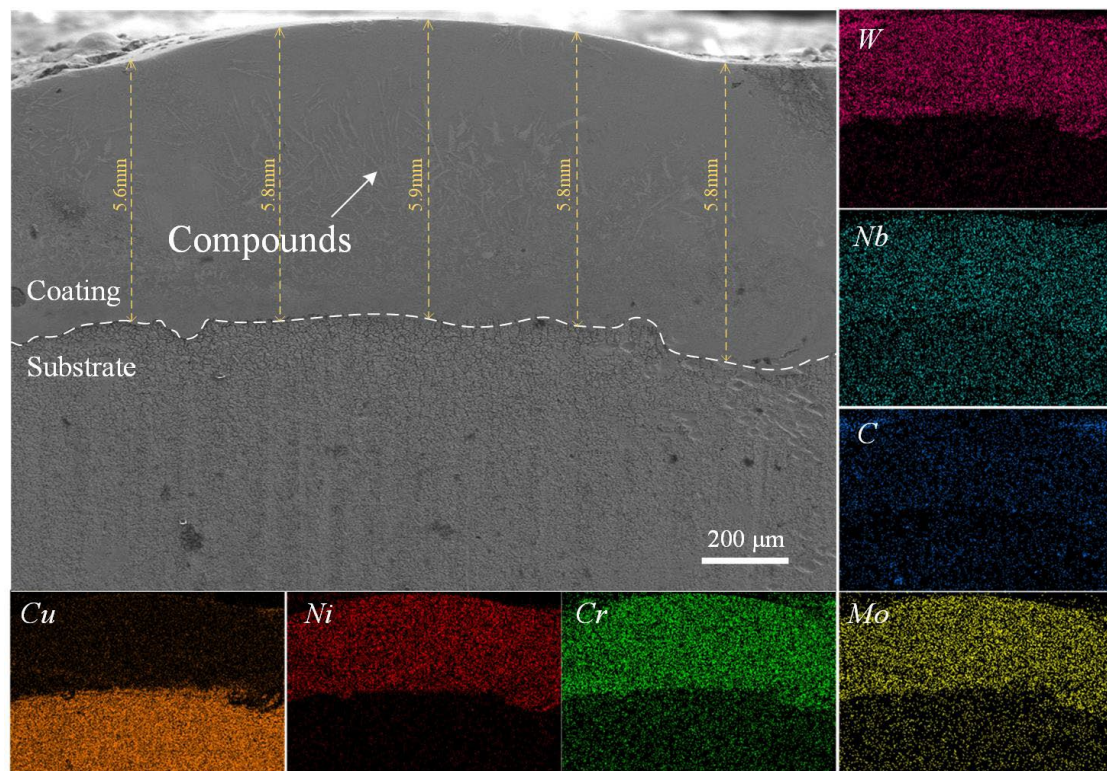


Figure 3. Cross-sectional morphology and element distribution of Inconel 718/WC coating.

Figure 4 shows the microstructure of Inconel 718/WC coating. Numerous columnar compounds are distributed within the coating, some of which exhibit short-range ordered precipitates with approximately triangular shapes. These short-range ordered precipitates can effectively pin dislocations, hinder plastic deformation, and thereby improve the hardness and wear resistance of the coating. Some relatively fine and irregularly distributed gray-white phases appear in the coating. Area scanning was performed on these phases to determine their element distribution, as shown in Figure 5. The coating microstructure is characterized by columnar compounds and short-range ordered precipitates. These functional precipitates enhance the mechanical properties through a dislocation strengthening mechanism, thereby providing microstructural support for the wear resistance.

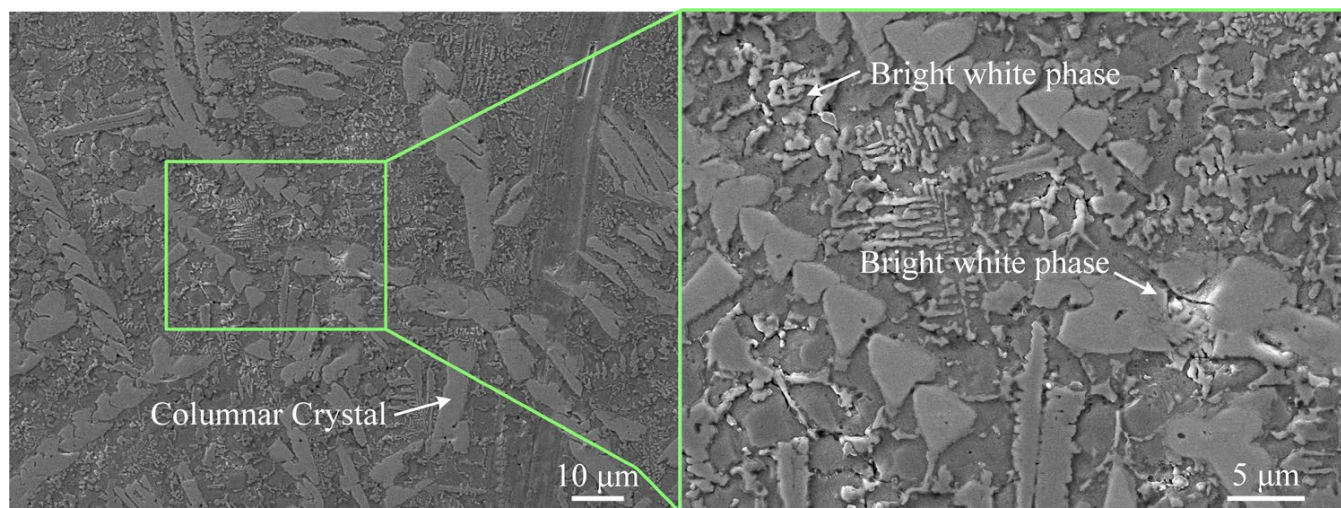


Figure 4. Microstructure of the Inconel 718/WC coating.

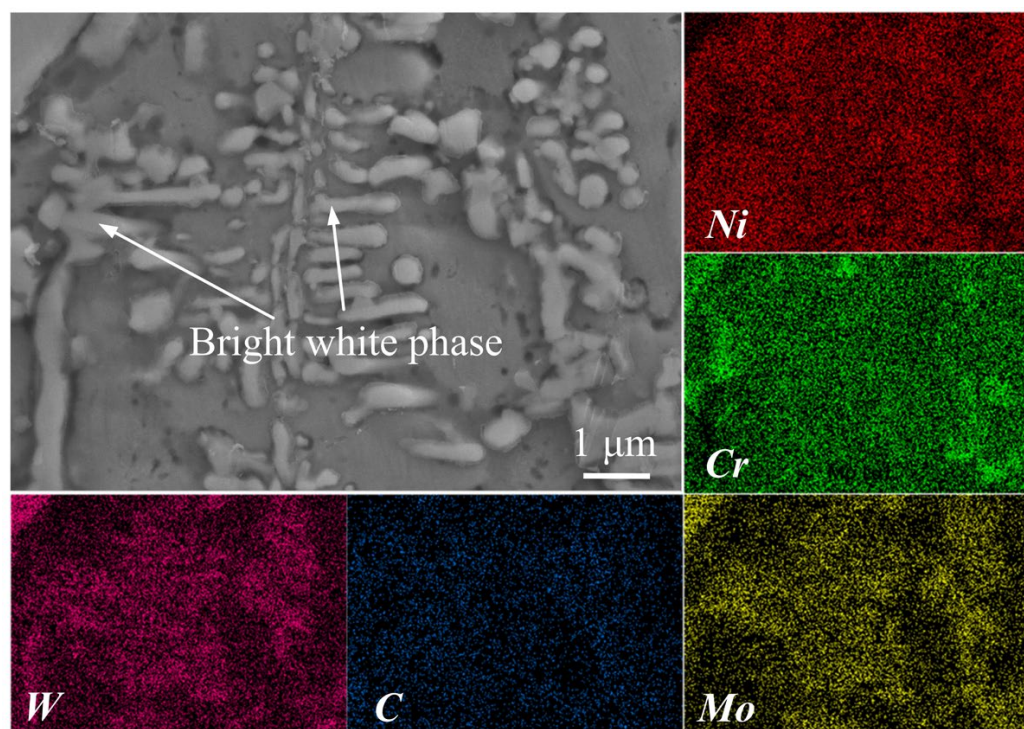


Figure 5. Microstructure and element distribution of the gray-white phases in the Inconel 718/WC coating.

Figure 5 shows the microstructure and element distribution of the gray-white phases in the Inconel 718/WC coating. The morphologies of these gray-white phase compounds are mostly rod-like and circular. Their sizes are small, typically less than 1 μm in width. These gray-white phases are hard and brittle compound particles containing W, Cr, and Mo elements. The protruding compounds are a multiphase structure, speculated to be $\text{M}_3\text{W}_3\text{C}$ and MC carbides. These compounds are dispersed within the γ -Ni matrix, providing second-phase strengthening by effectively hindering dislocation movement within the coating. At elevated temperatures, these compound particles can still effectively pin dislocations and grain boundaries, provide creep resistance, and maintain high hardness and wear resistance. The gray-white phase serves as a key strengthening constituent in the coating. Its fine, dispersed distribution and high-temperature stability represent the fundamental microstructural mechanism responsible for the coating's excellent mechanical properties and service performance at elevated temperatures.

Figure 6 shows the microstructure and element distribution at the bottom of the Inconel 718/WC coating. Based on the element distribution, the coating bottom can be divided into three parts: the coating, the transition zone, and the substrate. During the melting and solidification stage, element Cu diffused from the substrate into the coating, forming a transition zone approximately 40 μm wide. The element Ni from the composite coating also diffused into this zone, combining with Cu to form a solid solution, resulting in a metallurgical bond between the coating and substrate. Furthermore, the high G/R ratio inhibited sufficient crystal growth due to the high temperature gradient (G) and low solidification rate (R), causing solidification in a primary, fine state. Consequently, short compounds formed at the bottom. These high-hardness compounds, with skeletons of elements like Mo and W, are embedded in the γ -Ni matrix, which strengthens the coating. A metallurgical bonding zone formed by interdiffusion exists at the coating bottom. Concurrently, fine grains and hard compounds, induced by a high G/R ratio, collectively ensure the coating's adhesion strength and structural stability.

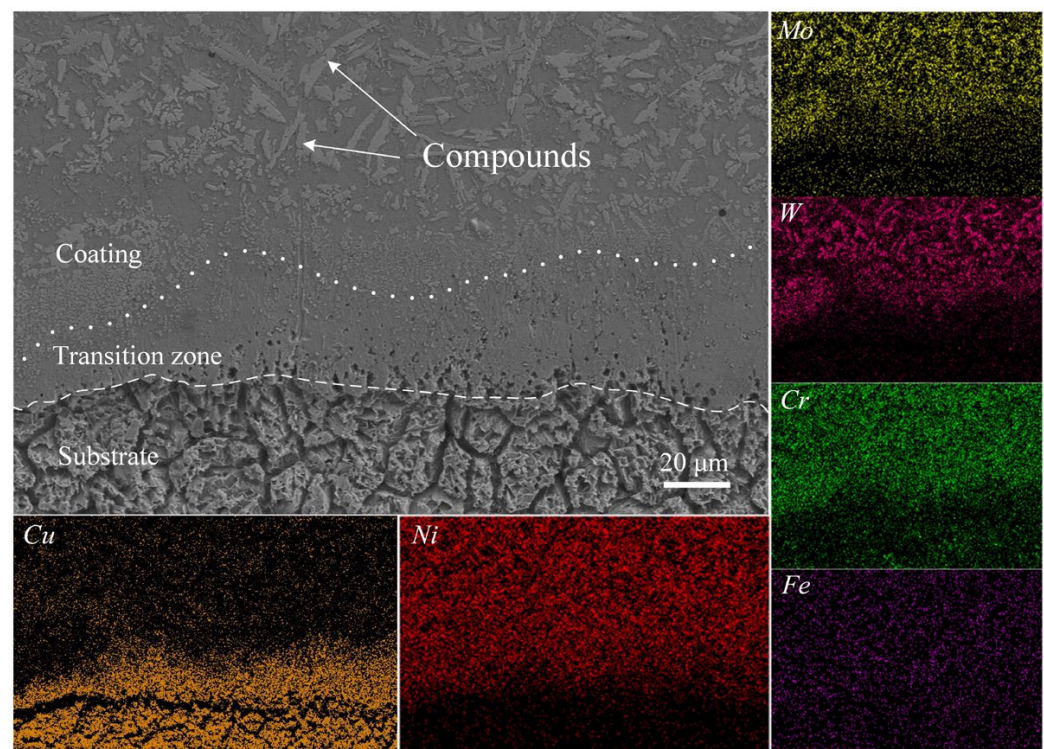


Figure 6. Microstructure and element distribution at the bottom of the Inconel 718/WC coating.

3.3. Microhardness

Figure 7 shows the cross-sectional microhardness of the Inconel 718/WC coating and the substrate. Compared to the substrate, the coating's microhardness is significantly higher. The maximum microhardness is 934.5 HV_{0.5}, and the average microhardness is 851.7 HV_{0.5}, which is about 11.5 times that of the substrate (74 HV_{0.5}). The laser cladding coating has a finer grain size. The presence of reinforcing phases, such as solid solutions and carbides, contributes to its high microhardness. The coating achieves a substantial improvement in surface hardness over the substrate through the synergistic effect of grain refinement strengthening and secondary phase precipitation strengthening. This enhancement establishes a fundamental basis for improving the wear resistance of mold copper plates.

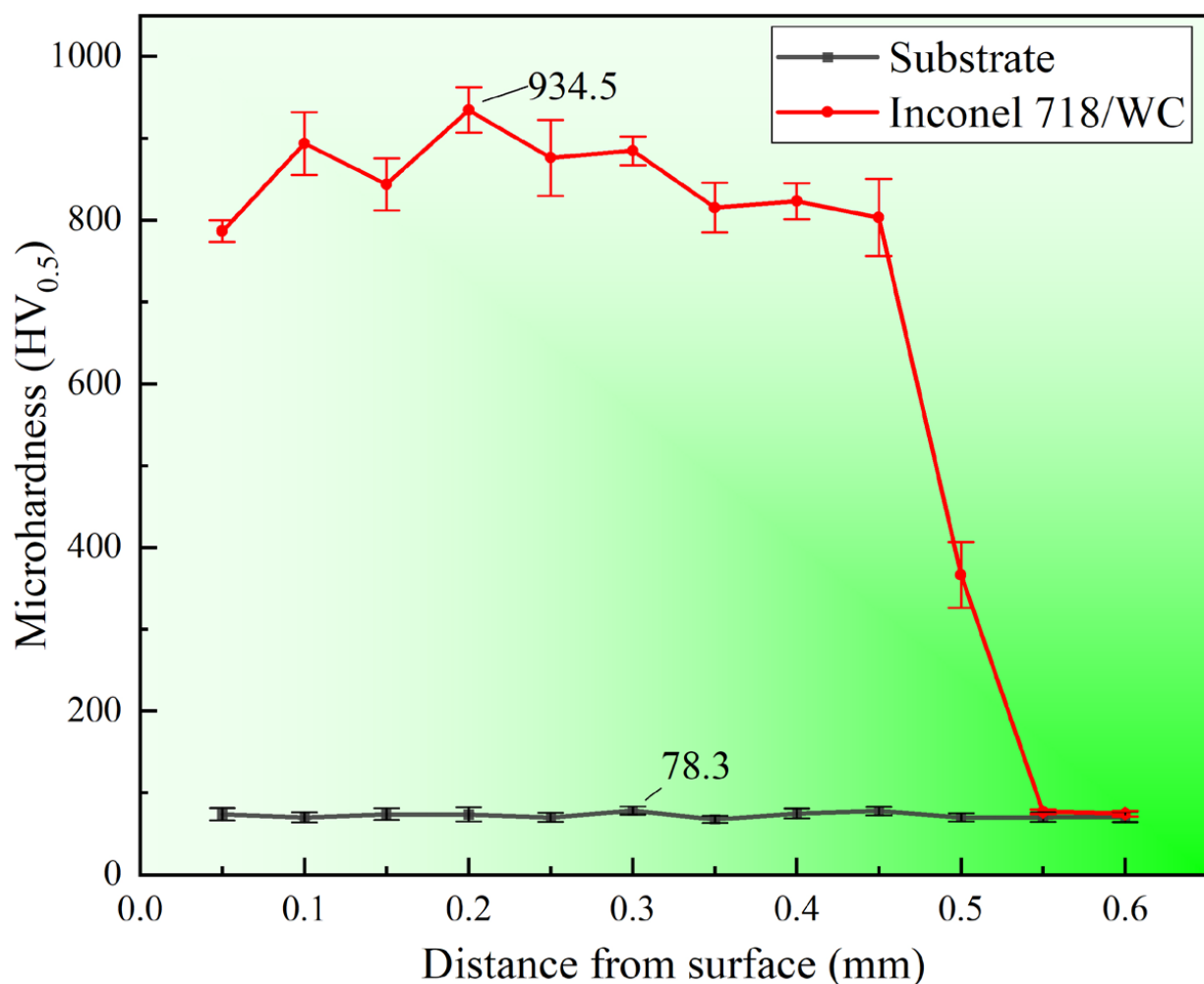


Figure 7. Cross-sectional microhardness of the Inconel 718/WC coating and the substrate.

3.4. Friction and Wear

Figure 8 shows the friction coefficient curves of the Inconel 718/WC coating and the substrate at 400 °C. The substrate and coating have similar average friction coefficients, 0.28 and 0.29, respectively. The substrate has a slightly lower friction coefficient and smaller amplitude fluctuations, which is related to the good anti-friction properties of copper. At the beginning of the test, the friction coefficient curves for both the coating and substrate fluctuate significantly. As friction proceeds, the curves gradually stabilize. This is attributed to the change in contact geometry between the friction pair, transitioning from initial point contact to area contact. During the predominantly point contact phase, the interaction

between the grinding ball and the friction surface is intense, which causes noticeable fluctuations in the friction coefficient curve. During the predominantly area contact phase, the interaction is relatively stable, which leads to a smoother curve. The coating has a large amplitude of friction fluctuation, which is caused by hard phases and high-hardness wear debris spalled from the coating during the friction process. Although the coating and substrate shared a similar average friction coefficient at 400 °C, the coating's distinct frictional fluctuations, induced by its hard phases, were governed by changes in contact morphology and associated wear mechanisms.

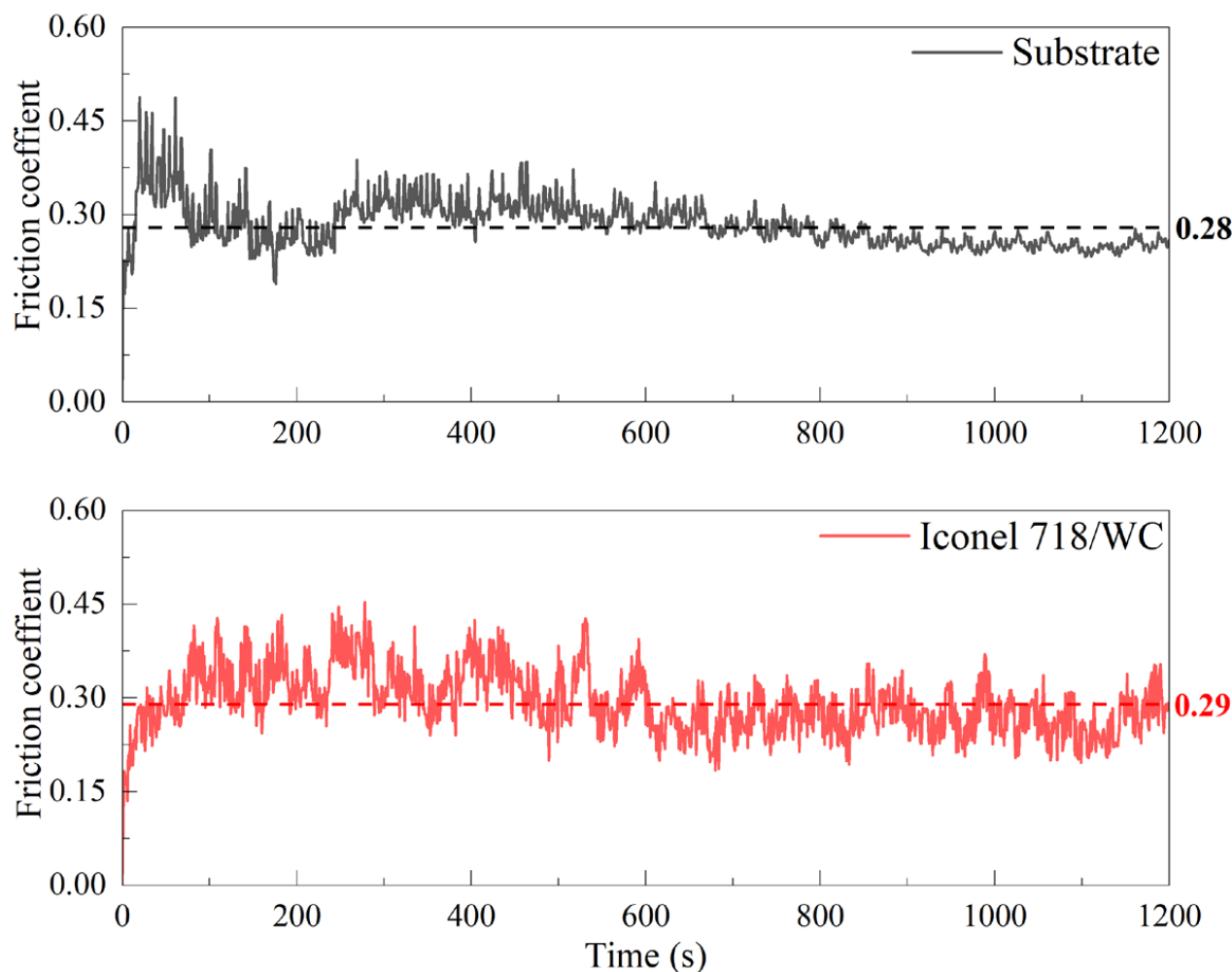


Figure 8. Friction coefficient curves of the Inconel 718/WC coating and substrate at 400 °C.

Figure 9 shows the wear rates of the Inconel 718/WC coating and substrate at 400 °C. At 400 °C, the substrate's wear rate is $9.75 \times 10^{-4} \cdot \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, while the Inconel 718/WC coating's wear rate is $3.48 \times 10^{-4} \cdot \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, only 35.7% of the substrate's wear rate. This significant improvement in wear resistance can be attributed to the grain refinement effect of the laser-prepared coating and strengthening phases, including the γ -Ni solid solution, carbides, and compounds like $\text{M}_3\text{W}_3\text{C}$. These microstructural features collectively contribute to increased hardness and high-temperature wear resistance. The coating achieved a significantly reduced wear rate and demonstrated far superior high-temperature wear resistance than the substrate, thereby ensuring long-term service performance for the mold copper plate.

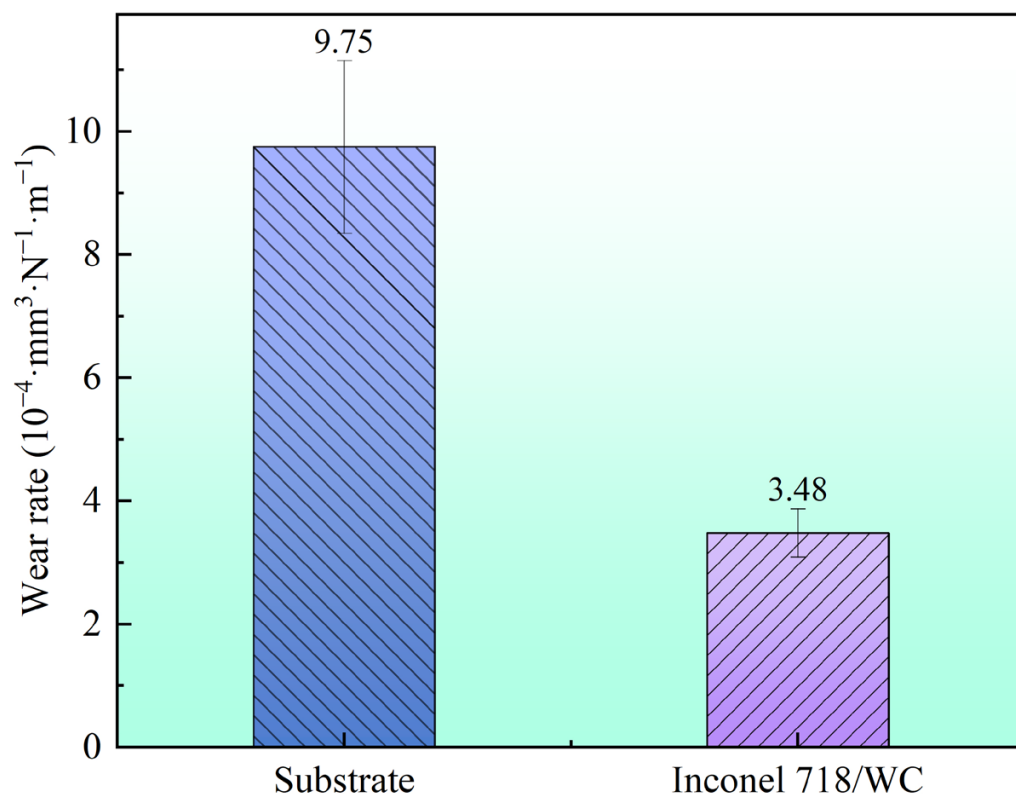


Figure 9. Wear rates of the Inconel 718/WC coating and substrate at 400 °C.

Figure 10 shows the wear morphology of the Inconel 718/WC coating. The coating surface displayed features including spalling, plowing grooves, and wear debris. The spalling was shallow and minor, presenting as discrete pits with no significant defects observed, resulting in a relatively smooth worn surface morphology. Under cyclic friction loading, certain hard-phase particles detached from the coating and participated in the subsequent wear process, rolling or sliding between the coating surface and the friction pair. This mechanism led to the observed spalling and plowing, confirming that abrasive wear was the dominant wear mechanism. Furthermore, the fine particles and small compounds released during friction reduced the direct contact area between the coating and the friction pair. This decrease in contact area lowered the interfacial interaction forces, thereby mitigating the overall wear severity. The coating's wear morphology primarily exhibited mild abrasive wear, with no significant failure defects observed. These features attest to its robust structural stability and anti-wear capability.

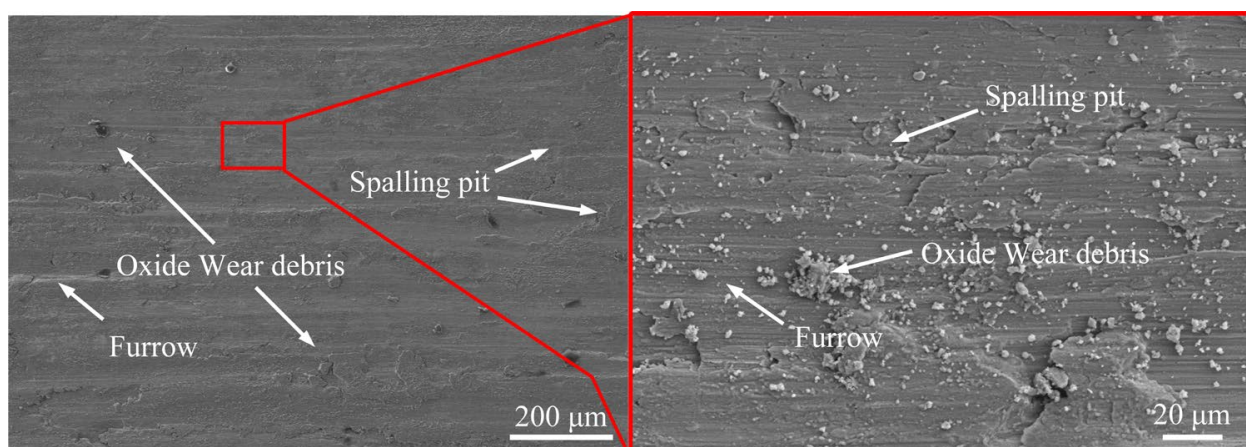


Figure 10. Wear morphology of the Inconel 718/WC coating.

Figure 11 shows the BEI and P1–P3 points scanning results on the worn coating surface. In the BEI, if the average atomic number is higher, the regions appear brighter. It can be seen that the worn coating surface includes black blocks, bright particles, and a gray background area. Through EDS point scanning technology, P1–P3 points were detected. The results indicate that the point P1 has extremely high atomic percentages of C and O (C: 41.59 at%, O: 51.31 at%), which is totally over 90%. It means that the black blocky substances are wear debris rich in oxides and carbides, formed through reactions between the grinding ball, environmental elements (C, O), and the coating surface under elevated temperature and pressure during the wear process. These debris layers act as an interfacial barrier that isolates the friction ball from the coating, thereby reducing plowing caused by hard contact and minimizing direct friction damage. No significant spalling of the oxide layer was observed, indicating that oxidation was confined to the superficial region without penetrating into the coating interior, thus preserving the overall structural integrity of the coating. The point P2 has high contents of W and Mo (W: 27.55 at%, Mo: 11.62 at%) along with a significant amount of C (25.04 at%). This indicates that the bright particles are hard reinforcing phases in the coating, speculated to be W/Mo carbides (such as W_2C and MoC). They possess extremely high hardness to improve the coating's wear resistance. The point P3 contains Ni and Cr as the main elements (Ni: 53.33 at%, Cr: 17.10 at%), along with other alloying elements like Co and Fe. This indicates that the gray background is the γ -Ni solid solution. It is relatively soft and primarily serves to fix the hard phases (P2). The wear mechanism of the coating is primarily typical abrasive wear, accompanied by significant oxidative wear. The outstanding wear resistance of the coating is mainly attributed to the dispersed, high-hardness W/Mo carbide phases. The coating's wear mechanism is dominated by typical abrasive wear, accompanied by significant oxidative wear. The superior wear resistance is primarily attributed to the uniformly dispersed high-hardness W/Mo carbide phases within the coating matrix.

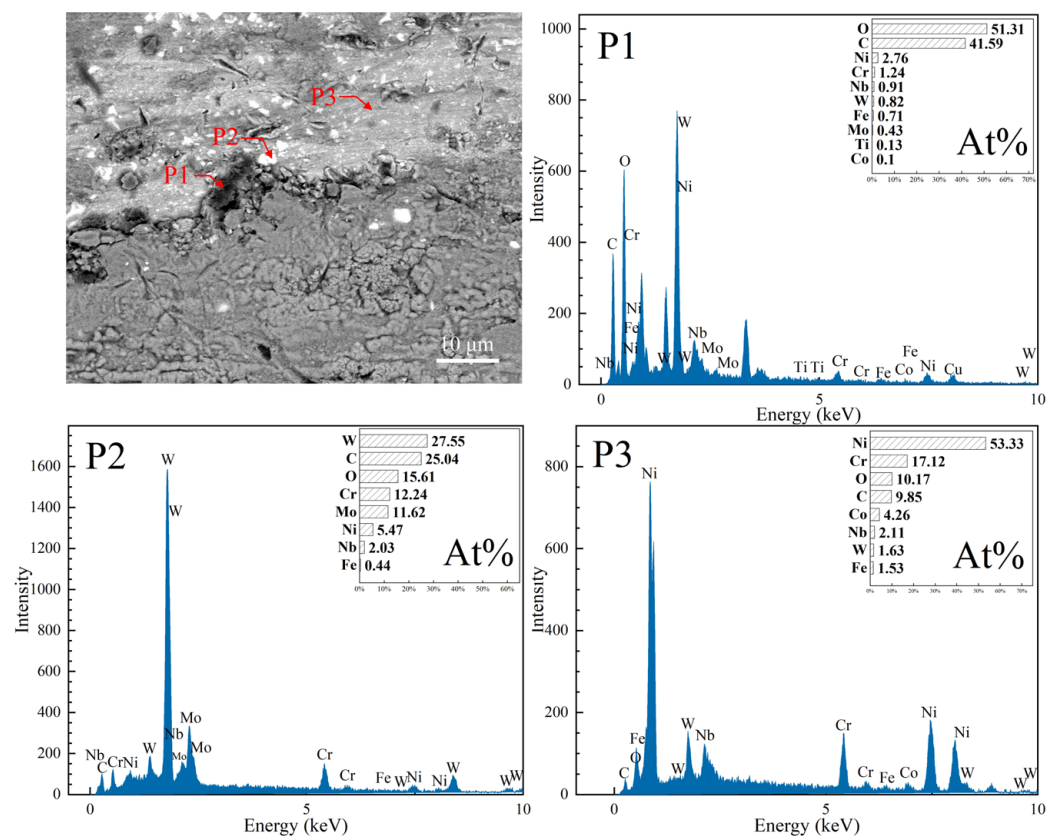


Figure 11. BEI and P1–P3 points scanning results on the worn coating surface.

4. Conclusions

- (1) This study successfully fabricated defect-free Inconel 718/WC composite coatings metallurgically bonded to a Cr-Zr-Cu alloy substrate using a CO₂ laser. The coatings primarily consist of γ -Ni solid solution and carbides such as M₃W₃C, MC, and W₂C. These carbides formed through the decomposition and subsequent reaction of WC particles within the molten pool.
- (2) The coating cross-section is dense and smooth, free of cracks and pores. Columnar compounds, some growing parallel to the surface, are distributed in the intermediate region. Elemental mapping confirmed limited interdiffusion of Ni, Cr, and W with the substrate, indicating a sound interfacial bond. Short-range ordered triangular precipitates and elongated/spherical light-gray phases (W, Cr, and Mo-rich carbides) are observed within the coating. These hard phases are dispersed in the γ -Ni matrix, effectively pinning dislocations and inhibiting plastic deformation, thereby enhancing mechanical properties. Fine compounds formed at the coating bottom due to the high thermal gradient, strengthening the bonding interface.
- (3) The composite coating had an average microhardness of about 851.7 HV_{0.5} and a maximum value of 934.5 HV_{0.5}. Its average microhardness was 11.5 times that of the substrate (74 HV_{0.5}). The significant enhancement in hardness is attributed to grain refinement strengthening and dispersion strengthening induced by various hard carbide precipitates.
- (4) During high temperature friction and wear at 400 °C, the coating and substrate demonstrated similar average friction coefficients (approximately 0.29). However, the wear rate of the coating was measured at $3.48 \times 10^{-4} \cdot \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, merely 35.7% of the substrate's wear rate, indicating substantial improvement in wear resistance. Analysis of the worn surfaces revealed that the coating's wear mechanism was primarily abrasive wear, accompanied by oxidative wear. The uniformly distributed hard carbides played a dominant role in resisting wear, while the γ -Ni matrix provided essential structural support. This synergistic interaction between the hard phases and ductile matrix resulted in exceptional high-temperature wear resistance and creep performance.

Future research should focus on optimizing powder composition and implementing graded coating architectures to better balance toughness, wear resistance, and cost-effectiveness.

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References

1. Louhenkilpi, S. *Treatise on Process Metallurgy*, 2nd ed.; Elsevier: Oxford, UK, 2024; pp. 343–383.
2. Guthrie, R.I.; Isac, M.M. Continuous Casting Practices for Steel: Past, Present and Future. *Metals* **2022**, *12*, 862. [\[CrossRef\]](#)
3. Vynnycky, M. Continuous casting. *Metals* **2019**, *9*, 643. [\[CrossRef\]](#)
4. Zhang, D.; Peng, Z.; Liu, Z.; Yu, J.; Yuan, L. Study on Wear Properties of High Hardness and High Thermal Conductivity Copper Alloy for Crystallization Roller. *J. Mater. Res. Technol.* **2024**, *28*, 3225–3231. [\[CrossRef\]](#)
5. Wu, K.; Li, K.; Hao, L.; Tang, J.; Jin, X.; Yang, J. Simulation and experimental study of shot peening strengthening technology for turbine disk fir-tree slots. *J. Alloys Compd.* **2025**, *1014*, 178744. [\[CrossRef\]](#)
6. Li, Y.; Pang, C.; Xue, L.; Li, X.; Wang, Q. Chemiresistive SnO₂-based hydrogen sensor fabricated by chemical bath deposition and chemical vapor deposition. *Sens. Actuators B Chem.* **2025**, *433*, 137543. [\[CrossRef\]](#)
7. Sidhu, T.S.; Agrawal, R.D.; Prakash, S. Hot corrosion of some superalloys and role of high-velocity oxy-fuel spray coatings—A review. *Surf. Coat. Technol.* **2005**, *198*, 441–446. [\[CrossRef\]](#)
8. Wang, J.; Miao, J.; Shi, D.; Zhang, J.; Zhao, Y.; Xia, Y. Sustainable stabilization/solidification of electroplating sludge using a low-carbon ternary cementitious binder. *Environ. Chem. Eng.* **2025**, *13*, 115022. [\[CrossRef\]](#)
9. Zhang, Y.; Liu, Z.; Lv, Z.; Cao, J.; Tong, Y.; Sun, M.; Cui, C.; Wang, X. Effect of SiC and TiC content on microstructure and wear behavior of Ni-based composite coating manufactured by laser cladding on Ti–6Al–4V. *Wear* **2024**, *552*, 205431. [\[CrossRef\]](#)
10. Gao, Z.; Niu, Z.; Gao, Z.; Li, J.; Bai, G.; Ke, L.; Yu, Y.; Zhang, C. Microstructure and wear behavior of in-situ synthesized TiC-reinforced CoCrFeNi high entropy alloy prepared by laser cladding. *Appl. Surf. Sci.* **2024**, *670*, 160720. [\[CrossRef\]](#)
11. Dai, R.; Xu, Z.; Gao, Q.; Alfano, M.; Yuan, J. Effect of processing parameters on the microhardness, shear, and tensile properties of layer-cladded Inconel 718. *J. Mater. Res. Technol.* **2024**, *28*, 4725–4737. [\[CrossRef\]](#)
12. Ari, A. Comprehensive analysis of morphology, microstructure, and mechanical characterization of parameters in the Inconel 718 laser cladding process on AISI 1050. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2024**, *238*, 10772–10784. [\[CrossRef\]](#)
13. Meng, Q.; Wang, C.; Liu, T.; Song, Q.; Xue, B.; Cui, H. Microstructure and performance optimization of laser cladding nano-TiC modified nickel-based alloy coatings. *Surf. Coat. Technol.* **2024**, *479*, 130583. [\[CrossRef\]](#)
14. Cheng, H.R.; Shin, K.H.; Kim, H.S. Enhancement of mechanical and tribological performance of Ti–6Al–4V alloy by laser surface alloying with Inconel 625 and SiC precursor materials. *Friction* **2024**, *12*, 2089–2107. [\[CrossRef\]](#)
15. Wang, Z.; Li, J.; Liu, Q.; Chen, L.; Lv, J.; Yu, T.; Zhao, J. No-impact trajectory design and fabrication of surface structured CBN grinding wheel by laser cladding remelting method. *Opt. Laser Technol.* **2025**, *181*, 111956. [\[CrossRef\]](#)
16. Kurtuluş, V.; Görgülü, B.; Eraslan, F.S.; Gecu, R. Improving wear and corrosion resistance of Ti-alloyed nodular cast irons by Al₂O₃ and SiC-reinforced Al₂O₃ coatings. *Surf. Coat. Technol.* **2025**, *498*, 131809. [\[CrossRef\]](#)
17. Zhao, J.; Li, R.; Feng, A.; Feng, H. Effect of rare earth La₂O₃ particles on structure and properties of laser cladding WC–Ni₆₀ composite coatings. *Surf. Coat. Technol.* **2024**, *479*, 130569. [\[CrossRef\]](#)
18. Li, Y.; Gao, Q.; Guan, X.; Tian, F.; Li, B.; Zhan, X. Effect of WC on the microstructure and wear resistance of Invar–WC coatings prepared by laser fusion cladding. *J. Mater. Res. Technol.* **2025**, *34*, 2285–2297. [\[CrossRef\]](#)
19. Ding, H.; Cui, T.; Wang, W.; Lin, Q.; Wang, L.; Yang, Y.; Yang, W.; Zhang, Q.; Xiao, Q.; Qi, H. Laser cladding WC/Fe composite coating on nose rail of turnout: Microstructure characteristics and wear behaviors. *Wear* **2025**, *570*, 205929. [\[CrossRef\]](#)
20. Han, W.; Xu, D.; Min, J.; Guo, Y.; Dai, G.; Sun, Z.; Chang, H.; Jia, Z. Influence of WC particle size on microstructural evolution and wear behavior of laser cladding WC/Ti₆Al₄V composite coatings. *Ceram. Int.* **2025**, *51*, 47119–47131. [\[CrossRef\]](#)
21. Qin, J.; Shu, L.; Wang, J.; Li, P.; Li, A.; Huang, T.; Dong, H. Study on the preparation and wear properties of laser clad Inconel 718/WC gradient composite coatings. *Mater. Today Commun.* **2024**, *41*, 111080. [\[CrossRef\]](#)
22. Cheng, Y.; Sun, Y.; Zhang, S.; Cheng, W.; Xu, Y.; Wei, S.; Luo, J. Corrosion and wear resistance of inconel 625 and inconel 718 laser claddings on 45 steel. *J. Alloys Compd.* **2025**, *1013*, 178368. [\[CrossRef\]](#)
23. Garcia, D.; Watanabe, K.I.; Marquez, L.; Arrieta, E.; Murr, L.E.; Wicker, R.B.; Medina, F. Microstructure and hardness properties for laser powder directed energy deposition cladding of Inconel 718 on electron beam powder-bed fusion fabricated Inconel 625 substrates: As-built and post-process heat treated. *Results Mater.* **2025**, *25*, 100660. [\[CrossRef\]](#)

24. Chen, J.; Yao, Z.; Wang, F.; Chi, Y.; Wang, Z.; Tofil, S.; Yao, J. Grain refinement and Laves phase dispersion by high-intensity ultrasonic vibration in laser cladding of Inconel 718. *J. Mater. Res. Technol.* **2024**, *308*, 563–8575. [[CrossRef](#)]
25. Ilanlou, M.; Razavi, R.S.; Nourollahi, A.; Hosseini, S.; Haghighat, S. Prediction of the geometric characteristics of the laser cladding of Inconel 718 on the Inconel 738 substrate via genetic algorithm and linear regression. *Opt. Laser Technol.* **2022**, *156*, 108507. [[CrossRef](#)]
26. Liu, Y.; Jin, H.; Li, G.; Xu, R.; Ma, N.; Liang, H.; Lin, J.; Xiang, W.; Zhang, Z. Microstructure and Mechanical Properties of Laser-Clad Inconel 718 Coatings on Continuous Casting Mold Copper Plate. *Lubricants* **2025**, *13*, 289. [[CrossRef](#)]
27. Xu, P.; Zhu, L.; Xue, P.; Yang, Z.; Wang, S.; Ning, J.; Qin, S. Microstructure and properties of IN718/WC-12Co composite coating by laser cladding. *Ceram. Int.* **2022**, *48*, 9218–9228. [[CrossRef](#)]

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