

Article

Effect of Laser Power on Microstructure and Tribological Performance of Ni60/WC Bionic Unit Fabricated via Laser Cladding

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Abstract

The unique structures and properties of natural organisms provide abundant inspiration for surface modification research in materials science. In this paper, the tribological advantages of radial ribs found on shell surfaces were combined with laser cladding to address challenges in material surface strengthening. Laser cladding technology was used to fabricate bionic units on the surface of 20CrMnTi steel. The alloy powder consisted of a Ni-based alloy with added WC particles. The influence of laser power (1.0 kW–3.0 kW) on the dimensions, microstructure, hardness, surface roughness, and tribological properties of the bionic units was investigated to enhance the tribological performance of the Ni60/WC bionic unit. The microstructure, phase composition, hardness, and tribological behavior of the bionic units were characterized using scanning electron microscopy (SEM), X-ray diffraction (XRD), a microhardness tester, and a wear tester. Experimental results show that the dimensions of the bionic units increased with laser power. However, beyond a certain threshold, the growth rate of the width and height gradually slowed due to heat conduction and edge cooling effects. The microstructure primarily consisted of equiaxed and dendritic crystals, with grain refinement observed at higher laser powers. The addition of WC resulted in average hardness values of 791 HV_{0.2}, 819 HV_{0.2}, 835 HV_{0.2}, and 848 HV_{0.2} across the samples. This enhancement in hardness was attributed to dispersion strengthening and grain refinement. Increasing the laser power also reduced the surface roughness of the bionic units, though excessively high laser power led to a roughness increase. The presence of WC altered the wear mechanism of the bionic units. Compared to the wear observed in the N60 sample, the wear amount of the WC-containing samples decreased by 73.7%, 142.1%, 157.5%, and 263.1%, respectively. Hard WC particles played a decisive role in enhancing tribological performance of the bionic unit.

Keywords: laser cladding; bionic unit; WC; Ni-based alloy; tribological performance



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1. Introduction

Wear and tear are major causes of component failure, often resulting in substantial economic losses [1]. Several strategies exist to improve the tribological performance of industrial components. While using high-performance materials can extend component lifespan, it also raises manufacturing costs [2,3]. Regular maintenance and timely part replacement can improve reliability but increase operating expenses [4]. Applying wear-resistant coatings to component surfaces can enhance reliability and service life while

reducing maintenance and replacement costs [5,6]. Laser cladding is currently one of the most promising surface strengthening technologies [7]. It uses high-energy laser beams to melt metal powders onto substrate surfaces, significantly improving wear, corrosion, oxidation, and thermal fatigue resistance [8–11]. Laser cladding offers substantial advantages for components operating under harsh conditions and is widely used in aerospace, marine, and other high-performance sectors. All of this is due to the many advantages of coatings prepared by laser cladding. Firstly, the coating achieved metallurgical bonding with the substrate, and a relatively shallow heat affected zone was formed [12,13]. Secondly, the rapid heating and cooling rates result in a uniform and dense microstructure of the coating [14]. Thirdly, the formation of in-situ intermediate phases and the retention of unmelted hard phases are beneficial for obtaining high-performance cladding layers [15]. Fourthly, laser cladding can achieve environmental protection, material saving, simple operation, and high controllability [16].

Organisms have evolved over billions of years to develop highly adaptive structures and functions [17]. For example, the radial ribs on shell surfaces are distinctive biological features that significantly influence tribological behavior. These ribs increase surface roughness and mechanical interlocking, thereby improving friction and reducing the risk of being swept away by flowing water. Additionally, the ribs help distribute external loads across the surface, mitigating localized wear and protecting internal structures. Bionic surface engineering draws inspiration from these intricate natural features and aims to replicate them on engineering material surfaces to meet a wide range of application needs [18]. In materials science and engineering, integrating bionic surface design with laser cladding enables precise microstructural control, imitation and enhancement of biological functions, and substantial improvement of overall material performance. This approach holds promise in fields such as aerospace, automotive manufacturing, and biomedicine.

A detailed study of laser processing parameters is essential for advancing laser cladding technology. Parameters such as laser power, scanning speed, and spot diameter significantly influence the cladding layer's microstructure, metallurgical bonding, and surface properties. Understanding the relationship between processing parameters and cladding quality allows for precise control and the production of coatings with excellent wear, corrosion, and heat resistance. In this paper, inspired by the radial ribs on shells, laser cladding was used to fabricate the bionic unit on 20CrMnTi steel. The alloy powder used was a Ni-based alloy with added WC particles. The effects of varying laser power (1.0 kW–3.0 kW) on the dimensions, microstructure, hardness, surface roughness, and tribological performance of the Ni60/WC bionic units were analyzed. This research aims to offer new insights and techniques for advancing the surface engineering of metallic materials.

2. Materials and Methods

2.1. Material and Laser Cladding

In this study, 20CrMnTi steel was selected as the substrate material. The cladding materials included Ni60 alloy powder, with a particle size of 320 mesh and spherical morphology, and WC powder, with a particle size distribution of 60–200 mesh and a block-shaped morphology. The 20CrMnTi steel used in this study was supplied by Xinjiang Bayi Iron and Steel Co., Ltd., located in Toutunhe District, Urumqi City, Xinjiang Province, China. Its chemical composition was provided by the manufacturer. The Ni60 powder was sourced from China Metallurgical New Materials (Nangong) Alloy Co., Ltd., situated in the Nangong Economic Development Zone, Xingtai City, Hebei Province, China. The Ni60 powder was prepared via vacuum atomization melting, and its chemical composition was also provided by the manufacturer. The WC particles were purchased from Zhuzhou Hard

Alloy Group Co., Ltd., located in Hetang District, Zhuzhou City, Hunan Province, China. These WC particles were produced using spray granulation followed by a sintering process. Their chemical composition was supplied by the manufacturer. The chemical compositions of the 20CrMnTi substrate, Ni60 alloy, and WC powder are summarized in Table 1. 20CrMnTi steel is widely used in key transmission components subjected to high cyclic loads, impact, and friction. Wear is the primary failure mode, leading to reduced dimensional accuracy, increased noise, and eventual malfunction. Traditional solutions include using high-alloy steels or deep carburizing/carbonitriding, which are time-consuming, energy-intensive, and require extensive post-processing. Laser cladding with Ni60/WC offers a surface-specific strengthening method. It allows selective enhancement of wear-prone regions while retaining the original bulk properties of the substrate. This reduces the need for high-cost base materials and complex heat treatments. Laser cladding also minimizes thermal distortion due to its precise, localized heating and results in smaller machining allowances and lower raw material costs. A strong metallurgical bond is formed between the coating and substrate, eliminating the need for additional heat treatments and shortening production cycles. Laser cladding was performed using a 3 kW high-power fiber laser system (Guangzhou Xingrui Laser Technology Co., Ltd., Guangzhou, China), with only the laser power varied across samples, while all other processing parameters remained constant. A coaxial powder-feeding method was employed for delivering the powder mixture into the melt pool. To prevent oxidation during processing, argon (Ar) gas was used as a shielding atmosphere at a flow rate of 20 L/min. Detailed laser cladding parameters, powder mixing ratios, and sample designations are provided in Table 2.

Table 1. Chemical composition of substrate and powder.

Element (wt.%)	C	B	Si	Cr	Mn	Ni	Fe	Ti	W
20CrMnTi	0.17–0.23	-	1.00–1.30	0.17–0.37	0.80–1.10	-	Bal	0.04–0.10	-
Ni60	0.5–1.1	3–4.5	3.5–5.5	12–20	-	Bal	≤5	-	-
WC	3.9	-	0.0118	0.0067	-	-	0.11	0.0008	Bal

Table 2. Processing parameters and sample number.

Sample Number Parameters	Laser Power (kW)	Scanning Speed (mm/min)	Wavelength (nm)	Spot Radius (mm)	Powder Delivery Rate (g/min)	Ni60 Content (wt.%)	WC Content (wt.%)
N60	2.0	200	1070	4	12	100	0
NWP1	1.0					70	30
NWP2	1.5						
NWP3	2.0						
NWP4	3.0						

2.2. Surface Roughness Measurement

The surface roughness (Ra) of the bionic unit was evaluated using a Veeco Wyko NT1100 optical profiler (Veeco Instruments Inc., Tucson, AZ, USA). For each sample, five replicate measurements were performed. An appropriate sampling length was selected in each case to ensure the accuracy and consistency of the average surface roughness values.

2.3. Microstructure Observation and XRD Measurement

The cross-sectional morphology and microstructure of the bionic units were examined using a scanning electron microscope (SEM) equipped with an energy-dispersive spectrometer (EDS) for elemental analysis (JEOL Ltd., Akishima, Tokyo, Japan). Phase composition of the cladded layers was conducted using an X-ray diffractometer (XRD) (Rigaku Corporation, Akishima, Tokyo, Japan), operated at 40 kV and 30 mA with Cu-K α

radiation. Diffraction patterns were recorded over a 2θ range of $20\text{--}90^\circ$ at a step size of 0.02° .

2.4. Hardness Measurement

The microhardness of the bionic unit was measured using a Vickers hardness tester (Mitutoyo Corp., Kawasaki, Kanagawa, Japan). A load of 200 gf was applied for 10 s during each measurement. Hardness was measured along the depth direction of the bionic unit cross-sections, beginning at the top of the clad layer and progressing toward the substrate, with measurements taken at 0.1 mm intervals. At each depth, ten measurement points were recorded, and the average of the ten values was reported as the hardness at that depth to minimize experimental error.

2.5. Wear Tests

Wear performance was evaluated using a ring-on-block wear testing machine, as illustrated in Figure 1. The manufacturer of the wear testing machine is Jinan Sida Testing Technology Co., Ltd. The company is located in Jinan City, Shandong Province, China. The samples were machined to dimensions of $17\text{ mm} \times 7\text{ mm} \times 7\text{ mm}$. Before the formal wear test, each sample underwent surface preparation. A file was used to polish the surface until a flat plane with an area of approximately 2 mm^2 was formed at the center. This flat surface served as the contact interface with the grinding roller. Temperature can significantly influence wear behavior. High temperatures may soften materials and increase plastic deformation. All tests in this study were conducted at room temperature (25°C) to avoid thermal softening and ensure that the observed effects were solely due to laser power variation. A precision electronic balance was used to determine the weight loss before and after the wear tests. Each test was repeated three times, and the average weight loss was taken as the final wear amount. The tests were conducted under the following conditions: 200 rpm rotational speed, 200 N applied load, and 20-min test duration. The primary purpose of a running-in stage is to eliminate initial surface defects and stabilize contact conditions. However, in this study, variations in laser power affected the surface roughness of the bionic units. Conducting a running-in procedure would quickly eliminate these surface differences, making it impossible to assess the influence of surface roughness on tribological performance. To preserve the original surface features, the running-in test was deliberately omitted. This approach enables a more accurate analysis of how surface topography affects frictional behavior. The wear test parameters were selected as follows. (a) Different friction speeds correspond to distinct wear mechanisms in the coatings. At low speeds ($<200\text{ rpm}$), adhesive wear is dominant. At medium speeds ($200\text{--}1000\text{ rpm}$), a combination of abrasive and oxidative wear typically occurs. This medium range is commonly used to accurately evaluate the conventional wear performance of coatings. To avoid the adverse effects of frictional heat on the tribological behavior of the bionic unit, a friction speed of 200 rpm was chosen in this study. At high speeds ($>1000\text{ rpm}$), additional cooling systems are required to prevent overheating. (b) Different loads help evaluate wear behavior under various working conditions. Low loads ($<50\text{ N}$) assess the load-bearing support offered by WC particles. Moderate loads ($50\text{--}150\text{ N}$) promote abrasive wear, while high loads ($>150\text{ N}$) test the coating's performance under severe conditions. To avoid overloading and ensure representative results, a load of 200 N was selected. (c) The friction coefficient curve of coatings usually includes an initial wear stage followed by a stable wear stage. In the initial stage, surface asperities are quickly worn down, leading to a sharp increase in the friction coefficient. In the stable stage, the coefficient tends to level off. Based on preliminary trials, a test duration of 20 min was determined to be suitable. The counter-body was a Cr18W4V steel grinding roller, with a hardness of approximately

595 HV_{0.2}. After testing, the worn surfaces of the samples were observed using SEM to identify wear mechanisms. To remove wear debris during testing, a copper wire brush was employed. It was mounted on a fixed bracket and remained in continuous contact with the rotating grinding roller, removing debris in real time. After each test, the brush was cleaned using ultrasonic treatment to eliminate any residual particles and prevent contamination of subsequent tests.

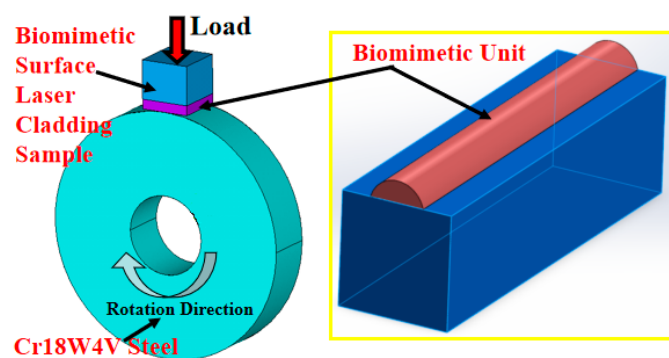


Figure 1. Schematic diagram of block-on-ring tribometer and bionic unit.

3. Results and Discussion

3.1. Dimensions

Figure 2a shows the cross-sectional morphology of the bionic units, highlighting both their height and width. Higher laser power resulted in greater energy input, which melted more powder and increased melt pool fluidity [19–21]. The Marangoni effect describes fluid motion driven by surface tension gradients. Surface tension, a result of intermolecular cohesion at the liquid interface, varies with temperature, concentration, and composition. A surface tension gradient causes fluid to flow from regions of lower tension to regions of higher tension, resulting in characteristic flow patterns. The intensified Marangoni effect promoted melt pool expansion in both width and height directions, ultimately increasing the dimensions of the bionic units. Figure 2b presents the measured dimensions. The bionic unit widths at different laser powers were 3.17 mm, 4.12 mm, 4.85 mm, and 5.12 mm, corresponding to growth rates of 29.9%, 17.7%, and 5.5%, respectively. As laser power continued to increase, the growth rate slowed due to thermal conductivity limitations and edge cooling. The bionic unit heights were 1.91 mm, 2.39 mm, 2.96 mm, and 3.25 mm, with respective growth rates of 25.1%, 23.8%, and 9.7%. Although the growth rate showed some irregularities, height consistently increased with laser power due to the increased amount of molten material available for deposition. Wang, S.S. et al. [22] also found a direct correlation between laser power and coating height. At the same laser power, the width of the bionic unit in the N60 sample (5.33 mm) was larger than in the NWP3 sample. This is because WC has a significantly higher melting point (~2600 °C) compared to Ni-based alloys (~1450 °C). The unmelted WC particles increased melt pool viscosity, suppressed lateral flow, and reduced the final width in the NWP3 sample. In contrast, the N60 alloy exhibited better fluidity, resulting in epitaxial spreading of the melt pool. However, the height of the bionic unit in the N60 sample (2.48 mm) was lower than in the NWP3 sample. This is attributed to the higher density of WC (~15.6 g/cm³ vs. ~8.9 g/cm³ for Ni-based alloys), which causes the WC particles to sink and aggregate at the melt pool bottom, forming a rigid skeletal support that increases the vertical build-up in the NWP3 sample.

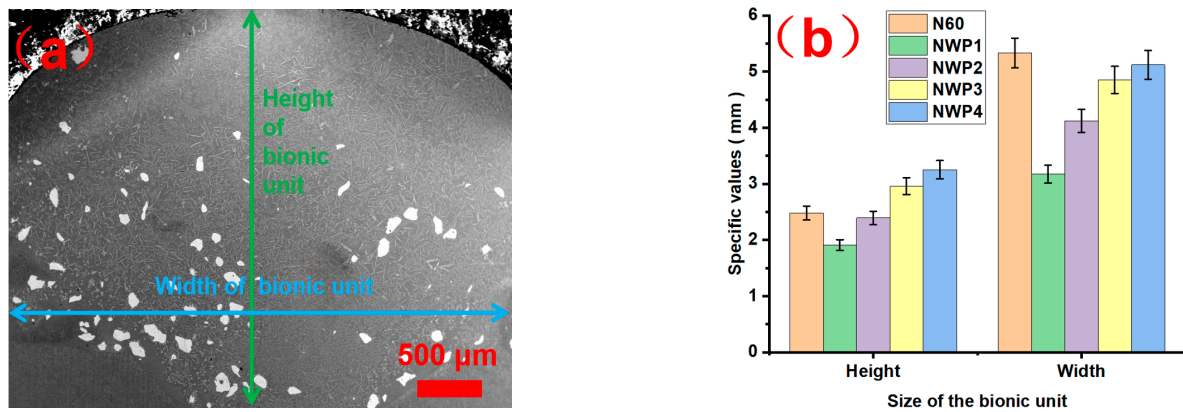


Figure 2. Cross section of bionic unit: (a) surface morphology of bionic unit of NWP4 sample; (b) height and width of each sample.

3.2. Microstructure

Laser power is a critical process parameter in laser cladding, as it governs the energy input per unit area into the molten pool [23,24]. When the laser power is too low, the metal powder does not absorb sufficient energy and cannot fully melt, resulting in poor metallurgical bonding between the bionic unit and the substrate. Conversely, excessive laser power can cause the metal powder to overheat and burn [25]. Zhou, S.F. et al. [26] reported that the metallurgical bonding strength between the coating and the substrate produced by laser cladding is higher than that achieved through other heat treatment methods. Figure 3 shows the longitudinal cross-sectional morphology of the bionic units fabricated under different laser powers. A distinct bonding line was visible between the bionic unit and the substrate. Most of unmelted WC particles were concentrated at the bottom of the bionic unit due to gravitational settling. Chen, J.S. et al. [27] pointed out that under low laser power, WC particles aggregate in the coating. Yan, Z.B. et al. [28] attributed the deposition of WC particles at the bottom of the coating to their higher density relative to the substrate. Notably, as the laser power increased, the number of visible WC particles in the bionic units decreased, which was attributed to their partial or complete melting under high-temperature conditions [29].

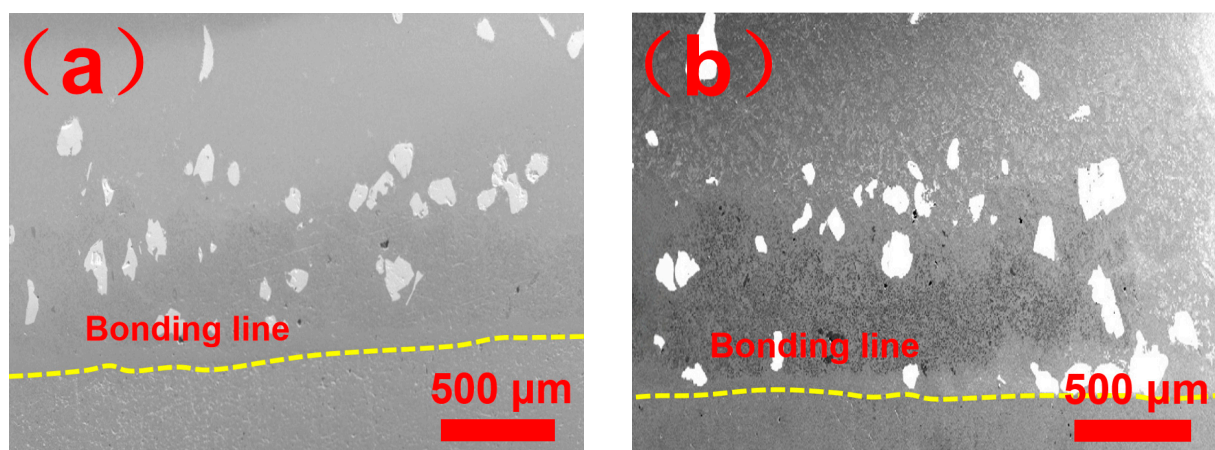


Figure 3. Cont.

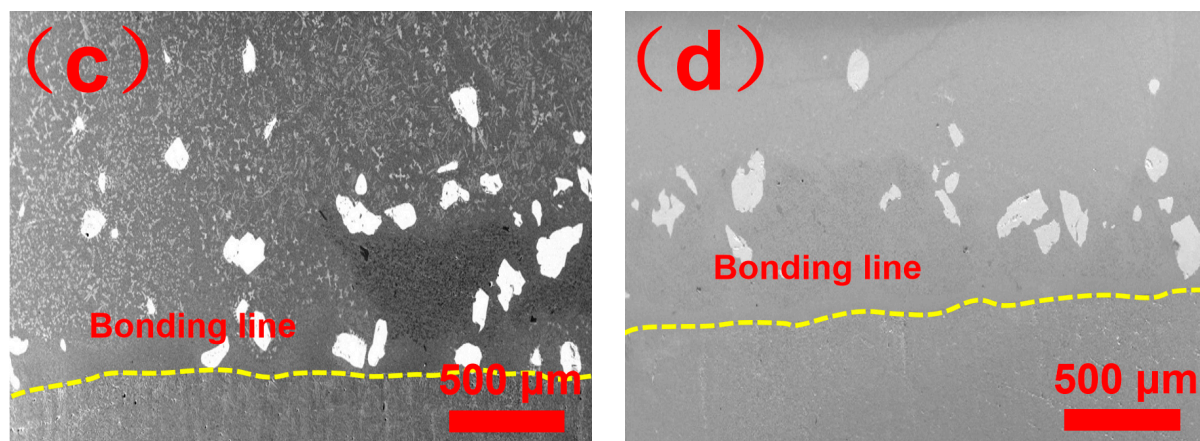


Figure 3. Longitudinal section of bionic unit: (a) NWP1 sample; (b) NWP2 sample; (c) NWP3 sample; (d) NWP4 sample.

Figure 4 reveals that the microstructure of the bionic units mainly comprises equiaxed and dendritic crystals. The upper regions of the bionic units were particularly affected by laser power. At lower laser power, incomplete melting led to coarse grains and a non-uniform distribution of WC particles. With increased laser power, the molten pool temperature rose, resulting in complete melting of the metal powder. The melting and partial decomposition of WC particles modified the local chemical composition, promoting non-uniform nucleation [30,31]. Additionally, unmelted WC particles and liberated carbon hindered grain growth, contributing to microstructural refinement [32]. Xu, L.F. et al. [33] reported that higher laser power promotes grain refinement in the coating microstructure. The uniform distribution of WC particles and carbides, acting as dispersed hard phases, was advantageous for improving the hardness and tribological properties of the bionic unit. In contrast, as shown in Figure 4d, the microstructure of the N60 sample (without WC) was coarser than that of the WC-containing samples. The addition of WC significantly refined the microstructure [34]. Due to relatively low temperature gradients and undercooling in the upper molten pool, heat primarily diffused downward, promoting the formation of equiaxed grains in the top regions. Figure 4e,f illustrates a morphological transition from equiaxed grains at the top to columnar and cellular dendrites deeper within the bionic unit. The substantial temperature gradient at the solid-liquid interface promoted directional solidification [35]. Grains grew preferentially perpendicular to the substrate due to the directional heat flow. In the intermediate region, where the cooling rate was lower and the temperature gradient was higher, columnar dendrites developed. Subsequently, as heat flow stabilized, new nucleation occurred on existing dendrites, forming disordered cellular dendrites. Figures 5 and 6 present EDS mapping of equiaxed and dendritic crystals. The tungsten (W) content was notably higher at equiaxed grain boundaries and within dendrites compared to other areas. In contrast, iron (Fe) content was lower in these W-enriched regions and more uniformly distributed elsewhere. This suggests limited diffusion of Fe from the substrate into the bionic unit due to rapid cooling and solidification during laser cladding, which restricts long-range elemental diffusion in 20CrMnTi steel.

Figure 7 shows the XRD patterns of all samples. All samples had similar primary phase compositions, except that the N60 sample lacked WC and W_2C diffraction peaks. Zhao, Y.C. et al. [36] noted that the decrease in diffraction peak intensity is caused by the dilution effect within the coating. With the addition of WC, the bionic unit mainly consisted of γ -(Ni, Fe), Ni_3Fe , WC, and W_2C . The γ -(Ni, Fe) phase formed a solid solution with other alloying elements [37]. Some WC particles retained their original shape, producing WC

peaks, while others reacted under high temperatures, breaking down and forming W_2C , as indicated by corresponding diffraction peaks.

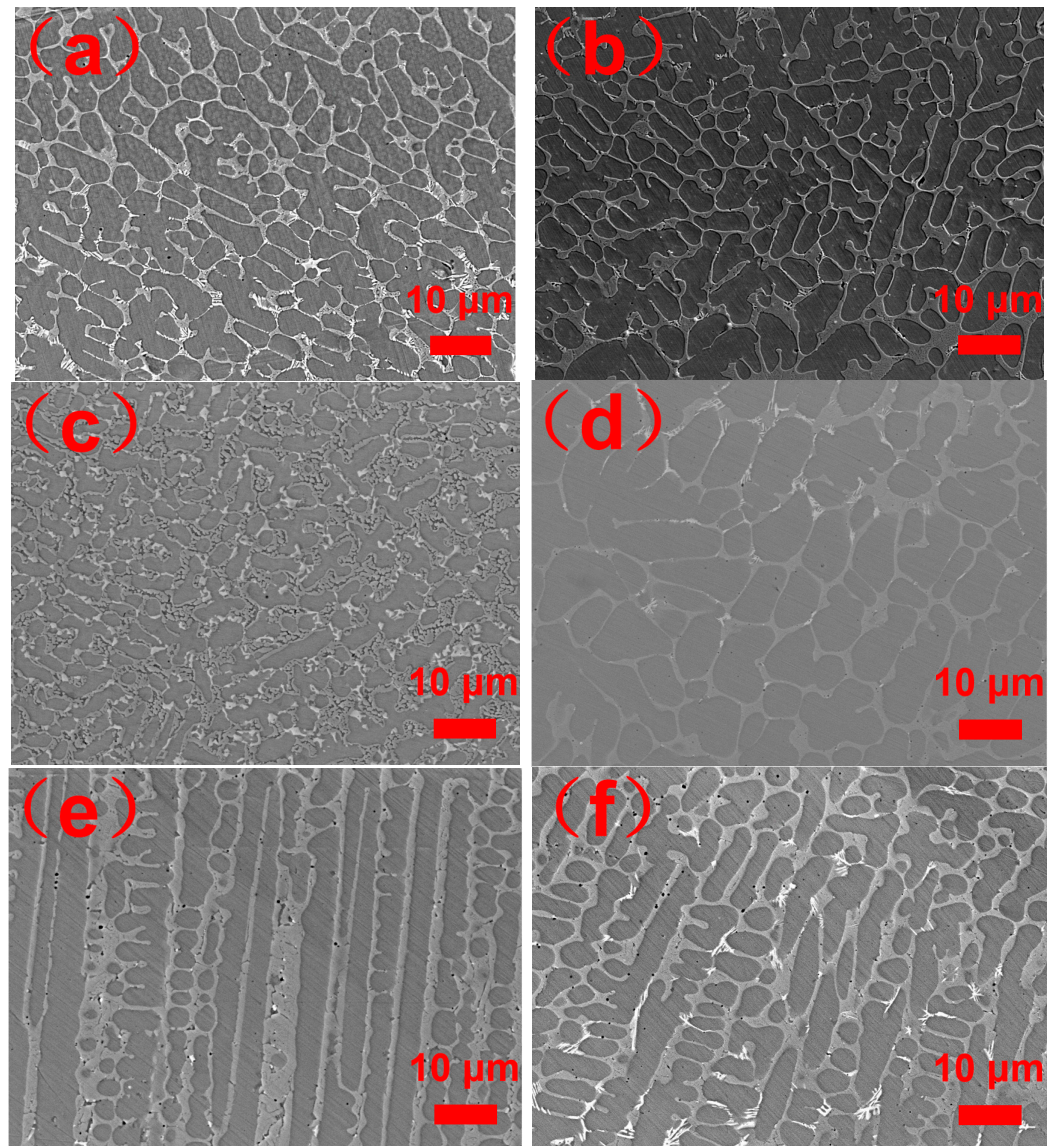


Figure 4. Microstructure of each sample: (a) upper region of NWP1 sample; (b) middle region of NWP3 sample; (c) upper region of NWP4 sample; (d) upper region of N60 sample; (e) central region of NWP4 sample; (f) lower middle area of NWP4 sample.

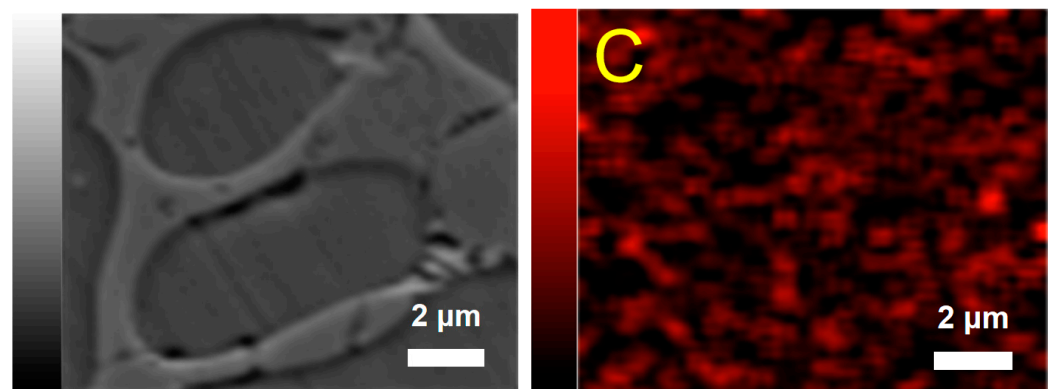


Figure 5. Cont.

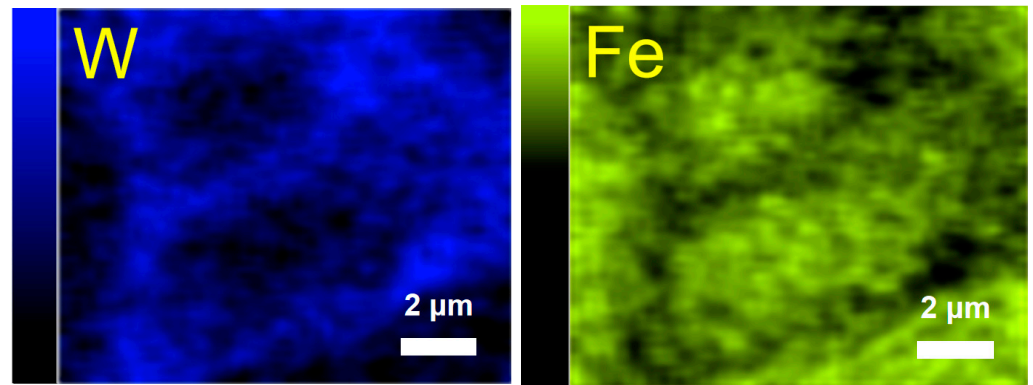


Figure 5. EDS mapping results of equiaxed crystals.

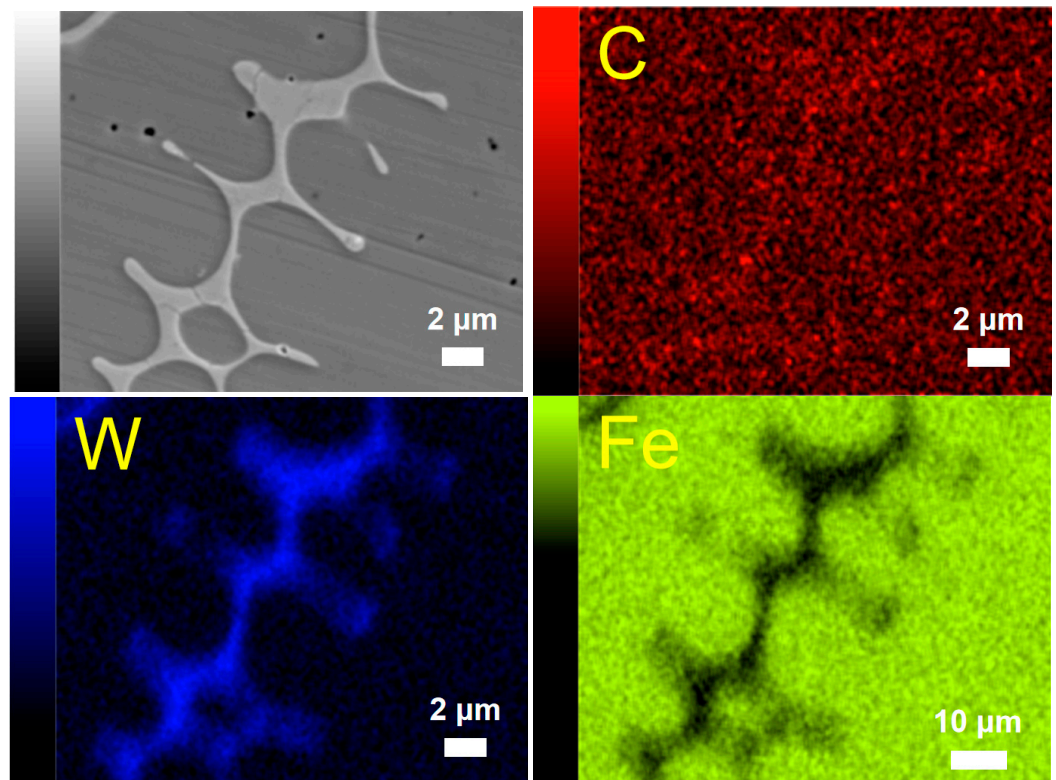


Figure 6. EDS mapping results of dendritic crystals.

As shown in Figure 8, compositional variations across WC particles indicate that Fe content decreases and W content increases from the exterior to the interior. The white precipitates surrounding WC particles are also rich in W, indicating partial decomposition and diffusion of WC. The presence of Fe is attributed to melting of the substrate by the laser, which allows Fe to diffuse into the molten pool and incorporate into the liquid phase [38].

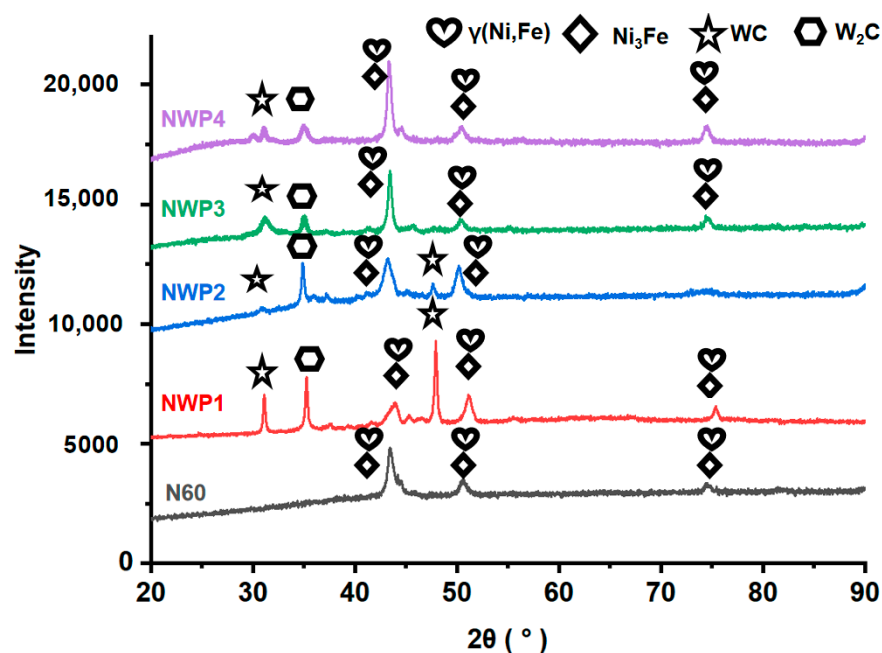


Figure 7. XRD patterns of each sample.

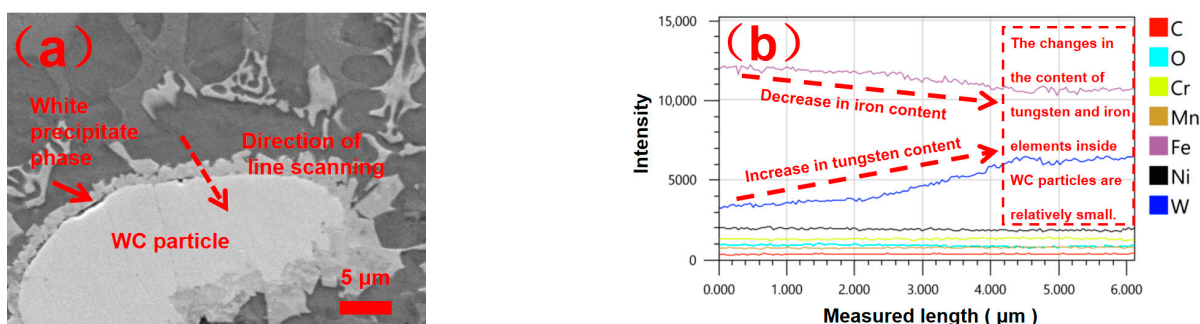


Figure 8. EDS line scan results of WC particle. (a) WC particles and their line scanning direction, (b) line scan results of WC particles.

3.3. Hardness

Figure 9 presents the microhardness profiles of the bionic units formed under different laser powers. Across all samples, the hardness initially increased and then decreased with depth from the surface. At low laser power, insufficient melting led to coarse grains and poor WC particle distribution, resulting in lower hardness [39]. As laser power increased, complete melting of WC particles, grain refinement, and the formation of hard carbides significantly enhanced the hardness of the bionic unit. Xu, Z.Q. et al. [40] identified that the incomplete melting of WC particles, resulting from insufficient laser power, is a primary cause of reduced coating hardness. The maximum hardness was observed at 3.0 kW, reaching 900 HV_{0.2}. The average hardness values for the WC-containing bionic units were 791 HV_{0.2}, 819 HV_{0.2}, 835 HV_{0.2}, and 848 HV_{0.2}, corresponding to increasing laser power. These values represent growth rates of average hardness of 3.5%, 1.9%, and 1.5%, respectively. Compared to the N60 sample (average 763 HV_{0.2}), the hardness improvements were 3.6%, 7.3%, 9.5%, and 11.1%, respectively. This confirms that the addition of WC significantly enhances hardness. Several mechanisms contribute to this hardness improvement: (1) dispersion strengthening from unmelted WC particles, (2) grain refinement, which increased hardness according to the Hall–Petch relationship, and (3) solid solution strengthening from W and C atoms released during WC decomposition [41–43]. Overall, the WC-containing bionic units exhibited 3.4 to 3.8 fold

the hardness of the 20CrMnTi substrate (approximately 220 HV_{0.2}), indicating significantly enhanced resistance to plastic deformation and improved tribological performance.

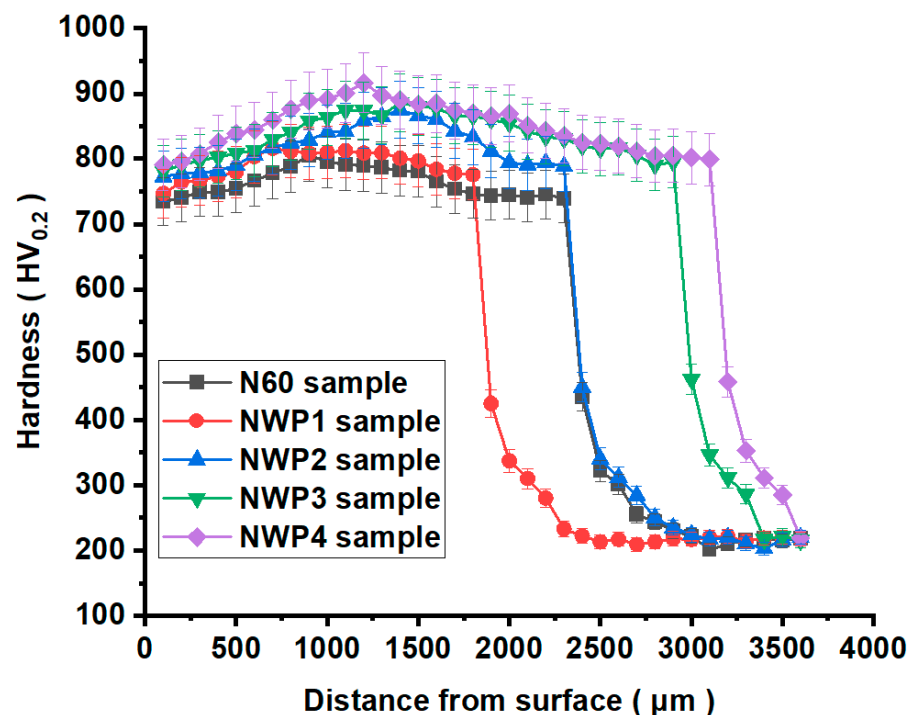


Figure 9. Hardness curves of various bionic units.

3.4. Surface Roughness

Figure 10 shows the surface roughness of the samples measured along the laser scanning direction. The roughness values for the WC-containing bionic units were 1.677 μm, 1.428 μm, 1.042 μm, and 1.245 μm at increasing laser powers. Initially, surface roughness decreased with increasing laser power, reaching a minimum at 2.0 kW, and then slightly increased. Laser power significantly affected surface morphology. At low power, the molten pool was small and poorly fluid, leading to incomplete melting and irregular surface formation [44]. Increasing the laser power enhanced melting and fluidity, promoting a stable molten pool and smoother surface finish. However, excessive power intensified the Marangoni effect and increased the risk of metal evaporation and spatter, thereby deteriorating surface quality. Thus, the relationship between laser power and surface roughness was nonlinear. Optimizing laser power was essential to ensure metallurgical bonding and achieved an acceptable surface finish. The N60 sample exhibited the lowest roughness (Ra 0.894 μm). The addition of WC increased surface roughness to varying degrees by 87.5%, 59.7%, 16.5%, and 39.2%, respectively. WC's high melting point (~2600 °C) hindered full melting, and the resulting unmelted or partially melted particles increased the viscosity of the molten pool. This impeded flow, creating surface irregularities. Moreover, differences in thermal expansion coefficients between WC and the Ni-based matrix could generate micro-stresses during rapid solidification, causing localized bulging and increased surface roughness.

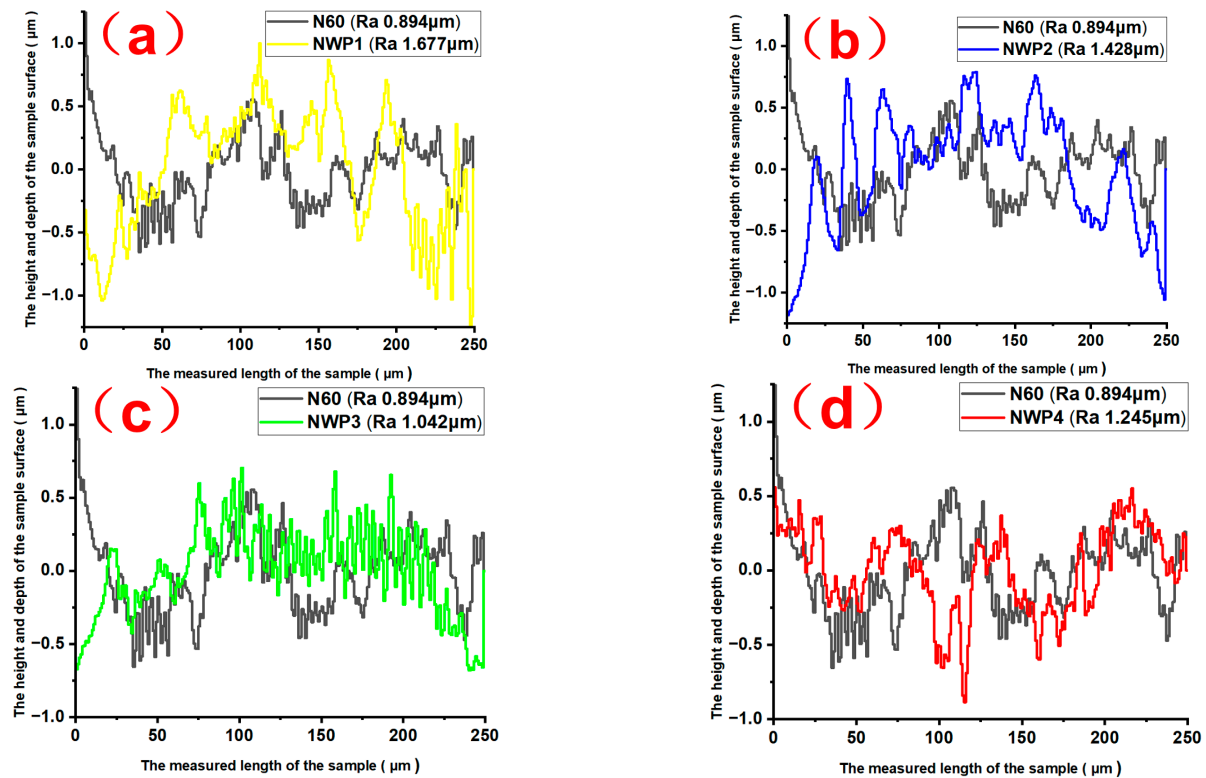


Figure 10. Surface roughness and two-dimensional curves of each sample: (a) N60 sample and NWP1 sample; (b) N60 sample and NWP2 sample; (c) N60 sample and NWP3 sample; (d) N60 sample and NWP4 sample.

3.5. Wear Test Results

3.5.1. Tribological Performance

Figure 11a shows the wear amount of the bionic units as 5.1 mg, 3.66 mg, 3.44 mg, and 2.44 mg, respectively. As laser power increased, the wear amount of the bionic units decreased continuously. Notably, the tribological performance of the bionic units exhibited a strong positive correlation with their hardness. Compared to the wear amount of the N60 sample (8.86 mg), the wear amount of the other samples decreased by 73.7%, 142.1%, 157.5%, and 263.1%, respectively. This significant improvement is attributed to the incorporation of WC particles, which effectively enhance the hardness of the bionic units and suppress the shear action of the grinding roller, thereby reducing material loss. Figure 11b illustrates the friction coefficient curves of each sample, which follow a similar trend. The wear process could be divided into two distinct stages: the running-in stage and the steady-state wear stage. During the running-in stage, the friction coefficient increased sharply. In the steady-state stage, the friction coefficient stabilized at a lower value. With increasing laser power, the average friction coefficients of the bionic units decreased to 0.229, 0.199, 0.188, and 0.168, respectively. Compared to the N60 sample (0.274), the average friction coefficient of the bionic units decreased by 19.6%, 37.6%, 45.7%, and 63.1%, respectively. The N60 sample exhibited the highest friction coefficient of 0.341 before stabilizing around 0.275. In contrast, the NWP4 sample showed a peak friction coefficient of 0.218 and stabilized near 0.155. The higher friction coefficient in the N60 sample was primarily due to its lower hardness, which resulted in easier material removal. As wear progressed and grooves deepened, the contact area between the sample and the grinding roller increased, leading to a rise in local temperature [45,46]. Once thermal equilibrium was achieved, the friction coefficient stabilized. The lower friction coefficients observed in the bionic units were primarily due to the presence of WC. As shown in Figures 12 and 13, during the wear process, the

relatively soft Ni-based matrix were preferentially, gradually exposing WC particles. These high-hardness particles became the actual contact points between the bionic units and the grinding roller. Zhang, K.W. et al. [47] confirmed the mechanical support provided by WC particles to the substrate during wear testing. While WC particles bore most of the mechanical load, the Ni-based alloy absorbed energy and buffered part of the stress. Consequently, the effective contact area decreased, leading to reduced friction [48]. The high hardness of WC particles played a decisive role in enhancing the tribological performance of the bionic units. The size and spatial distribution of WC particles significantly influence the tribological performance of bionic units. (a) Large WC particles provide mechanical support but can create stress concentrations. Under cyclic loading, they are more likely to detach, becoming abrasive particles and promoting three-body wear. Small WC particles are less resistant to plastic deformation, which can cause premature wear in localized regions. Once detached, these regions expose the softer matrix, leading to fluctuations in the friction coefficient. When both large and small particles coexist, height mismatches in the hard phases cause uneven stress distribution and accelerate coating delamination. (b) In WC-rich regions, local hardness is high, but excessive particle volume can weaken interfacial bonding with the Ni-based matrix, leading to delamination under stress. In WC-poor regions, reduced hardness makes the material more susceptible to wear, resulting in groove formation and peeling of adjacent material. Accordingly, wear morphology varies: abrasive wear dominates in WC-rich zones, while plastic deformation and adhesive wear are more prominent in WC-poor zones.

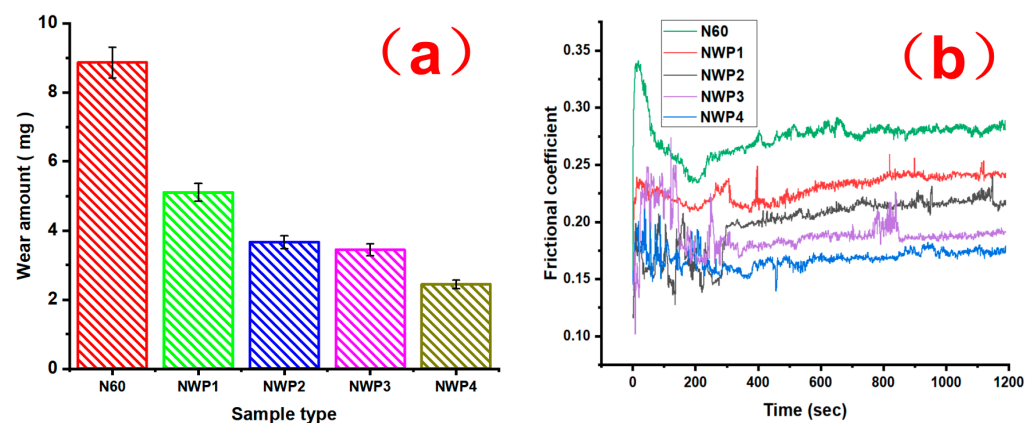


Figure 11. Wear test results: (a) wear amount of each sample; (b) friction coefficient of each sample.

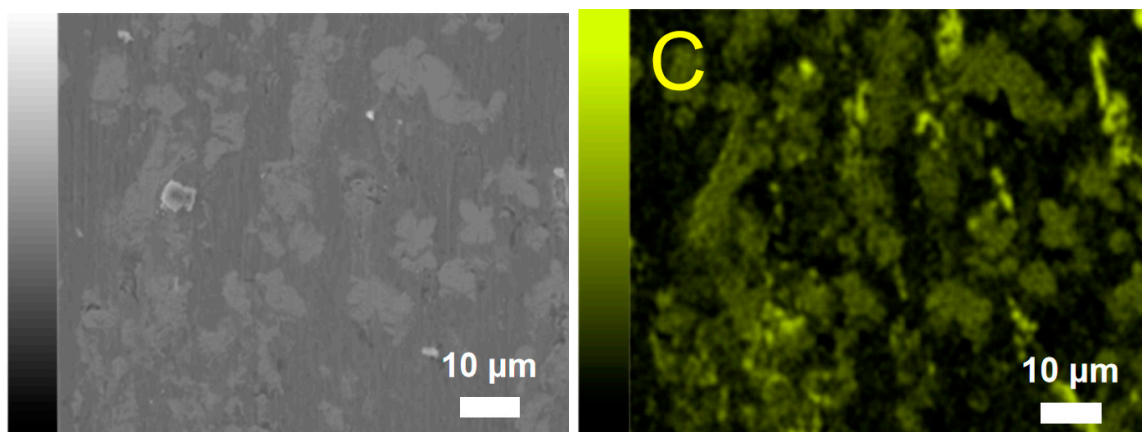


Figure 12. Cont.

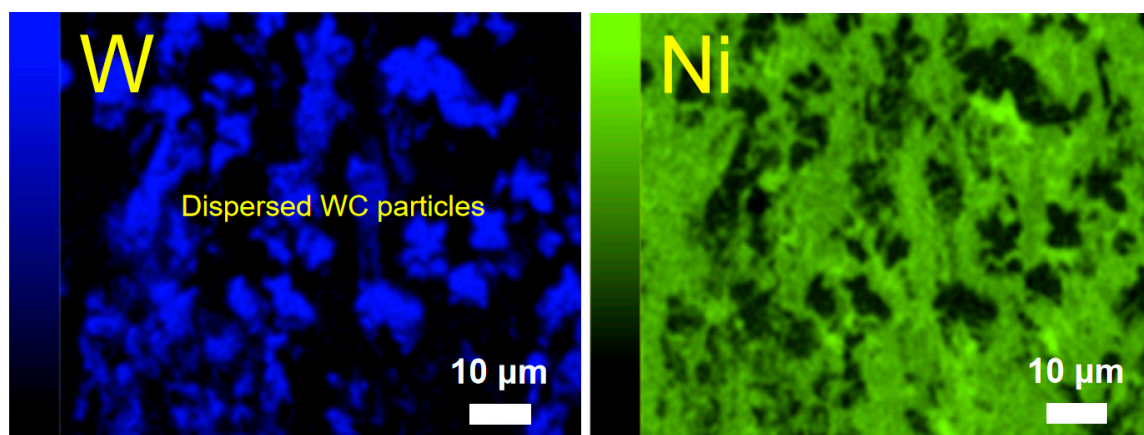


Figure 12. EDS mapping of exposed WC on NWP4 sample surface.

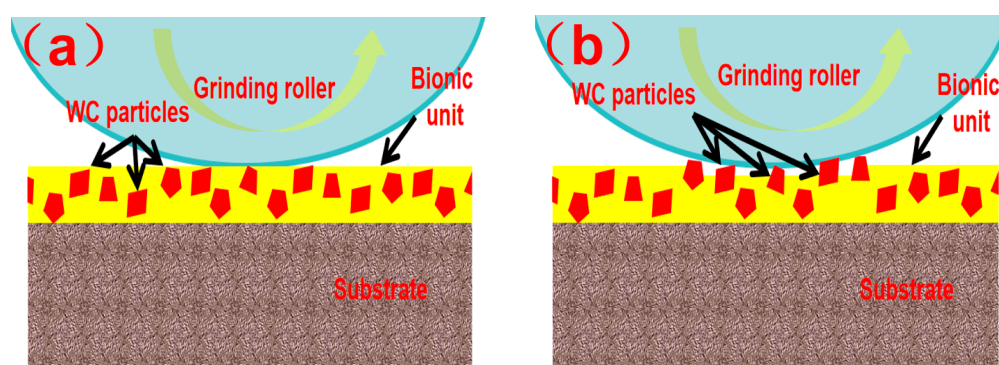


Figure 13. The function of WC: (a) WC embedded in the bionic unit; (b) WC exposed from the bionic unit.

3.5.2. Wear Morphology

Figure 14a displays the wear morphology of the N60 sample. Due to its relatively low hardness, surface material fractured and detached easily, generating fine debris. These particles remained trapped between the friction interfaces and contribute to three-body abrasive wear, leading to the formation of ploughing grooves and scratches [49,50]. The dominant wear mechanisms in the N60 sample were abrasive and oxidative wear. Figure 14b–d present the wear morphologies of bionic units fabricated at different laser powers. The addition of WC modified the wear mechanisms to a combination of adhesive, oxidative, and abrasive wear. Quazi, M.M. et al. [51] found that Ni/WC coatings exhibited similar wear mechanisms. Surface scratches due to abrasive action were evident. The increased hardness of the bionic units effectively resisted plastic deformation under frictional stress. As laser power increased, the severity of wear on the bionic units diminished. For example, peeling pits were visible on the NWP1 sample (Figure 14b), but their number was significantly reduced in the NWP4 sample (Figure 14d). This is because lower laser power leads to incomplete melting of WC particles, causing stress concentration around them and inducing peeling under shear stress. Figure 15 shows fine debris adhering to the surface of the NWP4 sample, indicating plastic deformation and material peeling during wear. This debris primarily consisted of iron oxides. The quantity of debris varied with laser power; the NWP1 sample exhibited more wear debris and a higher wear mass than the NWP3 and NWP4 samples. Generally, improved tribological performance correlated with a reduced amount of adherent abrasive debris.

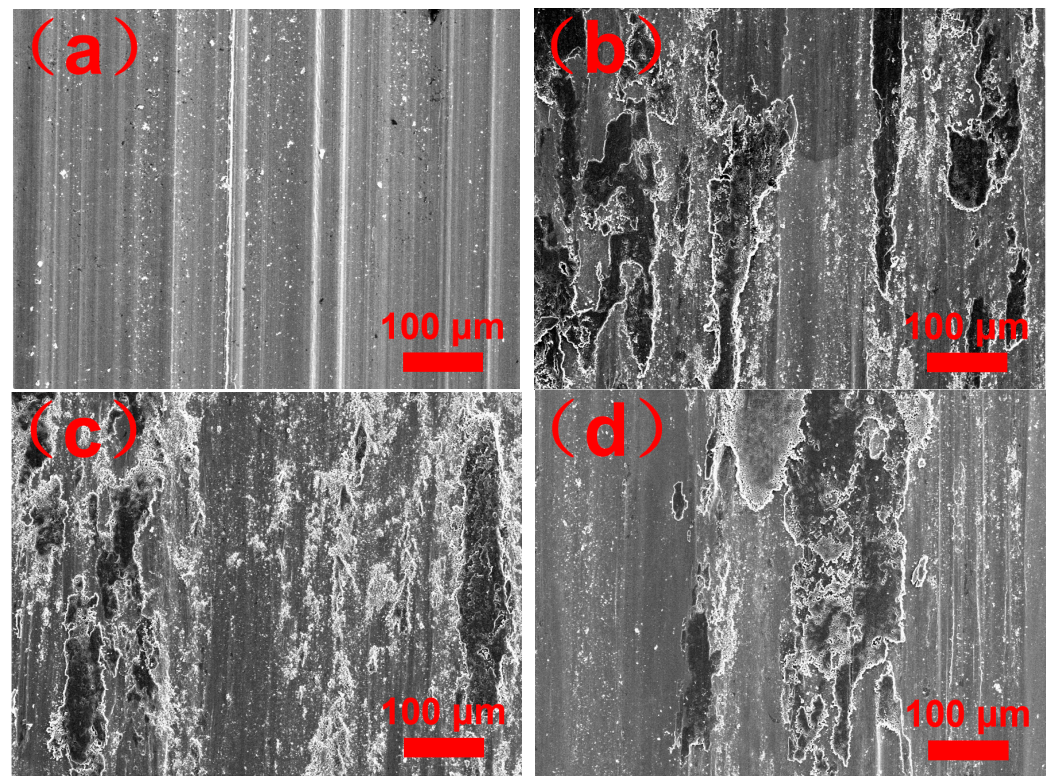


Figure 14. Worn morphology of samples: (a) N60 sample; (b) NWP1 sample; (c) NWP3 sample; (d) NWP4 sample.

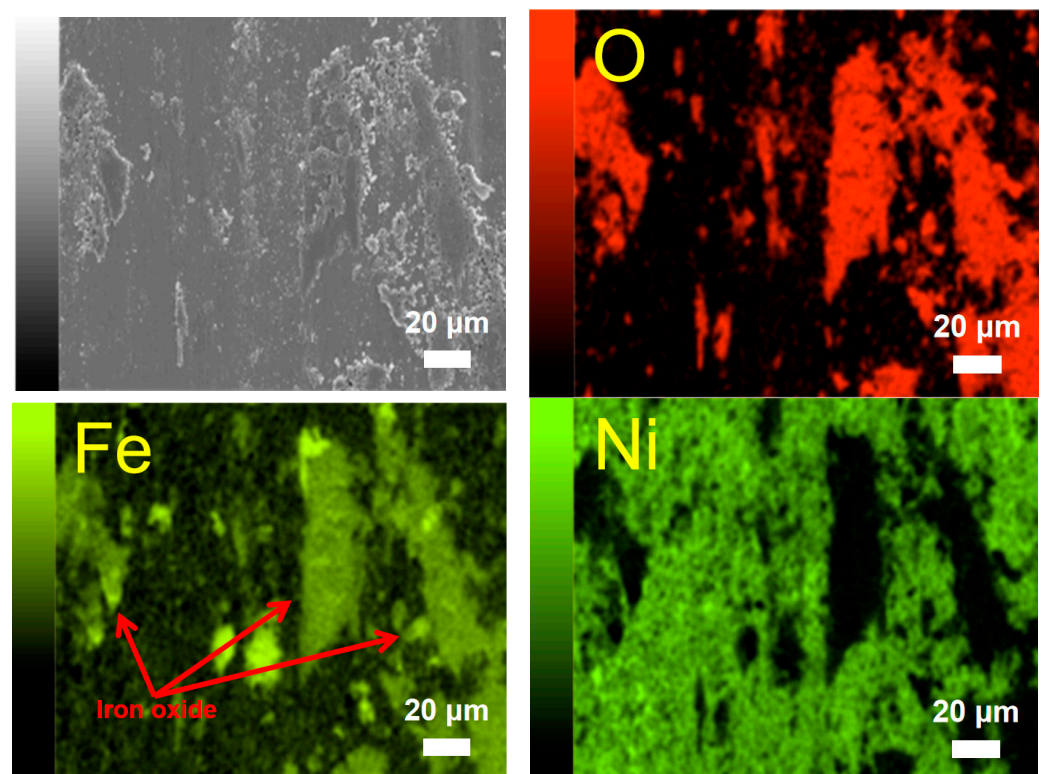


Figure 15. EDS mapping of worn surface of NWP4 sample.

3.5.3. The Wear Resistance Mechanism

(1) Dispersion Strengthening

At lower laser powers, insufficient melt pool temperature results in partial melting of WC particles. These incompletely melted particles tend to aggregate, impairing the tribological performance of the bionic units. Increased melt pool temperature improves elemental diffusion and mixing, facilitating the formation of various carbides. Both unmelted WC and newly formed carbides contribute to dispersion strengthening, enhancing wear resistance [52].

(2) Microstructure

Higher laser power increases melt pool temperature and improves the fluidity of the molten metal, promoting a more uniform distribution of WC particles in the Ni-based matrix. The large thermal gradients and rapid solidification rates during laser cladding result in fine-grained microstructures. Grain refinement enhances hardness and wear resistance by increasing the number of grain boundaries that inhibit plastic deformation [53]. Furthermore, higher laser power promotes interfacial reactions between WC and the Ni-based matrix, forming additional hard phases.

(3) Hardness

Rising laser power leads to increased hardness in the bionic units. The highest average and maximum hardness values recorded were 848 HV_{0.2} and 900 HV_{0.2}, respectively. Optimal laser power ensures complete melting of WC particles, releasing W and C atoms that form hard phases with the matrix. This significantly enhances both the hardness and tribological performance of the bionic units. Higher hardness improves resistance to material loss during friction.

(4) Surface roughness

Lower laser power results in irregular surface formation due to insufficient powder melting. These rough surfaces experience higher contact stresses, increasing both friction and wear. At appropriate laser powers, the improved melt pool fluidity leads to smoother surfaces and reduced roughness. However, excessively high laser power can lead to abnormal roughness increases. Lower surface roughness generally contributes to enhanced tribological properties.

4. Conclusions

In this paper, the principles of biomimetic engineering were applied to laser cladding technology by designing Ni60/WC bionic unit inspired by the radial ribs found on shell surfaces. The investigation focused on the effects of laser power on the geometric dimensions, microstructure, hardness, surface roughness, and tribological performance of the bionic unit. The experimental results demonstrated that the incorporation of WC particles significantly enhanced the tribological properties of the Ni60-based cladding, confirming the superiority of the biomimetic design. This work provides novel interdisciplinary insights into the design and optimization of laser-cladded coatings for wear-resistant applications. The following main conclusions were drawn:

The size of the bionic unit increased with laser power, though the growth rate of width and height eventually slowed due to limitations from heat conduction and edge cooling effects on the melt pool.

The bionic unit primarily consisted of equiaxed and dendritic crystals. With increasing laser power, improved melt pool temperatures led to complete melting of the metal powder. The presence of unmelted WC and free carbon particles impeded grain growth, resulting in refined microstructure.

The average hardness values of the WC-reinforced bionic units were 791 HV_{0.2}, 819 HV_{0.2}, 835 HV_{0.2}, and 848 HV_{0.2}, representing increases of 3.6%, 7.3%, 9.5%, and

11.1%, respectively, compared to the N60 sample (763 HV_{0.2}). The enhancement in hardness was due to dispersion strengthening from WC particles and grain refinement.

The surface roughness values at various laser powers were 1.677 µm, 1.428 µm, 1.042 µm, and 1.245 µm. As laser power increased, surface roughness generally decreased due to improved powder melting, although very high laser power caused roughness to rise again.

The tribological performance of the bionic unit was closely linked to its hardness. Compared to the wear amount of the N60 sample (8.86 mg), the wear amount of the bionic units decreased by 73.7%, 142.1%, 157.5%, and 263.1%, respectively. Friction coefficient behavior followed a two-stage process, initially rising during running-in, and then stabilizing. The inclusion of WC particles significantly reduced friction coefficients, with the excellent performance observed in samples fabricated at higher laser powers.

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