

Review

A Review of High Wear-Resistant Fe-Based Laser Clad Coatings: Alloy Design, Process Optimization and Post-Treatment

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Abstract

High-wear-resistant iron-based clad layers demonstrate substantial application potential in aerospace, automotive, and industrial equipment due to their excellent mechanical properties and extended service life. Laser cladding has emerged as a pivotal technology for the additive manufacturing and repair of critical components, characterized by rapid cooling rates, narrow heat-affected zones, and dense microstructures. However, fabricating high-wear-resistant Fe-based clad layers remains challenging, particularly in achieving a trade-off among hardness, wear resistance, and toughness. Excessively high hardness often compromises toughness, increasing susceptibility to cracking and reducing service reliability, whereas insufficient hardness undermines functional performance and shortens service life. This review synthesizes recent advances in microstructural design, control, and optimization of high-wear-resistant Fe-based clad layers, focusing on powder alloying design, process parameter optimization, and post-cladding strengthening treatments. The strengthening mechanisms and performance characteristics of key alloying elements, specifically Cr, B, Nb, Mo, and Ti, are summarized, and the effects of laser power, scanning speed, and powder feeding rate on the microstructure and properties are systematically discussed. Furthermore, the influence of post-treatment processes, including turning, grinding, ultrasonic rolling, and heat treatment, on wear resistance enhancement is also addressed. Finally, future development directions for laser cladding of high-wear-resistant Fe-based clad layers are proposed.

Keywords: laser cladding; Fe-based alloy; wear resistance; powder design; process optimization



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1. Introduction

Surface wear constitutes one of the primary failure modes of mechanical components, and the resulting equipment downtime and economic losses are considerable. As illustrated in Figure 1, laser cladding is an advanced surface modification technique that employs a high-energy laser beam to melt fed or pre-placed alloy powders, forming a thin clad layer on the substrate. This clad layer undergoes rapid solidification to yield a dense coating characterized by a robust metallurgical bond with the substrate [1–7]. Compared to conventional surface enhancement technologies, laser cladding offers distinct advantages, including high heating/cooling rates and a narrow heat-affected zone. Crucially, it allows for precise control over the dilution rate, which is defined as the proportion of

the substrate material melted into the cladding pool. A lower dilution rate minimizes the undesirable mixing of substrate elements into the clad layer, thereby preserving the intended chemical composition and wear-resistant properties. These attributes facilitate the formation of dense, fine-grained microstructures, endowing components with exceptional wear resistance [8–10]. The inherently rapid melting-solidification cycles characteristic of laser cladding expose materials to extreme thermal transients that, while promoting grain refinement, simultaneously induce deleterious residual tensile stresses arising from the mismatched cooling kinetics between the clad layer and the substrate. This trade-off is exacerbated by the frequent sacrifice of toughness in the pursuit of superior hardness and wear resistance, rendering these intrinsically brittle clad layers highly susceptible to cracking under persistent residual stress fields [11–16]. Consequently, the fundamental conflict between enhanced tribological performance and compromised structural integrity represents a critical bottleneck that continues to impede the broader industrial adoption of the high-wear-resistant clad layers [17,18].

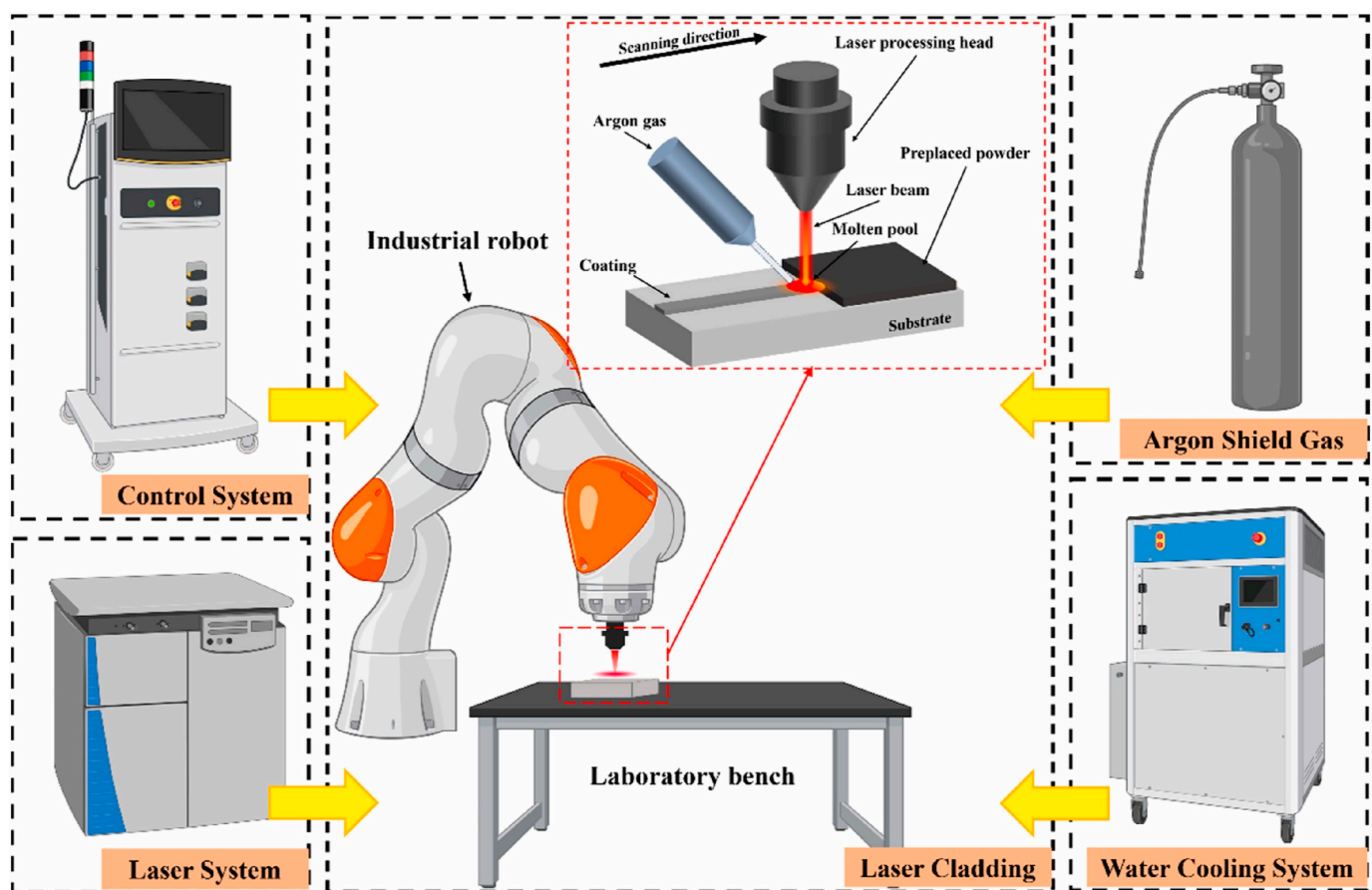


Figure 1. Schematic diagram of the laser cladding system [19].

Owing to their low cost and favorable mechanical properties, Fe-based alloys have consistently dominated the spectrum of laser cladding materials, representing a cornerstone for large-scale industrial engineering applications [20–24]. More importantly, given that most mechanical components are fabricated from cast iron, low-carbon steel, and related materials, the Fe-based alloys exhibit excellent wettability and closely matched coefficients of thermal expansion with these substrates. This compatibility creates favorable conditions for achieving high-quality metallurgical bonding interfaces [25–28]. However, the intrinsic characteristics of these alloys present significant challenges during processing; their poor self-fluxing capability and inadequate high-temperature oxidation resistance

frequently result in metallurgical defects, including porosity [29–31], inclusions [32–34], and microcracks [35–37]. While the incorporation of alloying elements is a standard strategy to enhance wear resistance through mechanisms such as second-phase hardening, grain refinement, and solid-solution strengthening, these interventions invariably incur a trade-off by degrading toughness and elevating susceptibility to cracking under rapid thermal cycling. These inherent flaws act as preferential sites for crack initiation, and subsequent propagation not only compromises the protective capacity of the cladding but also risks catastrophic spallation, leaving the substrate vulnerable to abrasive wear [38–40]. Consequently, the rational design of alloy powders is imperative to suppress defect formation at its source. Parallel to compositional optimization, the precise calibration of laser cladding parameters is critical for governing the thermal profile of the molten pool and solidification dynamics, which yields grain refinement and microstructural homogenization. Crucially, meticulous control of the dilution rate is required to balance substrate integration with compositional fidelity, as excessive dilution alters phase constituents and undermines the targeted hardness and wear resistance. Establishing optimized processing effectively suppresses porosity, inclusions, and cracking while enhancing mechanical performance without sacrificing the dimensional accuracy. Finally, the transition from merely qualified to high-performance clad layers necessitates post-treatment regimens, including machining [41], ultrasonic rolling [42], and heat treatment [43], to refine surface topography, impart compressive residual stresses, and tailor austenite fractions, thereby ensuring microstructural uniformity and long-term service reliability.

Based on these considerations, this paper systematically reviews recent research progress on the high-wear-resistant Fe-based clad layers. The discussion focuses on three main aspects. First, regarding composition design, the review examines how different alloying elements and reinforcing phases affect the microstructure and wear resistance of Fe-based alloys. Second, concerning process optimization, the analysis addresses how key variables, specifically laser power, scanning speed, and powder feeding rate, influence forming quality, service life, and process stability. Finally, with respect to post-treatment methods, the discussion explores the mechanisms by which turning and grinding, ultrasonic rolling, and heat treatment refine microstructure and relieve residual stresses. By summarizing the current state of research, this review analyzes major challenges and proposes future development directions, aiming to provide scientific guidance for the preparation and application of high-wear-resistant Fe-based clad layers.

2. Alloying Element Design

The performance of laser-clad layers is predominantly dictated by the compositional design of the feedstock materials [44]. An optimal alloying strategy must account not only for thermophysical compatibility with the substrate, specifically matching melting points and coefficients of thermal expansion, but also for leveraging the distinct strengthening potentials of individual elements [45]. Due to variations in the atomic radii, crystal structures, and chemical affinities, specific alloying elements exert a significant influence over the microstructure and comprehensive properties of the clad layers through mechanisms such as solid-solution strengthening, grain refinement, and second-phase precipitation during the rapid melting-solidification cycles [46]. Consequently, a thorough understanding of these elemental action mechanisms is imperative for the development of high-performance Fe-based clad layers. Table 1 provides a summary of the roles and mechanisms of commonly utilized alloying elements in Fe-based clad layers.

Table 1. Strengthening mechanisms of common alloying elements in Fe-based clad layers.

Element	Strengthening Mechanism
Ni	Ni stabilizes the austenite phase, elevates the γ -Fe content, and reduces the martensitic transformation temperature. Since hardness exhibits an inverse correlation with Ni content, the mechanical properties of the clad layer can be precisely tailored through compositional adjustments of Ni [47].
B	B facilitates the formation of the hard Fe_2B phase, significantly enhancing hardness and wear resistance. As the content of B increases, the morphology of borides evolves from a network-like structure to clusters, elongated rods, and lath-like shapes. However, excessive concentrations of B can induce the cracking phenomena [48].
Nb	NbC forms in situ during the cladding process, serving as heterogeneous nucleation sites to refine grains. Additionally, it promotes the formation of low-angle grain boundaries and elevates dislocation density, thereby enhancing erosion-wear resistance while simultaneously suppressing pore defects [49].
Mo	Mo induces lattice distortion, thereby conferring solid-solution strengthening. It promotes the transition from dendritic to equiaxed grains and reacts with carbon and boron to precipitate hard phases such as Mo_2FeB_2 . Furthermore, an appropriate content of Mo facilitates the formation of an amorphous phase, which synergistically enhances both hardness and wear resistance [50].
Ti	As a potent carbide-forming element, the Ti undergoes in situ reactions to generate TiC particles that are uniformly dispersed throughout the clad layer. These ceramic reinforcements impart grain refinement and dispersion strengthening, thereby significantly enhancing the hardness and wear resistance of the clad layer [51].
Si	Si confers the solid-solution strengthening while facilitating the deoxidation and slagging to mitigate porosity, and the optimal additions of Si can refine both grains and carbides. However, excessive concentrations risk forming the brittle Fe_3Si intermetallic compound, thereby increasing the susceptibility to the cracking of the clad layer [52].
Al	Al promotes the formation of BCC phases, specifically α -Fe and AlFe_3 , thereby enhancing the hardness of the clad layer. With increasing Al content, the microstructure undergoes a phase transformation from FCC to BCC, which elevates hardness while concurrently diminishing the plasticity [53].
Cr	The incorporation of Cr promotes solid-solution strengthening and facilitates the precipitation of eutectic boron-carbides, while simultaneously refining the grain structure, elevating martensite content, and minimizing retained austenite. Although an optimal Cr concentration enhances both hardness and wear resistance, excessive levels compromise the interfacial compatibility between carbides and the matrix [54].

In addition to the principal elements enumerated in Table 1, minor additions of W, V, C, Ni, and Si exert critical influences on the tribological performance of iron-based laser claddings. V facilitates the formation of finely dispersed, thermally stable carbides, such as VC, thereby enhancing high-temperature stability [55], while C acts as the primary determinant governing the type and volume fraction of precipitated hard phases [56]. Ni stabilizes the austenite matrix, simultaneously improving fracture toughness and mitigating susceptibility to cracking [57]. Si contributes through solid-solution strengthening, deoxidation, grain refinement, and the promotion of amorphous phases [58]. While acknowledging these contributions, this review prioritizes Cr, B, Mo, Nb, and Ti as representative agents that embody the primary strengthening mechanisms within iron-based systems. Specifically, Cr and B serve as classic formers of carbides and borides, which are indispensable for hard-phase precipitation and resistance to abrasive plowing. Mo provides multifunctional benefits, encompassing solid-solution strengthening, grain refinement, and the formation of complex borocarbides. In contrast, Nb and Ti function as archetypal in situ ceramic reinforcements, exemplifying heterogeneous nucleation, grain refinement, and dispersion strengthening. Consequently, a focused analysis of these five elements effectively encapsulates the core metallurgical principles governing wear resistance in iron-based cladding alloys.

Cr, functioning as a pivotal carbide-forming element, enhances wear resistance through a synergistic combination of solid-solution strengthening, hard-phase reinforcement, and microstructural refinement. When dissolved within the α -Fe or martensitic matrix, Cr induces lattice distortion that impedes dislocation motion, thereby elevating resistance to plastic deformation. Concurrently, it reacts with C and B to precipitate high-hardness phases, including Cr_7C_3 , $\text{M}_7(\text{C},\text{B})_3$, and $\text{M}_{23}(\text{C},\text{B})_6$, which bear external loads to mitigate abrasive indentation and micro-plowing. Corroborating these mechanisms, Han et al. [59] fabricated Fe- Cr_3C_2 composite claddings on the 35CrMo steel, characterizing a microstructure comprising austenitic dendrites and M_7C_3 carbides that facilitated sound metallurgical bonding; their results demonstrated that incremental increases in Cr_3C_2 content progressively elevated microhardness and sliding wear resistance. Similarly, Wang et al. [60] developed a high-Cr-V cladding on the same substrate using Cr_3C_2 and FeV_{50} , achieving a crack-free clad layer enriched in C, Cr, and V within dendritic regions to form a synergistic strengthening structure based on α -Fe, γ -Fe, and V_8C_7 . At additive levels of 15 wt.% Cr_3C_2 and 16 wt.% FeV_{50} , hardness increased from 62.9 to 66.1 HRC while the wear rate decreased sharply from 8.66×10^{-8} to $2.80 \times 10^{-8} \text{ mm}^3/(\text{N}\cdot\text{m})$, effectively tripling wear resistance. Further investigating compositional optimization, Shang et al. [54] revealed that Cr modulates the volume fractions of martensite, retained austenite, and eutectic borocarbides in T15 alloy claddings, identifying 9 wt.% Cr as the optimal concentration for achieving peak hardness of 880 $\text{HV}_{0.2}$ and a minimum wear rate of $2.85 \times 10^{-8} \text{ mm}^3/(\text{N}\cdot\text{mm})$. Complementary work by Yang et al. [61] on SS400 steel confirmed these benefits, reporting that Fe-Cr claddings reduced the wear rate from 1.96×10^{-5} to $0.0114 \times 10^{-5} \text{ mm}^3/(\text{N}\cdot\text{m})$. In sum, these studies substantiate that judicious additions of Cr suppress adhesive and abrasive wear by strengthening the matrix concurrently, providing hard-phase load support, and refining the microstructure.

B, a prototypical boride-forming element, enhances wear resistance by tailoring phase constitution and microstructural refinement. Due to its negligible solubility in iron matrices, B reacts readily with metallic elements during rapid solidification to precipitate high-hardness borides and borocarbides, thereby improving load-bearing capacity and plowing resistance. Bartkowski et al. [62] demonstrated that supplementing Fe-B systems with B_4C and Si promotes the formation of Fe_3B , Fe_2Si , and residual B_4C phases, which establish a rigid skeletal framework that inhibits abrasive penetration. This modification elevated the microhardness from approximately 400 to 1100 $\text{HV}_{0.1}$ while reducing wear mass loss from 0.08 g to 0.05 g. Similarly, Feng et al. [63] further demonstrated that trace B additions specifically at 0.75 wt.% in Fe-C-W-Cr-V-Nb-B clad layers lower the formation energy of Fe_3C and refine the eutectic structures, achieving a compressive strength of 3510 MPa and balancing hardness with 6.39% strain via a ductile γ -Fe matrix. Li et al. [48] reported that increasing B from 1.6 to 6.0 wt.% transforms boride morphology from continuous networks to discrete clusters and laths, with Cr-enriched Fe_2B formation at peak concentrations yielding 887.41 $\text{HV}_{0.2}$ hardness, a reduced friction coefficient from 0.4489 to 0.2138, and a shift in wear mechanisms toward oxidative dominance.

Fe-based self-fluxing alloys constitute an important class of Fe-based coating materials and are generally based on the Fe-Cr-B-Si-C system, with optional additions of Ni, Mn, Mo, or V. B and Si act as melting-point depressants and deoxidizing elements, improving melt fluidity, wettability, and slag formation during deposition. Cr, C, and B promote the formation of hard carbides, borides, and carboborides, resulting in a multiphase microstructure typically composed of α -Fe and/or γ -Fe matrices, eutectic constituents, and dispersed hard phases [64,65]. In Fe-based self-fluxing alloys, B concurrently facilitates fluxing reactions and ceramic reinforcement. Feldshtein et al. [64] confirmed that the laser alloying with B_4C , MoB, and TaB introduces dispersed borides and carbides that maximize

hardness and minimize wear rates. These findings confirm that judicious B optimization is critical, as while moderate additions refine microstructure and constrain plastic deformation, excessive concentrations promote coarse, continuous boride networks that predispose claddings to cracking and spallation.

Mo, functioning as a potent carbide former, primarily strengthens iron-based claddings through solid-solution hardening and grain-refinement mechanisms. At lower concentrations, Mo dissolves into the α -Fe matrix, inducing the lattice distortion that elevates yield strength, whereas higher additions instigate a significant evolution of in situ hard phases [66]. Ma et al. [67] observed that adding 4.0 wt.% Mo to Fe–Cr–B–Si claddings on Q235 steel facilitated the precipitation of Mo_2C , disrupting continuous $\text{M}_2(\text{B,C})/\text{M}_7(\text{C,B})_3$ borocarbide networks into finer dispersions. Similarly, Li et al. [68] reported that increasing Mo from 0.8 to 4.8 wt.% on 45 steel shifted the dominant phase from Fe_2B to Mo_2FeB_2 and transformed dendritic grains into equiaxed structures. This combined effect of solid-solution strengthening, phase transformation, and morphological refinement yielded a peak hardness of 720.2 $\text{HV}_{0.2}$ and transitioned the wear mechanism from severe adhesive-abrasive to predominantly abrasive wear. Extending these findings, Zhang et al. [69] demonstrated that 9 wt.% FeMo_{70} additions to Fe–Ti–B–Cr–Mo–C claddings on 5CrNiMo die steel promoted (Ti,Mo)C formation within a martensitic matrix, significantly enhancing high-temperature wear resistance. While beneficial, excessive Mo increases cracking susceptibility, necessitating precise compositional calibration aligned with specific processing parameters.

Nb typically manifests in iron-based laser claddings as in situ synthesized NbC particles, whose density closely matches that of the ferrous matrix to ensure uniform carbide distribution and thereby enhance hardness and wear resistance. Investigating medium-carbon steel claddings, Cao et al. [70] characterized the morphological evolution of NbC under varying solidification conditions, documenting structures ranging from petal-like and polyhedral to dendritic, networked, and granular forms. They elucidated that NbC particles engulfed by the advancing solid–liquid interface remained fine and dispersed, whereas those precipitating freely in the liquid phase developed into polyhedral or petal-like morphologies, with eutectic NbC forming last as networked or dendritic structures. Complementing this, as shown in Figure 2, Chen et al. [71] fabricated Fe–Cr–Nb–C claddings on high-carbon forged steel and demonstrated that increasing niobium content from 2.5 to 3.5 wt.% promoted the precipitation of nanorod-shaped NbC at grain boundaries, which restricted the formation of brittle chromium carbides. The semi-coherent NbC/matrix interface facilitated grain refinement, concurrently elevating hardness and wear resistance, with 4.5 wt.% Nb identified as the optimum concentration for achieving a well-dispersed micron-scale carbide distribution. Exceeding 5.5 wt.% Nb, however, induced particle agglomeration, stress concentration, and the formation of large spalling pits, ultimately degrading performance. Reinforcing these findings, Zhao et al. [72] employed a one-step synthesis route on gray cast iron to produce an NbC–Fe composite cladding containing approximately 95 vol.% NbC, which attained a nanohardness of 20.69 GPa and withstood scratch tests up to 100 N without delamination. Collectively, these investigations substantiate that precise control over Nb content and processing parameters is paramount to achieving an optimally distributed NbC reinforcement network capable of maximizing wear resistance.

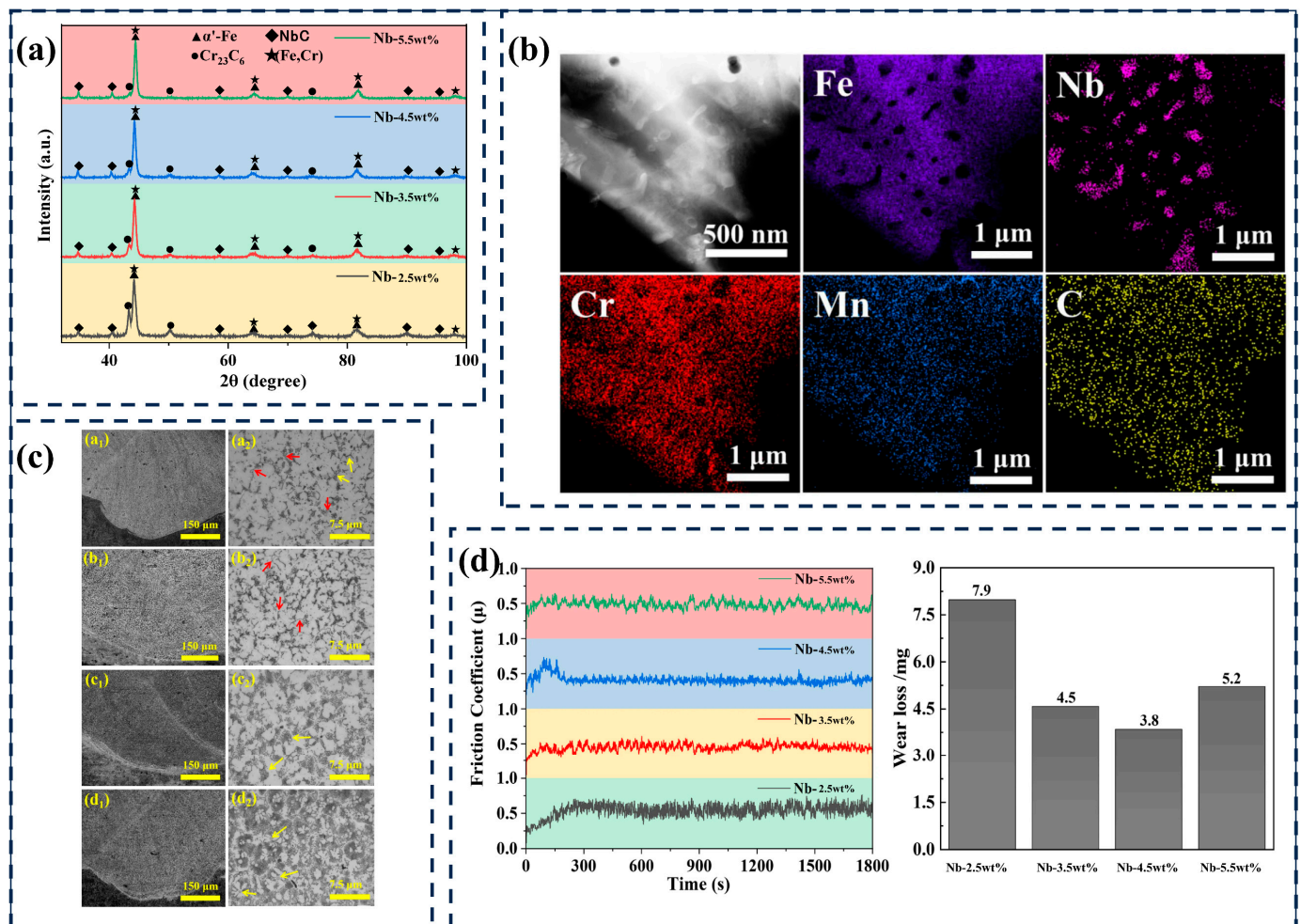


Figure 2. Characterization of clad layers with different contents of NbC: (a) XRD spectra, (b) TEM-EDS mapping, (c) metallographic images of (a₁–d₁) coating cross-sections and (a₂–d₂) magnified views of the coating regions, (d) friction coefficient curves and wear loss [71].

Ti functions as a potent carbide-forming element that reacts in situ with C and B during laser cladding to generate high-hardness ceramic phases, primarily TiC and TiB₂, which impart significant grain-refinement and dispersion-strengthening effects to iron-based claddings. Gao et al. [73] demonstrated that incorporating 1 wt.% titanium into Fe-based powders deposited on low-carbon steel transformed dendritic structures into equiaxed or cellular grains, refining and homogenizing the microstructure. This refinement stems from the high melting points of TiC and TiB₂, which precipitate prematurely to serve as heterogeneous nucleation sites, thereby accelerating nucleation rates while suppressing grain coarsening. Conversely, increasing the content of titanium to 4 wt.% exacerbated dilution effects and induced grain coarsening, resulting in a sharp decline in hardness; the 1 wt.% addition yielded optimal hardness and microstructural stability. Extending this investigation, Zhu et al. [74] utilized laser-directed energy deposition to fabricate high-chromium white cast iron claddings with Ti and TiC additions, identifying 6.55 wt.% Ti as the optimum concentration for high-stress abrasive wear resistance, which reduced volume loss by approximately 40% relative to titanium-free samples. X-ray diffraction analysis of worn surfaces revealed a complete austenite-to-martensite transformation that induced transformation hardening, further augmenting wear resistance. However, claddings containing 14.6 wt.% Ti, despite higher TiC fractions, were dominated by a soft α-Fe matrix incapable of undergoing martensitic transformation, thereby exhibiting diminished wear

resistance. Supporting these observations, Du et al. [75] noted analogous trends in plasma-sprayed TiC-reinforced Fe-Ni claddings on H13 steel, where TiC particles concentrated in the mid-upper regions to form a wear-resistant skeleton, while excessive Ti triggered particle agglomeration and burn-off, negating strengthening benefits. Taken together, these studies confirm that moderate Ti additions effectively homogenize microstructure and generate multicomponent ceramic reinforcements, constituting a cost-efficient strategy for enhancing the wear resistance of iron-based claddings.

In summation, alloy design constitutes the central pillar for advancing the wear resistance of iron-based laser claddings, leveraging a spectrum of metallurgical mechanisms including solid-solution strengthening, grain refinement, secondary-phase hardening, and microstructural homogenization. Cr and B operate primarily through the precipitation of high-hardness carbides, borides, and borocarbides, effectively elevating load-bearing capacity and anti-plowing resistance. Mo contributes via solid-solution effects and microstructural refinement while facilitating the formation of reinforcing phases such as Mo_2C and Mo_2FeB_2 . Concurrently, Ni and Ti generate in situ ceramic phases, specifically NbC, TiC, and TiB_2 , which serve as heterogeneous nucleation sites to restrict grain growth, disperse hard phases, and suppress plastic deformation and spalling. Notwithstanding these advantages, each element imposes inherent constraints. Excessive Cr and B promote the proliferation of coarse, continuous brittle networks that undermine phase-matrix compatibility and elevate cracking susceptibility, while superfluous Mo exacerbates segregation and residual stress accumulation. Similarly, surfeit additions of Ni or Ti induce ceramic agglomeration and interfacial decohesion. Consequently, judicious multi-element design strategies must capitalize on synergistic interactions, such as Cr-B boride toughening, Mo-assisted refinement, and Nb/Ti-mediated heteronucleation, while vigilantly circumventing the precipitation of excessive brittle phases, particle clustering, and matrix embrittlement to achieve an optimal equilibrium of mechanical properties.

Notably, alloying elements exhibit optimal effectiveness within specific ranges. Excess addition promotes the hard-phase coarsening, elemental segregation, and residual stress concentration, potentially inducing cracks that compromise service reliability. According to Griffith's fracture model, structural stress accumulating during molten pool solidification [76] can exceed the yield strength of the material, initiating and propagating microcracks toward the brittle fracture:

$$\sigma_f = \sqrt{\frac{E(2\gamma + \gamma_p)}{\pi C_z}} \quad (1)$$

where E is the elastic modulus, γ is the surface energy, γ_p is the plastic work per unit length for the extension of microcracks, and C_z is the characteristic flaw size. Consequently, compositional design must balance hard-phase content with matrix toughness and interfacial bonding. For instance, Dai et al. [77] added Co to WC/Fe claddings, improving reinforcement-matrix bonding and toughness while reducing cracking without sacrificing hardness. He et al. [78] showed nano-TiC outperforms micron-TiC in refining microstructure, homogenizing reinforcement distribution, and lowering residual tensile stress, thereby minimizing cracks while enhancing hardness and wear resistance. As alloy systems grow more complex, traditional trial-and-error approaches become inadequate. Future research should integrate thermodynamic calculations, microstructural simulations, and machine learning to establish the relationship model between composition, microstructure, and property. This enables the controllable design of wear-resistant phase composition, distribution, and volume fraction, supporting intelligent optimization of high-performance iron-based cladding layers [79,80].

3. Laser Cladding Processes

Beyond compositional design, laser-cladding parameters can be systematically classified into five coupled groups: laser-source and beam parameters, motion parameters, material-delivery and geometric parameters, atmospheric parameters, and deposition-strategy parameters [81–83]. These groups encompass laser type and operating mode, power, spot diameter or characteristic beam dimension, beam profile, focal position, scanning speed, powder or wire feeding rate, stand-off distance, nozzle configuration, shielding, carrier gas characteristics, overlap ratio, hatch spacing, and inter-track thermal history. Collectively, these variables determine the absorbed energy density, material catchment efficiency, molten-pool convection, cooling rate, and cyclic reheating, thereby controlling dilution, defect formation, microstructure, and wear resistance [84–86].

(1) Laser-source and beam parameters

Laser energy density, defined as the heat input per unit length or area, is a pivotal parameter calculated as:

$$E = P / (D \times V) \quad (2)$$

$$\eta = P / V \quad (3)$$

where P is laser power, D is spot diameter, and V is scanning speed. Energy density directly regulates powder melting, molten pool dimensions, cooling rates, and substrate dilution, ultimately determining the wear resistance. Wu et al. [87] fabricated the Fe-Cr-Mo-C-B-Si amorphous composite claddings on Q235 steel, achieving a maximum amorphous phase content of 66.06% and peak hardness of ~ 1200 HV_{0.5} at 125 J/mm². Wear volume loss was reduced to 4×10^{-4} mm³, representing a reduction of more than 70% compared to that at 86.67 J/mm². This optimum is achieved because the moderate energy input ensures complete melting while suppressing crystallization of the amorphous phase; this preserves the synergistic strengthening effect between the amorphous matrix and refined grains, thereby effectively mitigating abrasive wear. Conversely, Han et al. [88] reported that excessive energy density of 166.67 J/mm² on low-carbon steel coarsened grains, increased dilution, and weakened martensitic strengthening, reducing hardness from 548.3 to 421.4 HV_{0.1} and shifting the wear mechanism from pitting to severe adhesive wear. Similarly, Wang et al. [89] observed minimal porosity of 1.2% and optimal wear resistance at 97.2 J/mm² in Fe-Ni-Ti claddings on the AISI 1045 steel, a higher energy density of 111 J/mm² induced porosity, deepened furrows, and caused delamination. Luo et al. [90] corroborated these findings in Fe₃Al claddings, identifying 0.3 J/mm as optimal for achieving a dense microstructure, a low friction coefficient of 0.45, and a minimal wear rate of 0.09×10^{-3} mm³/(N·m). Thus, appropriately elevated energy density benefits melting quality, microstructural refinement, and hardness.

Laser power independently governs the molten pool temperature field, solidification dynamics, and interfacial bonding. As shown in Figure 3, Bartkowski [91] demonstrated that increasing the laser power from 500 W to 1100 W during the Fe/ZrC cladding decreased the ZrC reinforcement content and lowered the microhardness from 750 to 580 HV_{0.05}. This reduction was primarily attributed to dilution and particle agglomeration, although a sound metallurgical bond was achieved. The study further indicated that quantitative image analysis was more effective than conventional hardness profiling for capturing such microstructural heterogeneity. Wang et al. [92] studied the effects of power on the 42CrMo steel claddings, finding that higher power increased melt depth and dilution rate, transforming the microstructure from fine equiaxed grains to coarse microstructures. Maximum hardness of 586.86 HV_{0.1} occurred at 1600 W, balancing complete melting against excessive grain growth. Zhang et al. [93] utilized response surface methodology to optimize rectangular-spot cladding, identifying significant two-factor interactions: power

and scanning speed governing the thickness of the clad layer, and power and powder feeding rate dictating dilution and microhardness. They concluded that reducing power while increasing speed under constant feeding rates minimizes pool size, accelerates cooling, and refines grains. Operating within 2.4–2.7 kW achieved a target thickness of ~1 mm, dilution below 10%, and hardness exceeding 825 HV_{0.25}.

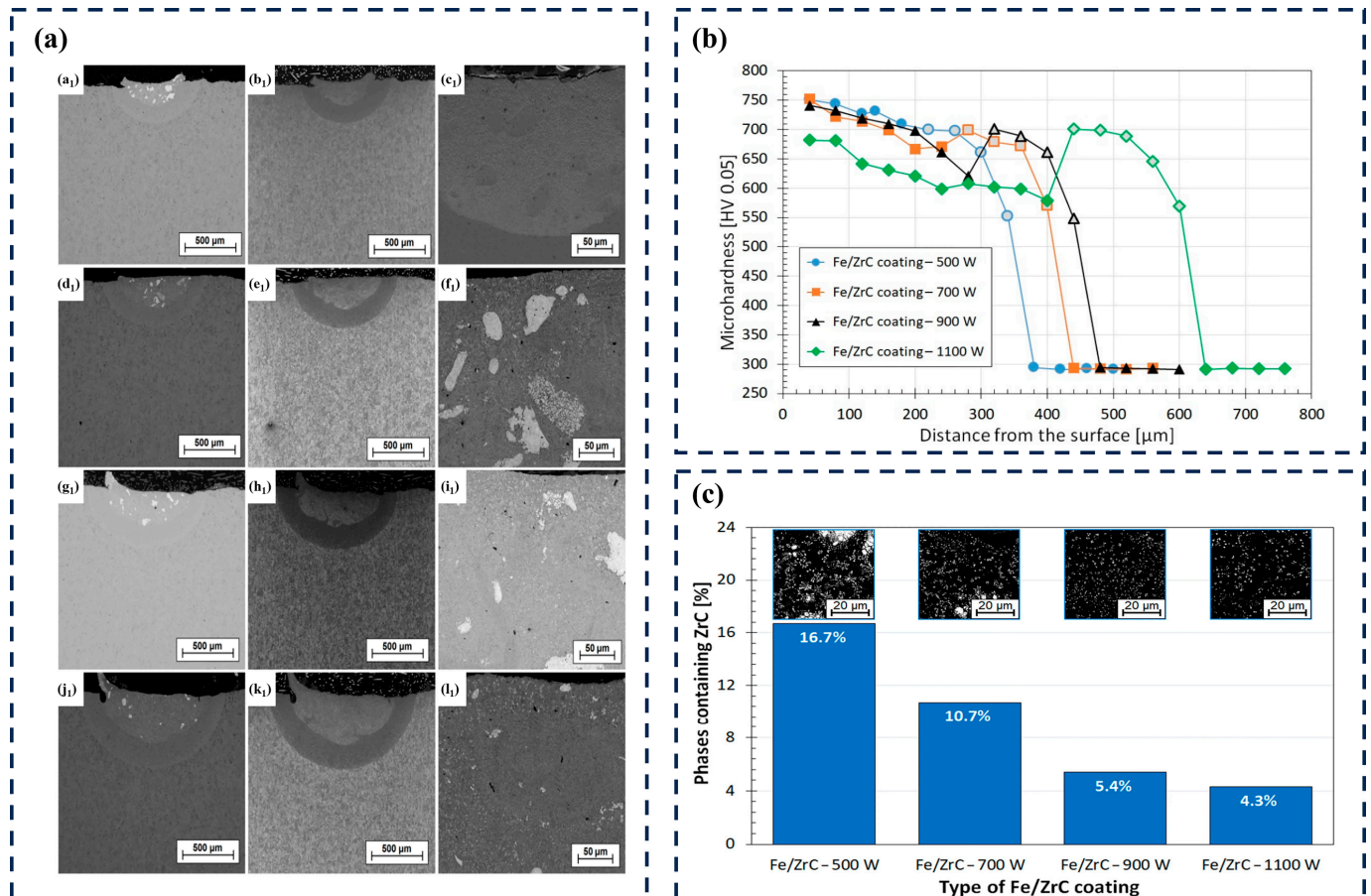


Figure 3. (a) backscattered electron (BSE) images, secondary electron (SE) images and magnified BSE image of the clad layers at (a₁–c₁) 500 W, (d₁–f₁) 700 W, (g₁–i₁) 900 W and (j₁–l₁) 1100 W, (b) microhardness distribution, (c) variation in the content of phases [91].

Laser-source characteristics should be discussed as a hierarchy of coupled parameters rather than merely identifying the equipment type. CO₂, Nd: YAG, diode, and fiber lasers have all been employed for laser cladding. Differences in wavelength, beam quality, energy-coupling efficiency, and attainable beam profile mean that identical nominal powers do not necessarily produce equivalent thermal conditions. The temporal operating mode further controls the heat-input history. In an Fe-based composite coating, pulsed-wave fiber-laser cladding refined the matrix grain size from 11.68 to 6.86 μm and increased the hardness by approximately 210 HV_{0.2} to 1160 HV_{0.2} compared with continuous-wave processing, without substantially changing the phase constitution [94]. However, the benefits of pulsed operation depend on pulse frequency, width, duty cycle, and peak power and should not be generalized independently of average heat input. The laser spot diameter represents another key characteristic because it determines both irradiance and the laser–powder interaction area. Using beam diameters of 0.75, 1.5, and 3 mm for austenitic stainless-steel deposition, Kong et al. [95] found that smaller beams generated higher cooling rates, finer grains, and better mechanical properties, whereas larger beams produced a more stable molten pool, less powder splashing, higher material utilization, and better surface

quality. Besides spot size, the spatial intensity distribution controls the temperature and flow fields within the molten pool. For the AISI 316L, Sattari et al. [96] showed that square beam profiles produced wider and larger molten pools, whereas circular profiles generated smaller but deeper pools. In addition, the laser attenuation was also highest when the powder-stream diameter matched that of a top-hat beam. Finally, the focal-plane position determines the effective spot diameter, power density, and overlap between the laser beam and powder stream. For 316 L stainless steel, positioning the powder focus below the substrate and the laser focus above it improved surface uniformity, with powder defocusing exerting the dominant effect [97]. Therefore, comprehensive reporting should include the laser type and power, along with the wavelength, temporal mode (continuous- or pulsed-wave), effective spot dimensions, and intensity distribution at the working plane. Additionally, beam-quality characteristics, focal position, and the adopted defocusing sign convention must be documented.

(2) Motion parameters

Scanning speed exerts a profound influence on cladding quality commensurate with that of laser power, governing the thermal history and solidification dynamics of the molten pool. Operating under fixed parameters aside from speed, low scanning velocities prolong the laser–powder interaction time, elevating the molten pool temperature and intensifying substrate melting. This excessive heat input amplifies dilution, degrades surface morphology, and ultimately diminishes the wear resistance. Conversely, excessively high speeds curtail the interaction duration, which compromises metallurgical bonding at the interface and similarly impairs tribological performance. Investigating this relationship on Q235 steel, Jian et al. [98] reported that escalating the scanning speed from 1.57 to 20.4 m/min reduced cladding thickness and dilution while augmenting deposition efficiency by approximately 2.25 times, concomitant with significant microstructural refinement as secondary dendrite arm spacing fell below 1 μm and Cr segregation diminished, signaling enhanced compositional homogeneity. However, hardness responses exhibit a non-monotonic trajectory relative to speed. Jiao et al. [99] observed in T15M high-speed steel claddings that a speed of 200 mm/min minimized defects and optimized solid-solution and fine-grain strengthening, thereby achieving peak hardness and superior wear resistance. In contrast, raising the speed to 300 mm/min precipitated performance deterioration characterized by fragmented block spallation. These collective findings substantiate that while elevated scanning speeds refine microstructure and homogenize composition, exceeding critical thresholds reduces dilution to detrimental levels, inducing interfacial deviations that compromise cladding integrity.

(3) Material-delivery and geometric parameters

Powder feeding rate governs the mass of powder introduced into the molten pool per unit time, directly controlling cladding thickness, dilution, and microstructure. An optimal rate mitigates issues arising from powder accumulation and uneven heating. Wang et al. [100] investigated the effects of conventional and high powder feeding rates, specifically 25 g/min and 60 g/min, on the 27SiMn steel substrates. High-speed feeding imparted preheat and kinetic energy to particles, reducing total energy consumption to 75.5% of the conventional process. This transformed coarse columnar grains into uniformly fine grains, increased microhardness by 9.4%, and reduced wear loss by 19.5%, shifting the mechanism from severe to slight adhesive wear. Reduced energy input also prevented excessive molten pool temperatures. Investigating the interplay between substrate geometry and processing parameters, Yin et al. [101] demonstrated that substrate diameter, laser power, and scanning speed interactively regulate dilution and hardness, as illustrated in Figure 4. Their analysis revealed that larger substrate diameters promoted grain coarsen-

ing, elevated dilution rates, and consequently reduced hardness. Utilizing a regression model for precise dilution prediction, they identified an optimal energy density window of 1.43–2.14 J/mm² for shafts measuring 40–60 mm in diameter, while recommending low-energy conditions for 30 mm shafts. Notably, substrate diameter emerged as the dominant factor governing hardness variation. Bartkowski et al. [102] investigated the effect of powder feeding rate on Fe/WC claddings deposited on S355 steel, demonstrating that higher feeding rates increased cladding thickness by 11–14% while significantly improving the spatial uniformity of WC particle distribution. Crucially, elevating the feeding rate enhanced the thermal capacity of the molten pool and reduced cooling rates, thereby eliminating the transverse surface cracks prevalent at lower feeding rates. Lower feeding rates favored the formation of dendritic or feather-like secondary carbides, whereas higher rates promoted the development of lath or rod-like morphologies. Mechanical characterization revealed that maximum hardness peaked at 1400 HV_{0.05} under a feeding rate of 12.50 g/min, substantially surpassing the 1100–1200 HV_{0.05} range observed at 6.25 g/min. These findings indicate that appropriately increasing the powder feeding rate refines the microstructure, elevates hardness, and enhances cladding density, although excessively high rates risk inducing incomplete melting, inclusion entrapment, and geometric instability.

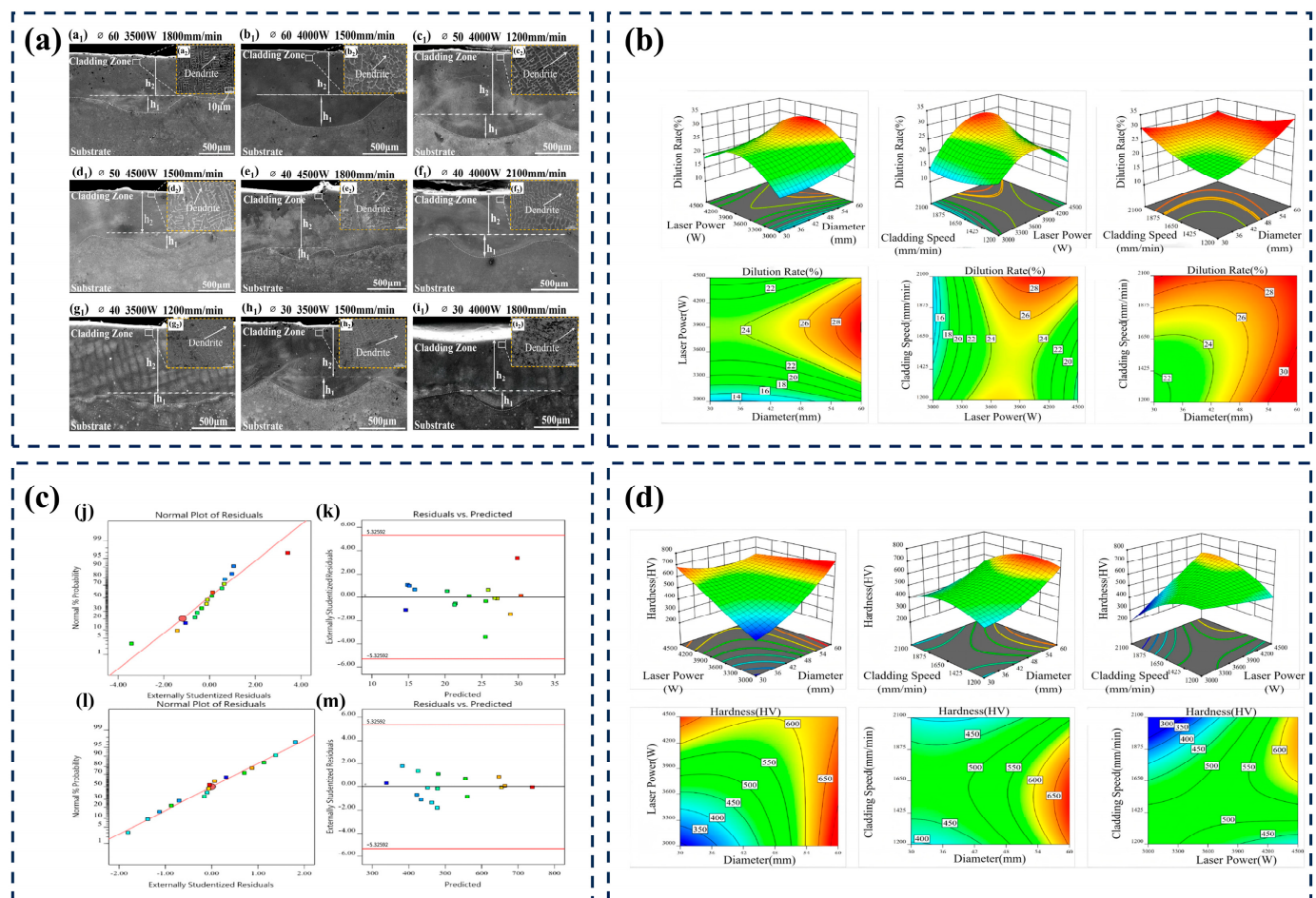


Figure 4. (a) SEM images of (a₁–i₁) macroscopic morphology and (a₂–i₂) microstructure, (b) interaction surface and contour plots of factors with dilution rate as the research target, (c) diagnostic analysis of (j,l) normal probability plots of the residuals and (k,m) relationships between predicted values and residuals, (d) interaction surface and contour plots of factors with diameter as the research target [101].

Laser defocusing distance and nozzle configuration jointly determine the spatial coupling among the laser beam, powder stream, and molten pool. Changing the laser defocusing distance modifies the spot diameter and power density, whereas powder defocusing distance or nozzle stand-off distance primarily controls the powder concentration and capture efficiency. For 316 L stainless steel, Zhu et al. [97] found that positioning the powder focus below the substrate and the laser focus above it improved surface quality, with powder defocusing exerting the dominant influence on track-height uniformity. Moreover, equal absolute defocusing distances do not necessarily produce equivalent results on opposite sides of the focal plane. Zhao et al. [103] reported that positive laser defocusing reduced top-surface height deviation and promoted self-stabilization, whereas negative defocusing provided better side-wall quality, reflecting differences in laser–powder coupling and particle adhesion. Nozzle geometry further determines powder-stream symmetry, focal position, and divergence. Off-axis nozzles are relatively simple but direction-dependent, whereas discrete and continuous coaxial nozzles enable multidirectional deposition. However, their performance depends on the outlet angle and width, internal-channel geometry, and stand-off distance. Optical diagnostics showed that nozzle-outlet diameter, shielding-gas flow, and nozzle-to-substrate distance significantly affected gas–powder focusing [104]. Gabor et al. [105] further demonstrated that narrow straight internal grooves reduced the tangential particle velocity and decreased powder-stream width by approximately 17–18%, thereby improving the powder focusing. Consequently, laser and powder defocusing distances should not be treated as isolated parameters. Their sign convention and reference plane should be stated explicitly, together with nozzle type, outlet dimensions, inclination angle, internal-channel structure, stand-off distance, and gas-flow conditions. The optimum configuration is system-specific and corresponds to effective overlap between the laser spot, powder-stream waist, and molten pool rather than simply the minimum geometrical distance.

(4) Atmospheric parameters

Shielding and carrier gases play distinct but strongly coupled roles in powder-fed laser cladding: shielding gas isolates the molten pool from the atmosphere and controls oxidation, whereas carrier gas governs powder transport, stream convergence, and particle capture. Although Ar, He, and N₂ are commonly used, direct comparisons of gas species for Fe-based alloys remain limited, and their suitability depends on the alloy composition and delivery system. Wirth and Wegener [106] demonstrated that changing the carrier-gas type and reducing its flow rate could markedly suppress melt-pool oxidation. However, the resulting cleaner surface exhibited lower laser absorptivity, indicating a trade-off between atmospheric protection and energy coupling. Gas purity, more appropriately quantified by the residual oxygen concentration around the melt pool, is particularly important for Fe-based alloys. During laser directed energy deposition of 18Ni300 maraging steel, reducing the oxygen concentration to 50 ppm suppressed surface oxidation and macroscopic cracking, modified dendritic solidification, and produced an ultimate tensile strength of 908 MPa [107]. Gas flow rate also affects the hydrodynamic and thermal behavior of the process. For AISI 316 L, the shielding-gas flow rate interacted with laser power, scanning speed, and powder feed rate to determine track geometry, dilution, and microstructural refinement [108]. Similarly, shielding-gas flow significantly influenced clad height, hardness, and the fraction of unmelted TiC particles in TiC-reinforced Fe-based coatings [109]. Carrier-gas flow controls particle velocity, powder-stream focal position, and powder utilization. For example, Gao et al. [110] obtained efficient delivery of 304 L powder at 6 L min^{−1} using a specific four-stream nozzle. Nevertheless, excessive carrier or shielding flow may defocus the powder jet, divert low-velocity particles, flatten and cool the molten pool, reduce powder capture efficiency, and promote gas-entrapment porosity [111]. Therefore, gas type, nominal purity or residual oxygen level, carrier- and shielding-gas flow

rates, nozzle geometry, and stand-off distance should be reported together. The optimum flow rate is system-specific and should not be transferred between different cladding systems without recalibration.

(5) Deposition-strategy parameters

The overlap ratio governs the remelting behavior, heat accumulation, and recrystallization of adjacent tracks, thereby dictating structural compactness, hard-phase distribution, and resultant wear mechanisms. Investigating Fe90 claddings on 65 Mn steel, Zhang et al. [112] evaluated overlap rates of 0%, 15%, 30%, and 45%, determining that 30% overlap yielded the highest hardness at approximately 942 HV_{0.1} while minimizing wear loss to 0.10 mg compared to 0.31 mg for the substrate. This optimum stems from the secondary melting of prior tracks, which refines dendritic structures and generates fine, supersaturated martensite and acicular phases that homogenize hard phases and mitigate abrasive indentation, plastic deformation, and adhesive wear. Corroborating the significance of calibrated overlap, Wang et al. [113] reported optimal performance on 45 steel at 46% overlap, achieving a dense, low-defect microstructure with 450 HV_{0.2} hardness, a friction coefficient of 0.412, and a wear rate of 0.17%. The enhanced inter-track heat flow under this condition promoted uniform grain growth and dispersed TiC reinforcements within the γ -[Fe, Ni] matrix, thereby reinforcing fine-grain strengthening effects while reducing particle spallation at pores and cracks. On 304 stainless steel, Bu et al. [114] attained the lowest wear rate of $3.91 \times 10^{-6} \text{ mm}^3/(\text{N}\cdot\text{m})$ at 80% overlap, a condition coinciding with a reduced grain size of 1.14 μm and a hardness of 517.691 HV_{0.1}. This high-overlap configuration increased grain boundary density and facilitated the formation of a stable tribofilm that provided lubricating and isolating effects to suppress micro-cutting and adhesion. Further elucidating microstructural dependencies, Sun et al. [115] correlated overlap rates of 30%, 50%, and 60% with the formation of dendritic, equiaxed, and cellular grain structures, respectively, each conferring distinct combinations of hardness, toughness, and wear resistance. Synthesizing these findings confirms that a moderate increase in overlap rate enhances inter-track remelting and grain refinement, thereby elevating hardness. However, excessively high ratios induce detrimental heat accumulation and residual stress buildup that compromise toughness and crack resistance. Consequently, calibrating the overlap ratio to strike an optimal balance between hardness and toughness remains paramount for fabricating high-integrity clad layers.

Beyond geometrical overlap, the inter-track and interlayer dwell times govern the thermal history experienced by previously deposited material. Each subsequent pass reheats the preceding track, and the peak temperature, duration, and number of these thermal cycles determine whether remelting, recovery, tempering, or precipitation occurs. Short dwell times generally promote heat accumulation and reduce cooling rates, whereas longer intervals lower the interpass temperature and may enable phase transformations before reheating. For AISI 420 stainless steel deposited on 300 M steel, increasing the idle time between tracks promoted in situ tempering of martensite and increased ductility from 2.7% to 17.4%, while restoring tensile and wear performance [116]. Similarly, 12CrNi2 low-alloy steel deposited using a 10 s inter-track dwell and a 2 min interlayer dwell achieved an ultimate tensile strength of 1007 MPa and an elongation of 19.3%, owing to the controlled formation of lath martensite [117]. In laser-directed energy deposition of 15–5 precipitation-hardened stainless steel, short dwell times intensified heat accumulation and interdendritic segregation of Ni, Cu, and Nb, whereas longer intervals allowed the deposited layer to cool below the martensite-start temperature, promoting martensitic transformation and subsequent Cu precipitation [118]. Increasing the interlayer cooling time from 0 to 15 s has also been reported to reduce substrate-surface residual stress by 24.2 MPa, although the benefit diminished at longer intervals. Therefore, no universal dwell time can be

prescribed; it should be optimized together with track length, overlap ratio, layer number, and alloy-specific transformation kinetics.

In summation, laser cladding parameters serve as pivotal determinants governing the microstructure, defect mitigation, and ultimate wear resistance of iron-based claddings. Collectively, these variables orchestrate the thermal field, fluid dynamics, solidification kinetics, and thermal cycling within the molten pool, thereby dictating critical outcomes such as grain size, hard-phase distribution, elemental segregation, porosity incidence, cracking susceptibility, and the integrity of interfacial metallurgical bonding [119,120]. Crucially, the pronounced coupling effects among these parameters necessitate a holistic optimization strategy, as isolated adjustments rarely satisfy the concurrent demands for superior forming quality, high hardness, exceptional wear resistance, and intrinsic crack immunity. Advancing this field requires the integration of in situ monitoring, multiphysics simulations, and artificial intelligence to construct robust predictive models that correlate process parameters with functional performance. Such frameworks enable the synergistic optimization of the entire parameter suite, thereby establishing a foundation for the stable fabrication and intelligent design of high-performance, wear-resistant claddings [121–123]. Pioneering methodologies, exemplified by Sun et al. [124] who employed a genetic algorithm-backpropagation neural network to predict temperature fields and microstructural evolution, substantiate that data-driven approaches provide robust, actionable guidance for precision parameter selection.

4. Post-Treatment Processes

The extreme thermal transients inherent in laser cladding frequently render clad layers afflicted with elevated surface roughness, detrimental residual tensile stresses, porosity, and microsegregation, all of which collectively compromise wear resistance [125,126]. Consequently, post-cladding treatments are indispensable for rectifying surface imperfections, optimizing microstructural evolution, and elevating service performance. Standard remediation strategies encompass mechanical machining, including turning and grinding [127,128]. Surface deformation strengthening techniques, such as ultrasonic rolling, shot peening, and deep rolling [129,130], and various thermal treatments, ranging from tempering and annealing to solution treatment and aging [131–133]. Contemporary research increasingly advocates for the strategic hybridization of these techniques to concurrently achieve superior wear resistance and enhanced surface integrity. Accordingly, this section delineates the specific impacts of turning, grinding, ultrasonic rolling, and heat treatment on the tribological performance of iron-based cladding systems.

As conventional finishing operations, turning and grinding primarily serve to eradicate surface irregularities and unmelted particulate matter while attaining dimensional accuracy, yet their capacity to enhance wear resistance remains circumscribed, positioning them largely as prerequisites for advanced strengthening protocols. Investigating an Fe–Cr–Ni cladding on AISI 1045 steel, Zhang et al. [134] demonstrated that elevating feeding rates from 0.2 to 0.4 mm/r increased surface roughness of R_z from 11.7 μm to 15.0 μm and modified residual stress states, wherein machining-induced topographical features such as feed marks and deep grooves functioned as preferential initiation sites for fatigue cracking and corrosive attack. Similarly, Dai et al. [135] observed that grinding WC/Fe composite claddings reduced surface roughness of R_a to a range of 0.06–0.52 μm contingent upon wheel condition; although this smoothing effect diminished asperity contact and abrasive plowing, it failed to fundamentally alter cladding hardness, a property intrinsically governed by the underlying microstructure. Moreover, ground surfaces retained inherent defects, including pits, microcracks, and fractured WC particles, partially negating the benefits of topographic refinement. Corroborating these limitations, Uddin et al. [136]

noted that grinding an AISI 431 cladding on low-carbon steel improved surface hardness but concurrently amplified porosity and microcracking, thereby compromising structural integrity until a subsequent post-treatment ameliorated these deficiencies, boosting micro-hardness by 32% and reducing wear volume by 38%. Taken together, these investigations substantiate that while turning and grinding optimize surface topography, they are ineffectual in eliminating internal porosity or residual tensile stresses, thereby imposing inherent constraints on their capacity to substantially elevate wear resistance [137,138].

Ultrasonic rolling is an advanced deformation technique that applies static pressure combined with high-frequency ultrasonic vibration to the cladding surface. This process induces severe plastic deformation, forming a gradient nanostructured clad layer with refined grains and compressive residual stress, thereby enhancing density, smoothness, and mechanical properties [139,140]. Wang et al. [141] applied coupled ultrasonic rolling and heat treatment to the Fe-based clad layer on the Q235 steel, achieving a surface roughness of $0.101\text{ }\mu\text{m}$, a 29.91% hardness increase, and 333.59 MPa compressive residual stress. As shown in Figure 5, Xu et al. [142] subjected 42CrMo steel claddings to a sequential finish turning and room-temperature ultrasonic rolling process, which reduced the surface roughness of R_a by 79.2% to $0.17\text{ }\mu\text{m}$, elevated the microhardness by 15.2% to 480.1 HV_{0.5}, and cut the porosity by 85.6% to 0.57%, while most notably driving the surface residual stress to shift from a 571.48 MPa tensile state to a 322.45 MPa compressive state. Tribological evaluation at 200 °C further demonstrated that the treated claddings exhibited respective 29.2% and 76.06% reductions in wear loss and wear rate relative to untreated controls. Zhang et al. [143] used ultrasonic high-frequency impact treatment on the high-speed cladDED 27SiMn steel, converting 306.92 MPa tensile stress to 92.18 MPa compressive stress and reducing roughness from $2.643\text{ }\mu\text{m}$ to $0.913\text{ }\mu\text{m}$, while significantly improving corrosion resistance in 3.5% NaCl solution. The technique also benefits fatigue performance. Cong et al. [144] applied ultrasonic rolling to 300 M steel repair claddings, reducing roughness by 55.4% and increasing surface hardness by 6.8%. The induced compressive stress layer counteracted cyclic tensile stresses, suppressing crack initiation and propagation and extending fatigue life, with optimal results after six rolling cycles. Overall, ultrasonic rolling synergistically improves wear resistance, corrosion resistance, and fatigue life by refining grains, closing defects, and introducing beneficial compressive stress.

Serving as a principal strategy for microstructural regulation, post-heat treatment utilizes precisely controlled heating temperatures, holding times, and cooling rates to promote carbide precipitation, retained austenite decomposition, and stress relaxation, thereby enabling the tailored optimization of hardness and wear resistance [145,146]. Investigating high-strength Fe-based claddings, Wang et al. [147] applied tempering treatments across a 450–650 °C range and found that processing at 500 °C specifically decomposed coarse M₂C carbides into refined M₆C and MC variants while reducing retained austenite content from 12.8% to near zero, which collectively elevated hardness from 881.2 HV_{0.5} to 927 HV_{0.5} and enhanced wear resistance by 21.7%, as corroborated by a corresponding increase in the friction coefficient from 0.60 to 0.73. Corroborating these benefits, Telasang et al. [148] demonstrated that tempering laser-cladDED AISI H13 steel at 550 °C for 2 h transformed the as-solidified martensite into a tempered matrix characterized by uniformly dispersed fine carbides, achieving a hardness of 550–650 HV_{0.2} that exceeded conventional substrate treatments by approximately 100 HV_{0.2} while significantly diminishing wear volume. Extending this approach to a quenching-and-tempering cycle, Guo et al. [149] heated samples to 850 °C for quenching before tempering at 250 °C, a process that precipitated lath martensite and refined the grain structure to elevate hardness from 521–540 HV to 587–633 HV, reduce the wear rate by approximately 52%, and shift the dominant wear mechanism from abrasion-dominated behavior to a combined regime of abrasion and fatigue wear.

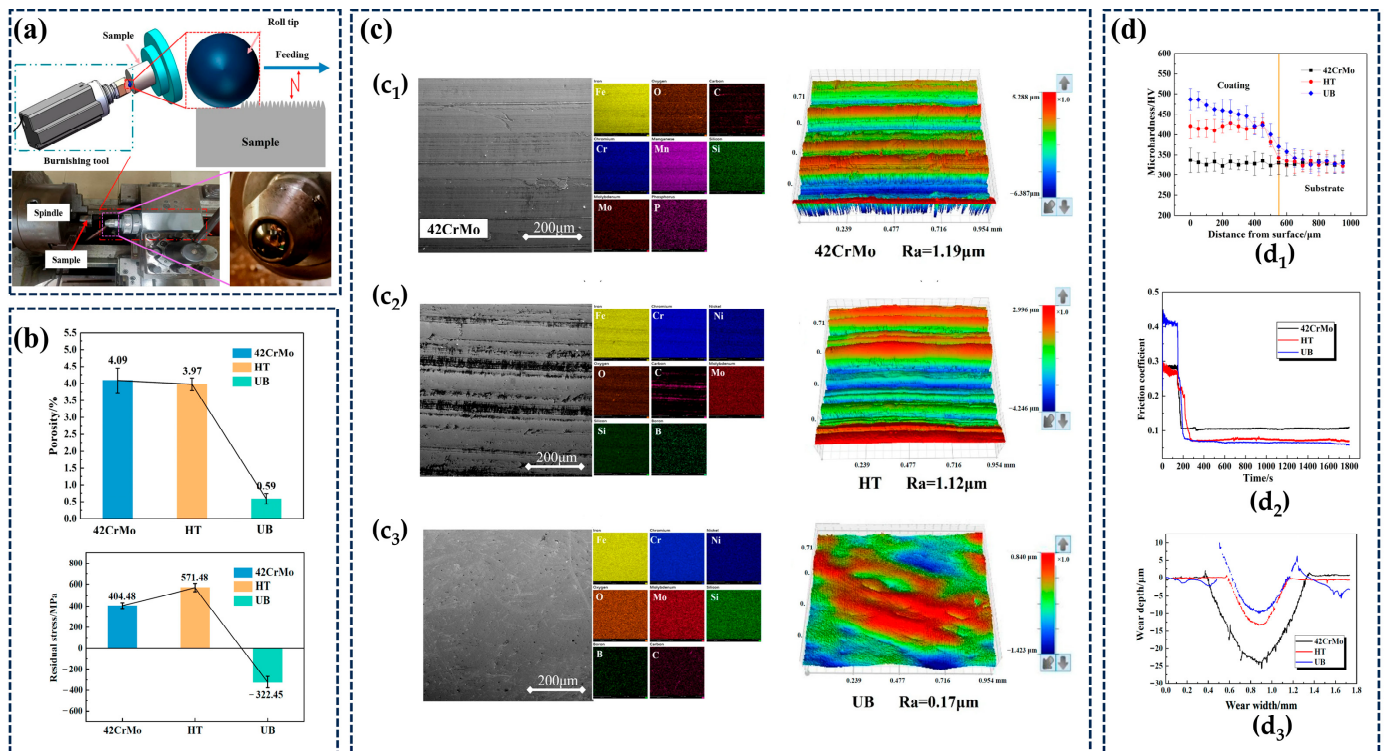


Figure 5. (a) Schematic diagram of ultrasonic rolling, (b) porosity and surface stress, (c) SEM surface morphology and EDS spectrum of (c₁) 42CrMo sample, (c₂) HT sample and (c₃) UB sample, (d) diagrams of (d₁) hardness, (d₂) friction coefficient and (d₃) wear loss for the clad layers [142].

Post-treatment technologies are critical for enhancing the wear resistance of iron-based clad layers. Conventional mechanical methods, such as turning and grinding, effectively improve surface roughness and dimensional accuracy but fail to eliminate internal defects like residual tensile stress and porosity, resulting in only marginal gains in wear resistance. In contrast, ultrasonic rolling utilizes severe plastic deformation to refine grains, close surface pores, and introduce beneficial compressive residual stress. This process significantly reduces surface roughness, boosts fatigue performance, and concurrently increases hardness, serving as a key method for balancing mechanical properties. Performance is further amplified when ultrasonic rolling is combined with moderate-temperature treatments or dwell-time holding processes. Heat treatment optimizes the microstructure by regulating carbide precipitation and distribution, decomposing retained austenite, and relaxing residual stress, with optimal results typically achieved near 500 °C. While distinct mechanisms drive these individual methods, single-technique approaches often fall short of meeting stringent industrial wear-resistance standards. Future research must prioritize integrated multi-post-treatment strategies that leverage synergistic effects to comprehensively optimize the surface integrity [150]. For instance, Liang et al. [151] validated this approach by combining CNC machining with ultrasonic rolling, demonstrating that such hybrid strategies outperform single-method treatments in coordinately regulating surface morphology and stress states.

5. Conclusions

Iron-based wear-resistant clad layers have seen substantial progress in alloy design, process control, and post-treatment. Precise regulation of laser parameters synchronizes thermal cycles to enhance forming quality and microstructural homogeneity. Complementary techniques such as machining, ultrasonic rolling, and heat treatment further improve

surface finish and relieve residual stresses. Nevertheless, wear resistance arises from the complex interplay of microstructure, stress, and defects, and its governing mechanisms are not yet fully elucidated. The prevalence of single-factor experiments limits the understanding of multi-physics interactions, while the integration of mechanistic and data-driven models remains nascent. A key future challenge lies in developing intelligent frameworks that fuse physical mechanisms with multi-source data to predict and optimize performance.

(1) To advance intelligent alloy composition design, it is essential to establish comprehensive databases correlating compositional parameters with microstructure and performance. By integrating thermodynamic calculations with machine learning algorithms, the precise manipulation of wear-resistant phases in terms of their type, distribution, and volume fraction can be achieved. Furthermore, mechanism-guided modeling should be employed to concurrently optimize hardness and crack resistance, moving beyond single-property targets to balance the wear performance with structural integrity, thereby significantly shortening development cycles and reducing costs.

(2) Achieving synergistic optimization requires integrating digital manufacturing with in situ monitoring to establish real-time feedback control systems that ensure cladding quality. Crucially, this integration must account for residual stress evolution during solidification. The coupling of multiphysics simulations with artificial intelligence facilitates the development of hybrid models capable of rapidly identifying optimal process parameters, thereby realizing the intelligent, multi-objective optimization of cladding morphology, hardness, wear resistance, and internal stress states.

(3) Tailoring post-treatment protocols centers on developing customized composite processing chains adapted to specific material compositions and targeted service environments. Mechanical and thermal treatments should be strategically sequenced to systematically regulate surface integrity. For instance, ultrasonic rolling not only refines the surface and improves wear resistance but also induces beneficial compressive residual stresses and reduces roughness, effectively suppressing fatigue crack initiation. This approach ultimately delivers simultaneous enhancements in wear resistance, corrosion/tribocorrosion resistance, and fatigue performance.

(4) Reconciling hardness, wear resistance, and toughness remains a critical challenge, as escalating hardness frequently degrades plastic compatibility, allowing residual stress concentrations at inherent defects to serve as initiation sites for fatigue failure. Future design should integrate these three metrics into a unified evaluation framework. Employing hardness-fatigue correlations, residual stress analytics, and advanced multi-objective algorithms will enable the construction of predictive models that deliver the optimal property equilibrium required for diverse operational applications, particularly under complex loading and corrosive environments.

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References

1. Zhang, Y.; Bai, P.; Li, Z.; Zhang, J. A Review of Laser Cladding Monitoring and Control Based on the Molten Pool Images. *Int. J. Adv. Manuf. Technol.* **2025**, *140*, 2317–2340. [\[CrossRef\]](#)
2. Li, K.; Yang, X.; Gu, Y.; Chen, M.; Ma, J.; Liu, Y. Review on Wear Resistance of Laser Cladding High Entropy Alloy Coating. *Int. J. Adv. Manuf. Technol.* **2025**, *141*, 4769–4801. [\[CrossRef\]](#)
3. Zuo, P.; Chen, S.; Wei, M.; Liang, J.; Liu, C.; Wang, M. Thermal Behavior and Grain Evolution of 24CrNiMoY Alloy Steel Prepared by Pre-Laid Laser Cladding Technology. *Opt. Laser Technol.* **2019**, *119*, 105613. [\[CrossRef\]](#)
4. Li, C.; Yu, Z.; Gao, J.; Zhao, J.; Han, X. Numerical Simulation and Experimental Study of Cladding Fe60 on an ASTM 1045 Substrate by Laser Cladding. *Surf. Coat. Technol.* **2019**, *357*, 965–977. [\[CrossRef\]](#)
5. Svetlizky, D.; Das, M.; Zheng, B.; Vyatskikh, A.L.; Bose, S.; Bandyopadhyay, A.; Schoenung, J.M.; Lavernia, E.J.; Eliaz, N. Directed Energy Deposition (DED) Additive Manufacturing: Physical Characteristics, Defects, Challenges and Applications. *Mater. Today* **2021**, *49*, 271–295. [\[CrossRef\]](#)
6. Pereira, J.C.; Zambrano, J.C.; Rayón, E.; Yañez, A.; Amigó, V. Mechanical and Microstructural Characterization of MCrAlY Coatings Produced by Laser Cladding: The Influence of the Ni, Co and Al Content. *Surf. Coat. Technol.* **2018**, *338*, 22–31. [\[CrossRef\]](#)
7. Maffia, S.; Furlan, V.; Previtali, B. Coaxial and Synchronous Monitoring of Molten Pool Height, Area, and Temperature in Laser Metal Deposition. *Opt. Laser Technol.* **2023**, *163*, 109395. [\[CrossRef\]](#)
8. Badea, D.O. Adaptive Powder Behavior Model for Dispersion and Recovery in Metal Additive Manufacturing. *Powders* **2026**, *5*, 8. [\[CrossRef\]](#)
9. Zhang, Y.; Bai, P.; Li, Z.; Zhang, J. Rapid Optimization of Iron-Based Alloy Laser Cladding Process Based on Orthogonal Experiment and Machine Learning for Q345. *Opt. Laser Technol.* **2025**, *182*, 112086. [\[CrossRef\]](#)
10. Sanchez-Poncela, M.; Ausejo, S.; Veiga, A.; Burgos, N.; Luno-Bilbao, C.; Río-Fernández, L.D.; Avello, A. Crack-Free Wear Resistance Coating on Carbon Steel Obtained by Directed Energy Deposition of Fe-Base Partial Amorphous Powders. *Results Mater.* **2024**, *21*, 100514. [\[CrossRef\]](#)
11. Zhang, B.; Liu, K.; Li, J.; Chen, B.; Huang, C.J.; Soboleva, N. A Comprehensive Review on the Rare Earth Elements Improving Microstructure and Properties of Laser Cladded Coatings. *J. Alloys Compd.* **2025**, *1036*, 181761. [\[CrossRef\]](#)
12. Luo, F.; Shi, W.; Xiong, Z.; Huang, J. Microstructure and Properties Analysis of AlCoCrFeNi High-Entropy Alloy/Iron-Based Amorphous Composite Coatings Prepared by Laser Cladding. *J. Non-Cryst. Solids* **2024**, *624*, 122732. [\[CrossRef\]](#)
13. Zhang, Y.; Lan, T.; Guo, Y.; Mao, G.; Xiang, C.; Wang, H.; Quan, G.; Zhang, J.; Zhou, J. Numerical and Experimental Study on the Effects of Process Parameters on Residual Stress in Laser Cladding. *J. Mater. Eng. Perform.* **2026**, *35*, 24316–24332. [\[CrossRef\]](#)
14. Ostolaza, M.; Arrizubieta, J.I.; Lamikiz, A.; Ukar, E. Study of the Flexural Behaviour and Bonding Strength of WC-Co Metal Matrix Composite Coatings Produced by Laser Directed Energy Deposition. *Surf. Coat. Technol.* **2023**, *463*, 129538. [\[CrossRef\]](#)
15. Ostolaza, M.; Zabala, A.; Arrizubieta, J.I.; Llavori, I.; Otegi, N.; Lamikiz, A. High-Temperature Tribological Performance of Functionally Graded Stellite 6/WC Metal Matrix Composite Coatings Manufactured by Laser-Directed Energy Deposition. *Friction* **2024**, *12*, 522–538.
16. Yamashita, Y.; Kamo, S.; Sato, Y.; Takenaka, K.; Ohkubo, T.; Tsukamoto, M. Laser-Assisted Substrate Heating for Crack Mitigation in Laser Metal Deposition. *Appl. Phys. A* **2025**, *131*, 991. [\[CrossRef\]](#)
17. Liu, K.; Wu, Y.; Gao, Z.; Ren, Y.; Li, J. Effect of WC Content on Cracking Susceptibility of Laser Cladding Ni60A + WC Layers by a New Testing Method. *Surf. Coat. Technol.* **2026**, *524*, 133266. [\[CrossRef\]](#)
18. Xiang, D.; Liu, Y.; Yu, T.; Wang, D.; Leng, X.; Wang, K.; Liu, L.; Pan, J.; Yao, S.; Chen, Z. Review on Wear Resistance of Laser Cladding High-Entropy Alloy Coatings. *J. Mater. Res. Technol.* **2024**, *28*, 911–934. [\[CrossRef\]](#)
19. Lian, G.; Gao, W.; Chen, C.; Huang, X.; Feng, M. Review on Hard Particle Reinforced Laser Cladding High-Entropy Alloy Coatings. *J. Mater. Res. Technol.* **2024**, *33*, 1366–1405. [\[CrossRef\]](#)
20. Yu, H.; Ju, J.; Yang, T.; Wang, C.; Zhang, T.; Peng, P.; Feng, T.; Ding, C.; Kang, M.; Wang, J. Experimental and Finite Element Simulation Studies of the Bio-Tribological Behavior of L-PBF Ti-6Al-4V Alloys with Various Surface Roughness. *Tribol. Int.* **2024**, *194*, 109514. [\[CrossRef\]](#)
21. Jat, V.K.; Patil, R.U.; Samant, S.S. Effect of Processing Parameters on Fatigue and Fracture Behavior of Powder Bed Fusion-Printed Metals: A Review. *J. Braz. Soc. Mech. Sci. Eng.* **2025**, *47*, 275. [\[CrossRef\]](#)
22. Liu, Y.; Zhang, X.; Zhang, H.-Y.; Li, C.; Cho, H.H.; Li, C. Investigation on Microstructure Evolution of Iron-Based Alloy via Synchronous Powder-Feeding Underwater Laser Additive. *Mater. Des.* **2023**, *230*, 111985. [\[CrossRef\]](#)

23. Aprameya, C.R.; Joladarashi, S.; Ramesh, M.R. Dry Linear Reciprocating Wear Behavior of Molybdenum-Reinforced SS316 Laser Claddings Deposited by Laser Directed Energy Deposition. *Results Surf. Interfaces* **2025**, *18*, 100407. [\[CrossRef\]](#)
24. Manoj, A.; Saurabh, A.; Narala, S.K.R.; Saravanan, P.; Natu, H.P.; Verma, P.C. Surface Modification of Grey Cast Iron by Laser Cladding for Automotive Brake Disc Application. *Wear* **2023**, 532–533, 205099. [\[CrossRef\]](#)
25. Yang, P.; Song, Y.; Wang, J.; Hu, F.; Xie, L. Semiconductor Laser Cladding of an Fe-Based Alloy on Nodular Cast Iron. *Weld. World* **2021**, *65*, 785–792. [\[CrossRef\]](#)
26. Zhang, H.; Sui, M.; Liu, Y.; Zhao, W.; Xiao, G.; Liu, S.; Fu, C.; Rao, W.-F. Laser Cladding High Wear and Tribo-Corrosion Resistant Fe-Based Defect-Free Layers on Nodular Cast Iron. *Ceram. Int.* **2026**, *52*, 4517–4526. [\[CrossRef\]](#)
27. Bartkowski, D.; Bartkowska, A.; Przystacki, D.; Jurči, P.; Kieruj, P. Microstructure and Selected Properties of Iron–Vanadium Coatings Obtained by the Laser Processing of a VC Pre-Coat Applied on Steel—Single and Multiple Laser Tracks Study. *Materials* **2022**, *15*, 6417. [\[CrossRef\]](#)
28. Teixeira, M.F.; Pacheco, J.T.; Da Silva, L.J.; Rabelo, A.; Pereira, M.; Niño, C.E. Laser Cladding of Metco 1040® (Fe-V-Mn-C) on Hadfield Steel: Effect of Processing Parameters on Microstructure and Wear Resistance. *Opt. Laser Technol.* **2021**, *142*, 107219. [\[CrossRef\]](#)
29. Lu, W.; Yang, Y.; Liu, Z.; Zhou, F. Laser Cladding Parameter Optimization for Reduced Porosity in Iron-Based Cladding. *J. Mater. Eng. Perform.* **2026**, *35*, 7827–7838.
30. Li, C.; Zhai, J.; Tian, L.; Lu, Y.; Li, X.; Kou, S. Fabrication of Fe-Based Amorphous Composite Coating by Laser Cladding. *J. Non-Cryst. Solids* **2022**, *589*, 121648. [\[CrossRef\]](#)
31. Patil, M.; Acherjee, B.; Manna, I. Enhancing Wear Resistance of Railway Wheel by Laser Surface Cladding of Martensitic Stainless Steel on High Carbon Rail Steel. *Mater. Today Commun.* **2025**, *42*, 111353. [\[CrossRef\]](#)
32. Yin, D.; Wang, M.; Song, M.; Zhou, J.; Wang, Y.; Zhang, M.; Dong, J. A Systematic Correlation Study on Process-Structure-Performance of Iron-Based Gradient Coatings by Laser Cladding for Rolling Mills. *Results Eng.* **2025**, *28*, 107560. [\[CrossRef\]](#)
33. Zhao, H.; Li, L.; Shen, M.; Hu, Q.; Zhou, H.; Xiao, Y.; Li, D.; Liu, S. Microstructure and Tribological Properties of Y2O3-Doped Fe-Based Alloy Coatings by Laser Cladding. *China Foundry* **2026**, *23*, 254–262. [\[CrossRef\]](#)
34. Ortiz, M.; Ramiro, P.; Alberdi, A.; Arruabarrena, J.; Lasheras, X. A Comparative Analysis of High Speed and Conventional Laser-Based Directed Energy Deposition Techniques Focused on Coating Applications for High Value-Added Components. *Int. J. Adv. Manuf. Technol.* **2025**, 1–9. [\[CrossRef\]](#)
35. Rong, C.; Liu, X.; Wang, Y.; Qiao, S.; Xu, X.; Yang, S.; Li, G.; Lu, F. Study on the Formation Mechanism of HAZ Microcracks in FB2 Heat-Resistant Steel by Laser Cladding. *Mater. Charact.* **2025**, *221*, 114750. [\[CrossRef\]](#)
36. Feng, Y.; Pang, X.; Feng, K.; Feng, Y.; Li, Z. A Method for Evaluating the Crack Resistance and Predicting the Preheating Temperature of High Hardness Coating Prepared by Laser Cladding. *Surf. Coat. Technol.* **2022**, *432*, 128076. [\[CrossRef\]](#)
37. Rajaei, H.; Menapace, C.; Amirabdollahian, S.; Perini, M.; Straffelini, G.; Gialanella, S. Microstructural and Tribological Evaluation of Brake Disc Refurbishing Using Fe-Based Coating via Directed Energy Deposition. *Metals* **2022**, *12*, 465. [\[CrossRef\]](#)
38. Wang, K.; Ji, Y.; Zhao, L.; Zhang, C.; Liu, L.; Liu, X. Crack-free Fe-based Metallic Glass Coatings by Extreme High-speed Laser Cladding and Their Phase Features Correlated Toughness. *Rare Met.* **2025**, *44*, 9263–9270. [\[CrossRef\]](#)
39. Zhang, H.; Guo, H.; Hu, X.; Tao, J.; She, W.; Zhao, C. Influence of Synchronized Pressure Rollers on Crack Suppression Mechanism and Properties of Ni60-WC Laser Cladding Layer. *JOM* **2026**, *78*, 3296–3310. [\[CrossRef\]](#)
40. Liu, L.; Lin, Y.; Peng, L.; Kang, X.; Wang, X. Progress in Microstructure Design and Control of High-Hardness Fe-Based Alloy Coatings via Laser Cladding. *Coatings* **2024**, *14*, 1351. [\[CrossRef\]](#)
41. Zhang, P.; Liu, Z. Effect of Sequential Turning and Burnishing on the Surface Integrity of Cr–Ni-Based Stainless Steel Formed by Laser Cladding Process. *Surf. Coat. Technol.* **2015**, *276*, 327–335. [\[CrossRef\]](#)
42. Wang, R.; Liu, H.; Chen, P.; Liu, X.; Hao, J.; Yang, H. Enhancing Wear Resistance of Laser-Clad AlCoCrFeNi High-Entropy Alloy via Ultrasonic Surface Rolling Extrusion. *Surf. Coat. Technol.* **2024**, *485*, 130908. [\[CrossRef\]](#)
43. Sun, G.F.; Wang, K.; Zhou, R.; Feng, A.X.; Zhang, W. Effect of Different Heat-Treatment Temperatures on the Laser Cladded M3:2 High-Speed Steel. *Mater. Des.* **2015**, *65*, 606–616. [\[CrossRef\]](#)
44. Kaspar, J.; Hilhorst, A.; Gerdt, L.; Müller, M.; Heidowitsch, M.; Kuczyk, M.; Bettanini, A.M.; Jacques, P.J.; Zimmermann, M.; Leyens, C. Combinatorial Alloy Design and Microstructure Evolution in Laser-Cladded Al–Co–Cr–Fe–Ni–Ti Compositionally Complex Alloys. *High Entropy Alloys Mater.* **2023**, *1*, 361–378. [\[CrossRef\]](#)
45. Singla, Y.K.; Maughan, M.R.; Arora, N.; Dwivedi, D.K. Enhancing the Wear Resistance of Iron-Based Alloys: A Comprehensive Review of Alloying Element Effects. *J. Manuf. Processes* **2024**, *120*, 135–160. [\[CrossRef\]](#)
46. Mei, K.; Jia, C.; Liu, G.; Wu, W. Study on Microstructure Evolution and Strengthening Mechanism of CuFeNiCoSi Biphasic High-Entropy Alloy by Co-Alloying of High Melting Point Elements Mo and Nb. *Intermetallics* **2025**, *185*, 108889.
47. Selvabharathi, R.; Rajarajan, P.C.; Kulathuran, K. Influence of Ni Alloy Content on Ni–BiFeO3 Crystal Pole Phase and Tribology of Laser (Fe–Co–Mn)X–Si–Cr–Mo Claddings Coating by FeCrMnX(0.5) Stainless Steel. *Int. J. Precis. Eng. Manuf.* **2025**, *26*, 2929–2945.

48. Li, Q.; Zhang, Y.L.; Zhang, L.; Wang, Q.; Zhao, Z.; Chen, D.X.; Jin, H.; Wang, Y.Y.; Zhang, J.W. Effect of Boron on the Microstructural Evolution and Wear Resistance of High-Hardness Fe-Based Alloy Coatings Prepared by Laser Cladding. *Surf. Coat. Technol.* **2023**, *458*, 129342.
49. Wang, T.; Wang, M.S.; Wang, Z.Y.; Xu, T.Z.; Wu, C.L.; Zhang, C.H.; Zhang, S.; Chen, H.T. Effect of in Situ NbC Synthesis via Laser Cladding on Microstructure and Slurry Erosion of Carbide-Reinforced Iron-Based Coatings. *Mater. Today Commun.* **2025**, *42*, 111314. [[CrossRef](#)]
50. Cao, S.; Liang, J.; Zhou, J. Evolution in Microstructure Features and Properties of Mo-Containing Fe-Cr-Ni-B-Si Composite Coatings by Laser Cladding. *Mater. Charact.* **2022**, *188*, 111926.
51. Wenchang, W.; Jiacheng, H.; Shuiping, Q.; Yan, H.; Dejun, K. Effect of Ti Mass Fraction on Microstructure, Salt Spray Corrosion and Electrochemical Performances of Laser Cladded Fe90–6%Al₂O₃ Coatings. *Mater. Today Commun.* **2023**, *35*, 106077.
52. Gao, Z.; Zhang, J.; Xiao, G.; Zhang, H.; Chen, H.; Yi, M.; Chen, Z.; Xu, C. Influence of Si-Content on the Microstructure and Wear Resistance of Multilayer Fe-Based Ultrafine-Grained Coatings Deposited by Laser Cladding Process. *Tribol. Int.* **2026**, *218*, 111704. [[CrossRef](#)]
53. Gomes, A.F.; Santos, H.C.D.; Seno, R.; Francisco, A.; Lima, N.B.D.; Almeida, G.F.C.; Reis, L.; Massi, M.; Couto, A.A. Laser Cladding of Iron Aluminide Coatings for Surface Protection in Soderberg Electrolytic Cells. *Metals* **2025**, *15*, 1337. [[CrossRef](#)]
54. Shang, F.; Xu, Z.; Chen, J.; Chen, L.; Lu, S.; Wang, S.; Jing, X.; Dubovyi, O. Effect of Cr on Wear Resistance and Mechanism of Preset-Powder Laser Cladding T15 Alloy Steel Coating. *J. Mater. Res. Technol.* **2024**, *29*, 4991–4999. [[CrossRef](#)]
55. Yang, X.; Chen, Y.; Zhang, Z.; Liu, Y.; Tao, S.; Li, G.; Chen, H. Study on Microstructure and Properties of Laser-Clad Fe-Based (Ti, V)C Composite Coatings. *Surf. Coat. Technol.* **2023**, *464*, 129552. [[CrossRef](#)]
56. Gao, Y.; Liu, Y.; Wang, L.; Yang, X.; Zeng, T.; Sun, L.; Wang, R. Microstructure Evolution and Wear Resistance of Laser Cladded 316L Stainless Steel Reinforced with In-Situ VC-Cr₇C₃. *Surf. Coat. Technol.* **2022**, *435*, 128264. [[CrossRef](#)]
57. Fang, Q.; Liu, Y.; Hu, D.; Zhao, Y.; Li, J.; Chen, H. Effect of Ni on the Microstructure and Properties of Laser Cladding 316 L + 410 Composite Stainless Steel Coatings. *Surf. Coat. Technol.* **2024**, *478*, 130465. [[CrossRef](#)]
58. Wang, Q.; Bai, X.; Sun, B.; Liu, J.; Cai, Z.; Liang, X.; Shen, B. Influence of Si on Tribological Behavior of Laser Cladded Fe-Based Amorphous/Crystalline Composite Coatings. *Surf. Coat. Technol.* **2021**, *405*, 126570. [[CrossRef](#)]
59. Han, B.; Li, M.; Wang, Y. Microstructure and Wear Resistance of Laser Clad Fe-Cr₃C₂ Composite Coating on 35CrMo Steel. *J. Mater. Eng. Perform.* **2013**, *22*, 3749–3754. [[CrossRef](#)]
60. Wang, H.; Zhang, S.; Zhang, C.; Wu, C.; Zhang, J.; Abdullah, A. Effects of V and Cr on Laser Cladded Fe-Based Coatings. *Coatings* **2018**, *8*, 107. [[CrossRef](#)]
61. Yang, Z.-Q.; Kuo, H.-M.; Chiang, H.-C.; Hung, C.-H. Enhanced Wear Resistance of Low Carbon Steel by Depositing Iron-Chromium Alloy Coating Using High-Power Laser Cladding. *Int. J. Adv. Manuf. Technol.* **2025**, *137*, 1133–1147. [[CrossRef](#)]
62. Bartkowski, D.; Bartkowska, A.; Piasecki, A.; Jurči, P. Influence of Laser Cladding Parameters on Microstructure, Microhardness, Chemical Composition, Wear and Corrosion Resistance of Fe–B Composite Coatings Reinforced with B₄C and Si Particles. *Coatings* **2020**, *10*, 809. [[CrossRef](#)]
63. Feng, Y.; Pang, X.; Feng, K.; Feng, Y.; Li, Z. Study on Microstructure and Compressive Properties of Fe-C-W-Cr-V-Nb Coating with Boron Addition. *J. Alloys Compd.* **2022**, *904*, 163986. [[CrossRef](#)]
64. Feldshtein, E.; Kardapolava, M.; Dyachenko, O. On the Effectiveness of Multi-Component Laser Modifying of Fe-Based Self-Fluxing Coating with Hard Particulates. *Surf. Coat. Technol.* **2016**, *307*, 254–261. [[CrossRef](#)]
65. Umanskyi, O.P.; Pareiko, M.V.; Storozhenko, M.S.; Krasovskyy, V.P. Wetting and Interfacial Behavior of Fe-Based Self-Fluxing Alloy–Refractory Compound Systems. *J. Superhard Mater.* **2017**, *39*, 99–105. [[CrossRef](#)]
66. Zhang, T.F.; Chen, Y.; Han, J.; Liang, F.; Wan, Z.; Zhang, S. The Role of Molybdenum in Regulating Passivation Stability and Tribocorrosion Resistance of Laser-Clad FeCoCrNiMo_x High-Entropy Alloy Coatings. *Corros. Sci.* **2026**, *264*, 113734. [[CrossRef](#)]
67. Xiaoli, M.; Kaiming, W.; Hanguang, F.; Jiang, J.; Yongping, L.; Dawei, Y. Effect of Mo Content on Microstructure and Properties of Laser Cladding Fe-based Alloy Coatings. *Surf. Rev. Lett.* **2018**, *25*, 1850077. [[CrossRef](#)]
68. Li, Q.; Wang, Q.; Zhang, L.; Chen, D.X.; Jin, H.; Li, J.D.; Zhang, J.W. Microstructure, Wear and Electrochemical Behaviors of Laser Cladding Fe-Based Coatings with Various Molybdenum Contents. *Mater. Res. Express* **2022**, *9*, 026504. [[CrossRef](#)]
69. Zhang, M.; Liu, S.S.; Luo, S.X.; Qu, K.L. Effect of Molybdenum on the High-Temperature Properties of TiC-TiB₂ Reinforced Fe-Based Composite Laser Cladding Coatings. *J. Alloys Compd.* **2018**, *742*, 383–390. [[CrossRef](#)]
70. Cao, Y.; Zhi, S.; Gao, Q.; Tian, X.; Geng, T.; Guan, X.; Qin, C. Formation Behavior of In-Situ NbC in Fe-Based Laser Cladding Coatings. *Mater. Charact.* **2016**, *119*, 159–165. [[CrossRef](#)]
71. Chen, M.; Zhou, H.; Liu, X.; Feng, Z.; Xiao, X.; Weng, L.; Yang, Y.; Jiang, Y. Morphology and Wear Resistance of Laser-Clad Fe-Cr-Nb-C Alloy Coatings. *Coatings* **2025**, *15*, 1055. [[CrossRef](#)]
72. Zhao, N.; Xu, Y.; Fu, Y. Mechanical Properties of One-Step in Situ Synthesized NbC-Fe Composite Coating. *Surf. Coat. Technol.* **2017**, *309*, 1105–1110. [[CrossRef](#)]

73. Gao, W.; Zhang, Z.; Zhao, S.; Wang, Y.; Chen, H.; Lin, X. Effect of a Small Addition of Ti on the Fe-Based Coating by Laser Cladding. *Surf. Coat. Technol.* **2016**, *291*, 423–429. [\[CrossRef\]](#)
74. Zhu, C.; Fordyce, I.; Sun, S.D.; Annasamy, M.; Fabijanic, D.; Short, K.; Paradowska, A.; Leary, M.; Brandt, M.; Easton, M. Effect of Ti and TiC Additions on the Microstructure and Wear Resistance of High Chromium White Irons Produced by Laser Directed Energy Deposition. *Wear* **2022**, *510*, 204519. [\[CrossRef\]](#)
75. Du, K.; Xu, L.; Wang, P.; Li, X.; Wu, Z.; Li, X.; Fan, W. Study on Mechanical Properties of Fe-Ni-Based TiC Plasma Cladding Layer Modified by Composite Iron Powder. *Coatings* **2024**, *14*, 1180. [\[CrossRef\]](#)
76. Shah, K.; Khurshid, H.; Ul Haq, I.; Anwar, S.; Shah, S.A. Numerical Modelling of Pulsed and Continuous Wave Direct Laser Deposition of Ti-6Al-4V and Inconel 718. *Int. J. Adv. Manuf. Technol.* **2018**, *95*, 847–860.
77. Dai, Q.-L.; Luo, C.; You, F. Crack Restraining Methods and Their Effects on the Microstructures and Properties of Laser Cladded WC/Fe Coatings. *Materials* **2018**, *11*, 2541. [\[CrossRef\]](#)
78. He, X.; Song, R.G.; Kong, D.J. Effects of TiC on the Microstructure and Properties of TiC/TiAl Composite Coating Prepared by Laser Cladding. *Opt. Laser Technol.* **2019**, *112*, 339–348. [\[CrossRef\]](#)
79. Chen, S.; Ni, L.; Zhang, Y.; Wang, Y.; Cui, T.; Liang, J.; Chen, J.; Wang, M. Laser Cladding of a Novel Fe-Based Coating with High Wear Resistance, Corrosion Resistance and Self-Lubricating Properties. *Surf. Coat. Technol.* **2024**, *478*, 130468. [\[CrossRef\]](#)
80. Yuan, G.; Chunyuan, Z.; Lingjie, D.; Chun, L.; Dejun, K. Effect of Co Content on Mechanical Properties of Laser Cladded WC Coatings: Insights from First-Principle Calculation and Machine Learning. *J. Aust. Ceram. Soc.* **2024**, *60*, 525–532.
81. Wu, D.; Rafid, M.; Sadid, N.; Hu, H. Laser-Clad Corrosion-Resistant Coatings for Waste Incineration Power Plants: Advances and Challenges. *J. Mater. Eng. Perform.* **2026**, 1–24. [\[CrossRef\]](#)
82. Pei, X.; Shen, D.; Zhang, Y.; Liu, G. Recent Research Developments in Laser Cladding Technology for Mold Steel Repair. *J. Mater. Eng. Perform.* **2026**, 1–33. [\[CrossRef\]](#)
83. Zhao, X.; Li, G.; Huang, R.; Qiao, Q.; Pu, J. Advance in the Research on the Key Technologies of Laser Cladding Repair of Roll. *Int. J. Adv. Manuf. Technol.* **2025**, *140*, 1211–1244. [\[CrossRef\]](#)
84. Ouis, A.; Taheri, M.; Khalaj, G.; Abbasi, S.M.; Abduvalieva, D.; Al-Hasnaawei, S. Processing of IN625-ZrB2 Composite Coating by Laser Cladding through Optimization and Definition of Line Energy and Powder Feeding Density Parameters. *Mater. Today Commun.* **2025**, *46*, 112838. [\[CrossRef\]](#)
85. Xu, Y.; Wang, D.; Wu, S.; Lu, H.; Yao, R.; Yang, J.; Jiang, F.; Takao, A. Research Progress on Defect Formation Mechanism and Process Optimization of Laser Cladding High Entropy Alloy Coatings. *Opt. Laser Technol.* **2025**, *187*, 112819. [\[CrossRef\]](#)
86. Yuan, J.; Geng, H.; Alfano, M. Multi-Response Optimization of M2 Steel Coatings Deposited by Co-Axial Laser Cladding on A2 Steel Tool Surfaces. *J. Mater. Res. Technol.* **2024**, *29*, 1102–1117. [\[CrossRef\]](#)
87. Wu, B.; Dong, P.; Yu, W.; Hu, C.; Zhang, F. Effect of Laser Energy Density on Amorphous Phase Content and Properties of Fe-Based Amorphous Coatings. *J. Therm. Spray Technol.* **2024**, *33*, 221–232.
88. Han, T.; Ding, Z.; Feng, W.; Yao, X.; Chen, F.; Gao, Y. Effects of Process Parameters on Microstructure and Wear Resistance of Laser Cladding A-100 Ultra-High-Strength Steel Coatings. *Coatings* **2024**, *14*, 669. [\[CrossRef\]](#)
89. Wang, Z.; Zhang, J.; Zhang, F.; Qi, C. Impact of Laser Energy Density on the Structure and Properties of Laser-Deposited Fe-Ni-Ti Composite Coatings. *Front. Mater.* **2024**, *11*, 1408333. [\[CrossRef\]](#)
90. Luo, X.; Zhang, K.; Cao, J.; Meng, G.; Yu, F.; Zhou, Y.; Zhou, H.; La, P.; Xie, H. Effect of Line Energy Density of the Laser Beam on the Microstructure and Wear Resistance Properties of the Obtained Fe3Al Laser Cladding Coatings. *Optik* **2022**, *261*, 169256. [\[CrossRef\]](#)
91. Bartkowski, D. Influence of Laser Beam Power on Microstructure and Microhardness of Fe/ZrC Coatings Produced on Steel Using Laser Processing—Preliminary Study on the Single Laser Tracks. *Materials* **2022**, *15*, 758. [\[CrossRef\]](#)
92. Wang, H.-Z.; Zhang, X.; Cheng-ming, C.; Ren, L.; Li, J. Research on the Influence of Laser Power on the Microstructure and Performance of Fe-Based Coating. *J. Therm. Spray Technol.* **2025**, *34*, 316–336. [\[CrossRef\]](#)
93. Zhang, Y.; Zhan, H.; Wan, Q.; Wang, R.; Zhang, X.; Wang, W. Multi-Objective Optimization of Process Parameters for Rectangular Laser Cladding of Fe-Based Alloy Wear-Resistant Coatings. *Surf. Coat. Technol.* **2025**, *503*, 131990. [\[CrossRef\]](#)
94. Zhang, H.; Zou, Y.; Zou, Z.; Zhao, W. Comparative Study on Continuous and Pulsed Wave Fiber Laser Cladding In-Situ Titanium–Vanadium Carbides Reinforced Fe-Based Composite Layer. *Mater. Lett.* **2015**, *139*, 255–257. [\[CrossRef\]](#)
95. Kong, Y.; Zhao, L.; Zhu, L.; Huang, H. The Selection of Laser Beam Diameter in Directed Energy Deposition of Austenitic Stainless Steel: A Comprehensive Assessment. *Addit. Manuf.* **2022**, *52*, 102646. [\[CrossRef\]](#)
96. Sattari, M.; Ebrahimi, A.; Luckabauer, M.; Römer, G.R.B.E. The Effect of the Laser Beam Intensity Profile in Laser-Based Directed Energy Deposition: A High-Fidelity Thermal-Fluid Modeling Approach. *Addit. Manuf.* **2024**, *86*, 104227. [\[CrossRef\]](#)
97. Zhu, G.; Li, D.; Zhang, A.; Pi, G.; Tang, Y. The Influence of Laser and Powder Defocusing Characteristics on the Surface Quality in Laser Direct Metal Deposition. *Opt. Laser Technol.* **2012**, *44*, 349–356. [\[CrossRef\]](#)
98. Jian, Y.; Liu, Y.; Qi, H.; He, P.; Huang, G.; Huang, Z. Effects of Scanning Speed on the Microstructure, Hardness and Corrosion Properties of High-Speed Laser Cladding Fe-Based Stainless Coatings. *J. Mater. Res. Technol.* **2024**, *29*, 3380–3392. [\[CrossRef\]](#)

99. Jiao, X.; Wang, J.; Wang, C.; Gong, Z.; Pang, X.; Xiong, S.M. Effect of Laser Scanning Speed on Microstructure and Wear Properties of T15M Cladding Coating Fabricated by Laser Cladding Technology. *Opt. Lasers Eng.* **2018**, *110*, 163–171. [\[CrossRef\]](#)
100. Wang, Q.; Qian, R.; Yang, J.; Niu, W.; Zhou, L.; Pan, X.; Su, C. Effect of High-Speed Powder Feeding on Microstructure and Tribological Properties of Fe-Based Coatings by Laser Cladding. *Coatings* **2021**, *11*, 1456. [\[CrossRef\]](#)
101. Yin, D.; Wang, M.; Wang, Y.; Zhang, M.; Dong, J.; Huang, Z.; Chang, J.; Zhao, H.; Naher, S. A Multiscale Study on Substrate Size Effect and Energy Density Regulation on Dynamic Response of Dilution Rate in Laser Cladding Iron-Based Coatings. *Coatings* **2025**, *15*, 694. [\[CrossRef\]](#)
102. Bartkowski, D.; Bartkowska, A.; Jurči, P. Laser Cladding Process of Fe/WC Metal Matrix Composite Coatings on Low Carbon Steel Using Yb: YAG Disk Laser. *Opt. Laser Technol.* **2021**, *136*, 106784. [\[CrossRef\]](#)
103. Zhao, P.; Zhang, Y.; Liu, W.; Zheng, K.; Luo, Y. Influence Mechanism of Laser Defocusing Amount on Surface Texture in Direct Metal Deposition. *J. Mater. Process. Technol.* **2023**, *312*, 117822. [\[CrossRef\]](#)
104. Nagulin, K.Y.; Iskhakov, F.R.; Shpilev, A.I.; Gilmudinov, A.K. Optical Diagnostics and Optimization of the Gas-Powder Flow. in the Nozzles for Laser Cladding. *Opt. Laser Technol.* **2018**, *108*, 310–320. [\[CrossRef\]](#)
105. Gabor, T.; Yun, H.; Akin, S.; Kim, K.-H.; Park, J.-K.; Jun, M.B.-G. Continuous Coaxial Nozzle Designs for Improved Powder Focusing in Direct Laser Metal Deposition. *J. Manuf. Processes* **2022**, *83*, 116–128. [\[CrossRef\]](#)
106. Wirth, F.; Wegener, K. Simulation of the Multi-Component Process Gas Flow for the Explanation of Oxidation during Laser Cladding. *Addit. Manuf.* **2018**, *24*, 249–256. [\[CrossRef\]](#)
107. Li, S.; Chen, B.; Tan, C.; Song, X. Effects of Oxygen Content on Microstructure and Mechanical Properties of 18Ni300 Maraging Steel Manufactured by Laser Directed Energy Deposition. *Opt. Laser Technol.* **2022**, *153*, 108281. [\[CrossRef\]](#)
108. Sun, J.; Zhao, Y.; Yang, L.; Zhao, X.; Qu, W.; Yu, T. Effect of Shielding Gas Flow Rate on Cladding Quality of Direct Laser Fabrication AISI 316L Stainless Steel. *J. Manuf. Processes* **2019**, *48*, 51–65. [\[CrossRef\]](#)
109. Deng, D.; Li, T.; Huang, Z.; Jiang, H.; Yang, S.; Zhang, Y. Multi-Response Optimization of Laser Cladding for TiC Particle Reinforced Fe Matrix Composite Based on Taguchi Method and Grey Relational Analysis. *Opt. Laser Technol.* **2022**, *153*, 108259. [\[CrossRef\]](#)
110. Gao, J.; Wu, C.; Liang, X.; Hao, Y.; Zhao, K. Numerical Simulation and Experimental Investigation of the Influence of Process Parameters on Gas-Powder Flow in Laser Metal Deposition. *Opt. Laser Technol.* **2020**, *125*, 106009. [\[CrossRef\]](#)
111. Sinclair, L.; Hatt, O.; Clark, S.J.; Marussi, S.; Ruckh, E.; Atwood, R.C.; Jones, M.; Baxter, G.J.; Lun Alex Leung, C.; Todd, I.; et al. An in Situ Imaging Investigation of the Effect of Gas Flow Rates on Directed Energy Deposition. *Mater. Des.* **2024**, *244*, 113183. [\[CrossRef\]](#)
112. Zhang, Y.; Zhang, L.; Wang, X.; Chen, F. Effect of Overlap Rate on Microstructure and Wear Resistance of Fe90 Alloy Cladding Layer by Laser Cladding on 65Mn Surface. *J. Mater. Eng. Perform.* **2025**, *34*, 22976–22983. [\[CrossRef\]](#)
113. Wang, Z.; Qi, C.; Zhang, F. The Overlap Rate Influences the Microstructure and Properties of Laser-Cladded Fe-Ni-Ti Composite Coatings. *Front. Mater.* **2024**, *11*, 1342926. [\[CrossRef\]](#)
114. Bu, X.; Xu, X.; Lu, H.; Liang, Y.; Bian, H.; Luo, K.; Lu, J. Effect of Overlap Rate on the Microstructure and Properties of Cr-Rich Stainless Steel Coatings Prepared by Extreme High-Speed Laser Cladding. *Surf. Coat. Technol.* **2024**, *487*, 131025. [\[CrossRef\]](#)
115. Sun, Y.; Li, C.; Wang, R.; Wang, Y.; Sun, H.; Han, X. Study on the Mechanism of Influence of Different Overlap Rate on the Remelting and Recrystallization Behavior of the Front First Cladding Layer. *Appl. Phys. A* **2025**, *131*, 363. [\[CrossRef\]](#)
116. Da Sun, S.; Fabijanic, D.; Barr, C.; Liu, Q.; Walker, K.; Matthews, N.; Orchowski, N.; Easton, M.; Brandt, M. In-Situ Quench and Tempering for Microstructure Control and Enhanced Mechanical Properties of Laser Cladded AISI 420 Stainless Steel Powder on 300M Steel Substrates. *Surf. Coat. Technol.* **2018**, *333*, 210–219. [\[CrossRef\]](#)
117. Zhao, X.; Lv, Y.; Dong, S.; Yan, S.; Liu, X.; Liu, Y.; He, P.; Lin, T.; Xu, B.; Han, H. The Martensitic Strengthening of 12CrNi2 Low-Alloy Steel Using a Novel Scanning Strategy during Direct Laser Deposition. *Opt. Laser Technol.* **2020**, *132*, 106487. [\[CrossRef\]](#)
118. Im, H.J.; Ryou, K.; Kang, T.H.; Jimbo, S.; Nambu, S.; Han, J.; Choi, P.-P. Thermally Driven Changes in the Microstructure and Mechanical Properties of Martensitic 15–5 Precipitation-Hardened Stainless Steel during Directed Energy Deposition. *Addit. Manuf.* **2023**, *74*, 103729. [\[CrossRef\]](#)
119. Yuan, W.; Li, R.; Chen, Z.; Gu, J.; Tian, Y. A Comparative Study on Microstructure and Properties of Traditional Laser Cladding and High-Speed Laser Cladding of Ni45 Alloy Coatings. *Surf. Coat. Technol.* **2021**, *405*, 126582. [\[CrossRef\]](#)
120. Wang, W.; Zheng, Y.; Zheng, W.; Shen, Z.; Hu, M.; Wang, Y.; Feng, D.; Ma, Y.; Cai, Z.; Yang, J. Dilution Induced Variation of Microstructure and Mechanical Properties on Co-Cr-Fe-Ni High Entropy Alloy Coatings Prepared by Laser Cladding. *Surf. Coat. Technol.* **2024**, *493*, 131256. [\[CrossRef\]](#)
121. Hu, K.; Huang, Q.; Wang, L.; Zhou, Y.; Li, W. Optimization of Multi-Track, Multi-Layer Laser Cladding Process Parameters Using Gaussian Process Regression and Improved Multi-Objective Particle Swarm Optimization. *Int. J. Adv. Manuf. Technol.* **2025**, *137*, 3503–3523. [\[CrossRef\]](#)
122. Sun, Y.; Li, C.; Liu, J.; Sun, H.; Li, S.; Han, X. Optimization of Pulse Laser Cladding Process Parameters and Analysis of Heat and Mass Transfer and Phase Transformation Based on GA-BP Neural Network. *Appl. Phys. A* **2025**, *131*, 306. [\[CrossRef\]](#)

123. Deng, Z.; Chen, T.; Wang, H.; Li, S.; Liu, D. Process Parameter Optimization When Preparing Ti(C, N) Ceramic Coatings Using Laser Cladding Based on a Neural Network and Quantum-Behaved Particle Swarm Optimization Algorithm. *Appl. Sci.* **2020**, *10*, 6331. [\[CrossRef\]](#)
124. Li, C.; Jia, T.; Han, X.; Jiang, X. Study on Parameter Optimization of Laser Cladding Fe60 Based on GA-BP Neural Network. *J. Adhes. Sci. Technol.* **2023**, *37*, 2556–2586.
125. Sun, P.; Wang, F.; Tang, C.; Wang, D.; Lai, T.; Zhang, H.; Huang, Y. Temperature-Dependent Microstructure, Wear, and Corrosion Behavior of Fe-Cr-B Coatings Fabricated by Induction Heating Assisted Laser Cladding. *Mater. Charact.* **2026**, *231*, 115878. [\[CrossRef\]](#)
126. Wu, W.; Zhao, M.; Zhu, X.; Song, W.; Zhao, Y.; Yu, T. Influence of Low Speed-Wire Electrical Discharge Machining Strategy on Surface Roughness and Quality of Laser Cladding Ni204. *Surf. Interfaces* **2025**, *74*, 107742. [\[CrossRef\]](#)
127. Li, Y.; Liu, J.; Hu, Z.; Tan, N.; Zhang, G.; Li, Q. Microstructure and Properties of Laser Cladding Turning Machining Scrap. *Opt. Laser Technol.* **2022**, *147*, 107614. [\[CrossRef\]](#)
128. Meng, T.L.; Wang, T.F.; Lin, M.; Ng, Y.; Tan, X.Y.; Teo, S.L.; Tan, C.K.I.; Lim, R.; Liu, H. Grinding- and Robotic Hammer Peening-Induced Modifications in the near-Surface Regions of Laser-Cladded Inconel 718 Coatings. *Surf. Coat. Technol.* **2024**, *489*, 131130. [\[CrossRef\]](#)
129. Kushwaha, A.; Sivasubramanian, J.; Khan, M.D.A.; Masanta, M.; Basu, A. Ultrasonic Shot Peening (USSP) Post-Treatment of Ni Laser Cladding on Mild Steel. *Mater. Today Commun.* **2024**, *41*, 111076. [\[CrossRef\]](#)
130. Liu, S.; Tian, Z.-J.; Gao, X.-S.; Lv, F. Effect of Ultrasonic Peening on Microstructure and Properties of Laser Rapid Forming GH4169. *Optik* **2018**, *172*, 443–448. [\[CrossRef\]](#)
131. Zhang, Y.; Guo, L.; Yin, L.; Deng, Z.; Wang, X.; Liu, S. Effect of Heat Treatments on Microstructure and Corrosion Resistance of Laser-Cladded Inconel 625 Coatings. *Int. J. Electrochem. Sci.* **2025**, *20*, 101200. [\[CrossRef\]](#)
132. Wang, D.; Li, W.; Wang, Q.; Zhao, T.; Zhang, Y.; Chen, D.; Zhang, J. Effect of Heat Treatment on the Microstructure and Properties of Laser Cladding Cu-Containing 316L Stainless Steel Coating. *Surf. Coat. Technol.* **2025**, *514*, 132573. [\[CrossRef\]](#)
133. Yuan, J.; Zhao, X.; Wei, A.; Li, D.; Arif, A.F.M.; Alfano, M. Impact of Post-Heat Treatment on the Mechanical and Tribological Properties of GH4169/V Coatings Produced by Laser Cladding. *Wear* **2025**, *571*, 205829. [\[CrossRef\]](#)
134. Zhang, P.; Ji, G.; Lv, T.; Hu, S.; Wang, B.; Liu, Z. The Influence of Turning and Burnishing on Corrosion Resistance of Laser Cladded Fe–Cr–Ni Layer from Viewpoints of Thermodynamics and Kinetics. *Arch. Civ. Mech. Eng.* **2022**, *23*, 3. [\[CrossRef\]](#)
135. Dai, Q.; Liu, L.; You, F.; Luo, C. Grinding Performance of Laser Cladding WC/Fe Coatings by Different Adding Methods of WC Particles. *Machines* **2022**, *10*, 910. [\[CrossRef\]](#)
136. Uddin, M.; Santifoller, R.; Hall, C.; Schlaefel, T. A Grinding-Burnishing Approach to Enhancing Surface Integrity, Tribological, and Corrosion Behavior of Laser-Cladded AISI 431 Alloys. *J. Manuf. Sci. Eng.* **2022**, *144*, 071003.
137. Uddin, M.; Santifoller, R.; Hall, C.; Schlaefel, T. Effect of Combined Grinding–Burnishing Process on Surface Integrity, Tribological, and Corrosion Performance of Laser-Clad Stellite 21 Alloys. *Adv. Eng. Mater.* **2023**, *25*, 2201332. [\[CrossRef\]](#)
138. Shen, X.; Su, H.; Wang, J.; Zhang, C.; Xu, C.; Bai, X. New Approach towards the Machining Process after Laser Cladding. *Arch. Civ. Mech. Eng.* **2021**, *21*, 8. [\[CrossRef\]](#)
139. Zheng, K.; Lin, Y.; Cai, J.; Lei, C. Corrosion Resistance and Tribological Properties of Laser Cladding Layer of H13 Die Steel Strengthened by Ultrasonic Rolling. *Chin. J. Mech. Eng.* **2022**, *35*, 137. [\[CrossRef\]](#)
140. Wang, X.; Zheng, Y.; Liu, J.; Cai, Z.; Du, X.; Wang, H. Study on the Enhancement of Surface Integrity and Wear Resistance of Iron-Based Coatings by Ultrasonic Surface Rolling Process. *J. Mater. Res. Technol.* **2025**, *36*, 4898–4912. [\[CrossRef\]](#)
141. Wang, J.; Zhang, C.; Shen, X.; He, J. A Study on Surface Integrity of Laser Cladding Coatings Post-Treated by Ultrasonic Burnishing Coupled with Heat Treatment. *Mater. Lett.* **2022**, *308*, 131136. [\[CrossRef\]](#)
142. Xu, N.; Jiang, X.; Shen, X.; Peng, H. Improving the Surface Integrity and Tribological Behavior of a High-Temperature Friction Surface via the Synergy of Laser Cladding and Ultrasonic Burnishing. *Lubricants* **2023**, *11*, 379. [\[CrossRef\]](#)
143. Zhang, J.; Zhao, C.; Bai, Q.; Li, Q.; Chen, C.; Liang, J. Effect of Ultrasonic High-Frequency Percussion on the Microstructure and Corrosion Resistance of Fe-Based Alloy Coatings by High-Speed Laser Cladding. *Mater. Lett.* **2023**, *335*, 133769. [\[CrossRef\]](#)
144. Jiahui, C.; Jiahao, W.; Song, Z.; Lei, W.; Li, H. Impact of Ultrasonic Surface Rolling Processes on Microstructures and Fatigue Properties of 300M Steel Laser-Cladding-Repaired Components. *J. Mater. Eng. Perform.* **2025**, *34*, 1459–1469. [\[CrossRef\]](#)
145. Li, M.; Han, B.; Song, L.; He, Q. Enhanced Surface Layers by Laser Cladding and Ion Sulfurization Processing towards Improved Wear-Resistance and Self-Lubrication Performances. *Appl. Surf. Sci.* **2020**, *503*, 144226. [\[CrossRef\]](#)
146. Guo, W.; Li, X.; Ding, N.; Liu, G.; He, J.; Tian, L.; Chen, L.; Zairi, F. Microstructure Characteristics and Mechanical Properties of a Laser Cladded Fe-Based Martensitic Stainless Steel Coating. *Surf. Coat. Technol.* **2021**, *408*, 126795. [\[CrossRef\]](#)
147. Wang, X.; Ding, R.; Hu, C.; Yang, D.; Wu, Y.; Liu, L.; Lin, X. Influence of Tempering Treatment on the Microstructure Evolution and Mechanical Properties of Laser-Cladding High-Strength Iron-Based Alloy Coatings. *J. Mater. Res. Technol.* **2025**, *38*, 4662–4675. [\[CrossRef\]](#)

148. Telasang, G.; Dutta Majumdar, J.; Wasekar, N.; Padmanabham, G.; Manna, I. Microstructure and Mechanical Properties of Laser Clad and Post-Cladding Tempered AISI H13 Tool Steel. *Metall. Mater. Trans. A* **2015**, *46*, 2309–2321. [[CrossRef](#)]
149. Guo, W.; Zhang, L.; Xu, C.; Chai, R.; Gao, Z.; Kogo, B.; Chizari, M.; Zhang, C.; Wang, B. Study on the Wear Resistance of Laser Cladding Iron-Base Alloy by Heat Treatment. *Mater. Res. Express* **2018**, *6*, 026572. [[CrossRef](#)]
150. Li, Q.; Bai, Q.; Zhao, C.; Chen, C.; Liu, Y. Microstructure Evolution of Laser Cladding Coatings Treated by Multi-Pass Power Spinning. *Mater. Charact.* **2023**, *199*, 112819. [[CrossRef](#)]
151. Liang, J.; Wu, D.; Liu, S.; Wang, H.; Yu, J. Research on Hybrid Remanufacturing Process Chain of Laser Cladding, CNC Machining and Ultrasonic Rolling for Aero-Engine Blades. *J. Manuf. Processes* **2024**, *110*, 331–349. [[CrossRef](#)]

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