

Article

Tribological Analysis of Laser-Cladded Martensitic and Mixed-Alloy Coatings: Correlating Microstructure, Hardness, and Wear Response

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Abstract

High-strength quenched and tempered steels such as EN 42CrMo4, widely used for marine shaft applications due to their high strength, toughness, and fatigue resistance, are nevertheless susceptible to surface degradation under severe dry sliding conditions. To enhance surface integrity and tribological performance, this study investigates laser-cladded AISI 410L and mixed AISI 410L / AISI 4140 (50/50 wt.%) coatings deposited on EN 42CrMo4 steel using a high-power diode laser (HPDL). Two-layer coatings were produced, and selected specimens underwent post-cladding stress-relief heat treatment to mitigate residual stresses and temper as-solidified microstructures. Microstructural characterization revealed refined dendritic and martensitic morphologies, while the mixed-alloy coatings showed increased carbide formation and improved hardness homogeneity. The mixed AISI 410L / AISI 4140 coatings achieved significantly higher microhardness values ($\approx 530\text{--}555$ HV) compared to single-alloy 410L coatings ($\approx 310\text{--}420$ HV). Tribological testing under dry sliding conditions (Al_2O_3 counterbody, 5 N load, 0.5 m/s sliding speed) demonstrated that the mixed-alloy coatings exhibited substantially lower steady-state friction coefficients ($\mu \approx 0.65\text{--}0.69$) and markedly reduced specific wear rates ($\approx 11\text{--}17 \times 10^{-14} \text{ m}^3/\text{Nm}$) compared to the 410L coatings ($\approx 150\text{--}175 \times 10^{-14} \text{ m}^3/\text{Nm}$). Post-cladding heat treatment further stabilized friction behaviour and reduced wear in the mixed-alloy system by tempering martensite and alleviating localized stress concentrations. Wear mechanism analysis revealed a transition from severe abrasive wear with fatigue-induced delamination in the 410L coatings to predominantly mild abrasive wear in the mixed-alloy coatings, accompanied by localized plastic deformation. Overall, the results establish clear correlations between microstructure, hardness, and tribological response, demonstrating that mixed-alloy laser cladding is an effective strategy for enhancing the dry sliding performance of EN 42CrMo4 steel in demanding marine applications.

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Keywords: laser cladding; high-strength steel; microstructural characterization; wear behaviour; friction coefficient; wear mechanisms

1. Introduction

Surface degradation caused by wear, erosion, and corrosion remains one of the primary factors limiting the service life of steel components operating under severe mechanical and environmental conditions. Medium- and low-alloy steels such as AISI 410, 4140, 420, and related martensitic or ferritic–martensitic grades are commonly used in power generation, petrochemical, rail, marine, and tooling industries due to their favourable balance between

strength, toughness, and cost. However, under sliding, abrasive, or tribo-corrosive loading, these materials often exhibit insufficient surface durability, leading to premature failure and increased maintenance requirements. Consequently, surface engineering approaches that selectively enhance surface properties while preserving bulk integrity have attracted sustained research interest [1].

Wear performance of clad steels depends strongly on microstructure, dilution, carbide distribution, hardening transformations, and processing route. Across the available literature, a number of consistent trends emerge.

Friction-surfaced AISI 410 coatings exhibit excellent wear resistance due to their fully martensitic microstructure, achieving performance comparable to hardened bulk 410 steel, while MMAW coatings with δ -ferrite show inferior wear due to reduced hardness and microstructural heterogeneity [2]. Studies on multilayer 15-5PH laser-clad coatings on U75V railway steel reveal that wear resistance diminishes with each subsequent layer as substrate dilution decreases carbon enrichment; nonetheless, the first layer exhibits a ~95% reduction in wear rate relative to the substrate, owing to martensitic refinement and friction-induced martensite transformation during sliding contact [3]. Similar effects of dilution and phase evolution are reported in hybrid 410/2205 clads, where the top martensitic-austenitic layer shows highest hardness and lowest wear, while intermediate duplex layers provide toughness and reduce crack susceptibility during sliding wear [4].

Among the available surface modification technologies, laser-based processes—including laser cladding (LC), laser metal deposition (LMD), laser surface hardening, and laser surface remelting—have emerged as particularly effective solutions for both surface enhancement and in situ repair of high-value components. These techniques are characterized by highly localized heat input, rapid solidification rates, controlled dilution, and strong metallurgical bonding between coating and substrate, resulting in refined microstructures and minimal distortion compared with conventional arc-based cladding or thermal spray processes [1,5].

The tribological performance of laser-processed steels is governed not only by hardness enhancement but also by the dominant wear mechanisms activated during service. Studies on martensitic stainless steels consistently show that refined martensitic microstructures suppress severe adhesive wear by limiting plastic deformation, while carbide precipitation and secondary phase distributions improve resistance to abrasive micro-cutting. Conversely, excessive dilution, retained δ -ferrite, or heterogeneous microstructures can promote delamination, oxidative wear, and accelerated material removal under sliding conditions [6,7].

Laser surface hardening and surface remelting studies on AISI 410, 410S, and 420 steels further demonstrate that wear resistance is strongly correlated with hardened layer depth, martensite morphology, and thermal history. Although AISI 420 generally achieves higher peak surface hardness due to its higher carbon content, AISI 410 typically develops deeper hardened layers under identical laser parameters, which is advantageous under high contact stresses or subsurface-dominated wear conditions. Optimal tribological performance has been reported at intermediate scan speeds, where sufficient martensitic transformation is achieved without excessive hardness gradients or residual stress concentration [6,7].

In laser-clad martensitic stainless steels such as AISI 410 and 420, residual stress development plays a critical role in both mechanical integrity and wear performance. Rapid thermal cycling during laser processing induces complex residual stress fields, with tensile stresses often concentrated near the surface and compressive stresses dominating within the clad or dilution zones. While compressive stresses can enhance fatigue and wear resistance, tensile stresses may promote crack initiation and premature failure. Post-cladding heat treatment has been shown to effectively reduce tensile residual stresses and homogenize

stress distributions without significantly degrading hardness, thereby improving overall tribological stability [8].

Laser metal deposition of low-carbon 410L stainless steel represents an additional pathway for producing wear-resistant coatings with balanced strength and ductility. As-built LMD 410L microstructures typically consist of ferrite, Widmanstätten ferrite, martensite, and fine (Fe,Cr)₂₃C₆ precipitates, which transform into refined martensitic structures after appropriate heat treatment. Although several studies emphasize the mechanical property enhancement achieved through heat treatment, limited attention has been given to the direct correlation between these microstructural transformations and wear mechanisms in laser-deposited low-carbon martensitic stainless steels [9].

Hybrid surface engineering approaches, combining thermal spraying with subsequent laser modification, have also demonstrated significant improvements in wear and corrosion resistance [10]. Laser remelting of HVOF-sprayed WC–Co and Inconel-based coatings reduces porosity, refines carbide distribution, and improves coating–substrate bonding, resulting in superior tribological performance compared with as-sprayed coatings. These findings highlight the importance of controlled laser–material interaction in tailoring microstructure and wear behavior across different coating systems [11].

Laser-directed energy deposition (L-DED) coatings of AISI 410L show wear behaviour comparable to commercial AISI 410 valve plugs, even without post-heat treatment. As-built coatings contain martensitic–ferritic microstructures that provide adequate hardness, while heat treatment modifies hardness and microstructure but does not significantly alter microabrasive wear performance, suggesting that L-DED can successfully restore worn components without extensive thermal processing [12]. In mixed-powder laser cladding of 410L and 4140 steels, higher 410L ratios produce harder coatings with superior wear resistance, while higher 4140 content improves toughness; this enables tailoring tribological performance by adjusting alloy composition during deposition [13].

Despite the substantial body of work on laser-based surface modification of steels, several gaps remain. In particular, a unified understanding of how microstructural evolution, dilution effects, residual stress development, and phase stability collectively govern wear mechanisms across different laser cladding and laser deposition routes is still lacking. Moreover, comparative tribological assessments linking processing-induced microstructural features to dominant wear modes remain limited, especially for martensitic stainless steel claddings designed for repair and refurbishment applications.

In this context, the present work aims to systematically investigate the tribological behavior of laser-processed steel claddings, with emphasis on the interrelationship between microstructure, hardness distribution, and prevailing wear mechanisms. Detailed microstructural characterization and microhardness analysis have been reported separately [13,14] and are therefore not repeated here, allowing the present study to focus specifically on wear performance and mechanism-based interpretation.

2. Materials and Methods

2.1. Materials and Laser Process

Disk shape specimens of EN 42CrMo4 steel, with a diameter of 80 mm and thickness of 96 mm, were selected as substrates. It should be noted that the shaft was retrieved from an industrial ship repair operation. Information regarding the original supplier or manufacturer was not available. This limitation is inherent to real-world repair cases and does not compromise the validity of the present investigation, as the material identity was ensured through certification and complementary laboratory analyses. The chemical composition (%) of the substrate is presented in Table 1. Customized ferritic stainless steel AISI 410L powder, along with customized medium carbon micro-alloyed steel AISI

4140 powder, were used as cladding materials. Laser cladding was performed using an off-axis HPD Laser, operating at a power (P) of 2400 W, and a travel speed (U) of 12 mm/s, resulting in a source energy of 0.2 kJ/mm ($Q_s = P/U$) and a heat input of 0.1 kJ/mm ($Q = n \times Q_s$, where $n = 0.5$ is the HPD Laser efficiency). These parameters were selected based on preliminary trials and prior work [13,14]. They ensured defect-free deposition with sufficient metallurgical bonding while limiting excessive dilution and thermal distortion.

Table 1. Chemical composition of EN 42CrMo4 steel and steel powders.

		C	Si	Mn	Cr	Mo	S	P	Ni	Fe
Powders	AISI 410L	Max 0.03	Max 1.0	...	11.5–13.5	...	Max 0.03	...	Max 0.9	Balance
	AISI 4140	0.38–0.43	0.15–0.30	0.75–1.00	0.8–1.1	0.15–0.25	0.04	0.035	...	Balance
Substrate	EN 42CrMo4 steel	C	Ni	Mo	F	N	Cr	Mn	Fe	
		0.410	0.23	0.60	0.013	0.004	0.970	0.163	Balance	

Prior to the cladding process, the substrate was subjected to a preparation procedure that included grinding and cleaning, followed by preheating using propane torches until a temperature of 160 °C was reached, in order to reduce residual stresses. Four nozzles were used to transfer the powders, with a total deposition rate of 14 g/min ($\dot{m} = 14$ g/min). The spot size of the laser beam used was 3.5 mm in diameter following Gaussian distribution.

Two coatings were applied: one using AISI 410L stainless steel alloy powder and the other using a 50–50% mixture of AISI 410L and AISI 4140 powders (MIX). Both coatings were deposited in the same manner, with a 1.5 mm step size and a 34 mm step width. Each coating was composed of two layers. The chemical compositions of the materials are provided in Table 1, while the particle size distribution (PSD) for both powders ranges from 50 μ m to 150 μ m, according to the powder supplier specifications. SEM micrographs of powders are illustrated in Figure 1. Particle size distribution data were provided by the powder supplier. A detailed PSD curve was not available; however, the specified particle size range was sufficient to ensure stable powder flow and consistent laser cladding conditions.

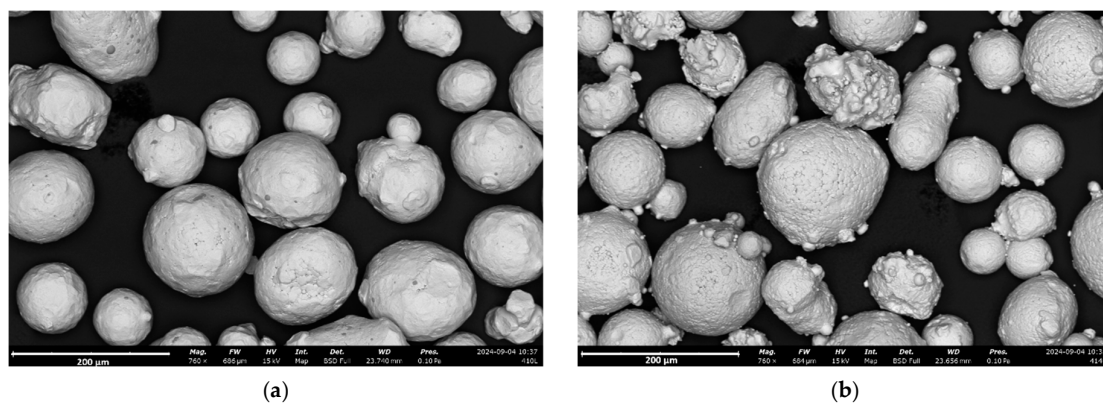


Figure 1. SEM micrographs: (a) AISI 410L powder particles, (b) AISI 4140 powder particles.

A fully AISI 4140 coating was not investigated in the present study due to the well-documented limitations of cladding medium-carbon steels by laser processes. AISI 4140, with its relatively high carbon content, is highly susceptible to martensite formation, hydrogen-induced cracking, and solidification cracking when deposited as a standalone cladding material, particularly under rapid cooling conditions typical of laser cladding [15].

Previous studies have shown that laser cladding of medium- and high-carbon steels often requires extensive preheating, interpass temperature control, or complex post-cladding heat treatments to avoid cracking and loss of coating integrity. In contrast, AISI 410L stain-

less steel offers improved weldability, lower cracking susceptibility, and stable cladding behaviour, making it a suitable base material for laser-deposited coatings.

The objective of this work was therefore to evaluate alloy blending as a microstructural engineering strategy, where AISI 4140 was incorporated as a secondary alloying constituent to enhance hardness and wear resistance while preserving cladding integrity and process stability. The 50/50 AISI 410L/AISI 4140 composition represents a balanced compromise between hardness enhancement and crack resistance, enabling the development of defect-free coatings with superior tribological performance.

X-ray diffraction (XRD) analysis was not performed in the present study. Phase identification was instead inferred from a combined analysis of coating chemistry, microstructural morphology observed by optical microscopy and SEM, and microhardness evolution across the clad layers and heat-affected regions. For Fe-based laser-clad systems such as AISI 410L and AISI 4140, the expected phases and transformation products (primarily martensite, ferrite, and carbide precipitates) are well established in the literature and can be reliably correlated with microstructural features and hardness trends.

2.2. Post Laser Cladding Heat Treatment

One set of coated specimens underwent a post-laser cladding stress-relief heat treatment immediately after deposition, while still at the preheat temperature, to minimize the risk of hydrogen-induced cold cracking. The heat treatment consisted of controlled heating at 50 °C/h to 650 °C, a one-hour hold at 650 °C, followed by controlled cooling at 50 °C/h to 350 °C, and final air cooling to room temperature. This post-HT cycle was designed to temper martensite formed during the LCD process and relieve residual stresses, thereby reducing hardness, lowering cracking susceptibility, and improving ductility and toughness [15–18]. The treatment was carried out in an RHF 15/15 Carbolite furnace.

2.3. Characterization Techniques

A comprehensive metallographic and microhardness characterization was carried out on the clad specimens. Cross-sectional samples were prepared according to standard metallographic procedures, including mechanical grinding, polishing, and chemical etching. Two etchants were employed to reveal the microstructure: 2% Nital (2% HNO₃ in methanol) for specimens coated with mix powder (AISI 4140 + AISI 410L powder, hereafter MIX), and Kalling's No. 1 solution (1.5 g CuCl₂, 33 mL H₂O, 33 mL ethanol, 33 mL HCl) for those coated with AISI 410L (hereafter 410L). Macrostructural features were examined using an Olympus SZX10 stereomicroscope (EVIDENT, Tokyo, Japan). Microstructural characterization was performed with a ZEISS Axiotech optical microscope (ZEISS, Oberkochen, Germany) equipped with image analysis software, and further detailed observations—including phase and chemical composition assessment—were conducted using a Thermo Scientific Phenom XL SEM with EDS (Thermo Fisher Scientific Inc., Wilmington, Delaware, USA). However, a detailed microstructural characterization of laser-clad AISI 410L/AISI 4140 mixed coatings, including SEM, EDS mapping, and XRD analysis, has been previously reported by Roussos et al. [9]. In the present study, the microstructural discussion is intentionally limited, as the investigation focuses primarily on the tribological behavior of the laser-clad coatings and on establishing correlations between hardness, friction response, and wear performance rather than on an extensive microstructural analysis. Vickers microhardness profiles were obtained on cross-sections of the coatings using a Qness 60 A+ EVO tester (QATM, Mammelzen, Germany) under a 0.3 kgf load (HV0.3).

The tribological and wear behaviour of the coatings was assessed using a CSEM Instruments pin-on-disk tribometer in accordance with ASTM G99. Before testing, the

coatings were ground and polished to achieve a surface roughness of approximately 0.2 μm Ra. Wear tests were performed under unlubricated ambient conditions (25 °C, 60% relative humidity) over a continuous sliding distance of 942 m. Throughout the test, the coefficient of friction was continuously monitored, and weight loss for both the specimens and the counterbody was determined using an electronic balance with a precision of 10^{-4} g. Prior to weighing, all samples were ultrasonically cleaned in acetone to remove debris.

In addition, each coating's specific wear rate was calculated by Equation (1):

$$k = \frac{V}{W \cdot s} \quad (1)$$

where V the volume loss in m^3 , W the applied load in N and s the sliding distance in m.

The counter body was a sphere of Al_2O_3 of 6 mm in diameter. Sliding speed and normal load were kept constant at 0.5 m/s and 5 N, respectively, for 10,000 cycles (Table 2). The testing parameters were chosen to promote measurable wear without premature coating failure, ensure operation within the mild-to-severe wear transition regime and allow comparison with prior tribological studies on laser-cladded steels [13,16].

Table 2. Tribological testing parameters.

	Non-Heat-Treated (NHT) MIX	Heat-Treated (HT) MIX	Heat-Treated (HT) 410L	Non-Heat-Treated (NHT) 410L
Counter body	Al_2O_3 ball			
Track diameter (mm)	30	30	30	30
Load (N)	5	5	5	5
Number of Cycles	10,000	10,000	10,000	10,000
Sliding speed (m/s)	0.5	0.5	0.5	0.5
Rotation speed (rpm)	318	318	318	318

Each tribological test was repeated three times, and the reported friction coefficients and wear rates represent average values, with standard deviations reported in corresponding Tables.

Subsequently, the wear tracks were examined using scanning electron microscopy to identify the wear mechanisms active during the friction tests.

3. Results and Discussion

3.1. Macroscopic Observations

Macroscopic examination of the laser-cladded coatings revealed uniform, continuous layers with good metallurgical bonding to the EN 42CrMo4 substrate, consistent with the cladding behaviour reported in the reference study [14]. The multi-layer deposition produced well-defined tracks with stable bead geometry and minimal surface waviness, indicating steady thermal conditions during processing. No macroscopic defects—such as cracks, lack of fusion, or excessive porosity—were observed in either the single-alloy or mixed-powder coatings, suggesting that the selected laser parameters and preheating strategy effectively controlled thermal gradients and dilution effects. Variations in layer thickness and penetration depth followed the trends documented in the reference work, reflecting the influence of powder composition and energy input on melt pool dynamics. This macroscopic integrity provides a reliable foundation for evaluating the tribological behaviour of the coatings, as uniform layer morphology and defect-free interfaces are

essential for ensuring consistent stress distribution and wear performance under sliding contact (Figure 2 and Table 3).

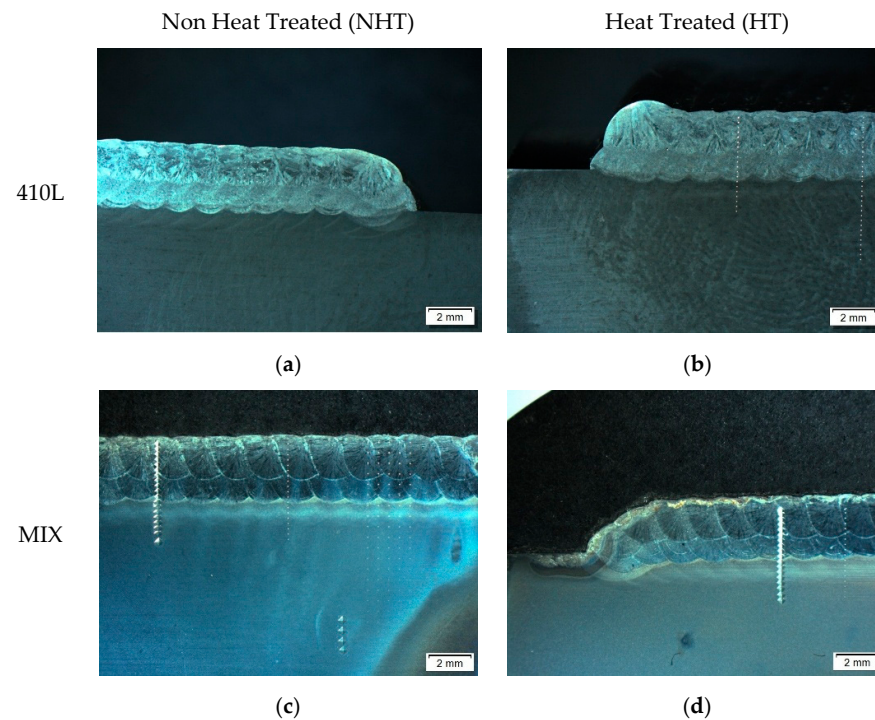


Figure 2. Stereoscopic macrographs of cross-sections of (a) NHT 410L, (b) HT 410L, (c) NHT MIX and (d) HT MIX coatings [14]. The images show the complete layer architecture, including the substrate, penetration zone, and both cladded layers. Microhardness marks are also visible. Quantitative coating thickness values are reported separately.

Table 3. Size measurements in coatings.

	410L (NHT & HT)	MIX (NHT & HT)
Coating thickness (mm)	2.84 ± 0.11	2.59 ± 0.10
Penetration depth (mm)	0.52 ± 0.04	0.56 ± 0.05
1st Layer thickness (mm)	0.94 ± 0.05	0.91 ± 0.05
2nd Layer thickness (mm)	1.86 ± 0.08	1.61 ± 0.07

Although dedicated low-magnification macrographs were not acquired, the cross-sectional micrographs presented in Figure 2 capture the complete coating thickness and clearly resolve the substrate, penetration zone, and individual cladded layers. The full layer architecture is therefore fully visible within the reported fields of view, and quantitative coating thickness values are provided separately based on multiple cross-sectional measurements.

3.2. Microstructural Analysis

Microstructural characterization of the laser-cladded coatings revealed distinct morphological features across the substrate, interface, and deposited layers, consistent with the previously reported microstructural trends [14]. The base metal exhibited the typical tempered-martensitic or bainitic microstructure of EN 42CrMo4 steel, with uniformly distributed carbides and no alteration attributable to the cladding process.

At the interface between the first layer and the substrate, a partially mixed zone (PMZ) was observed in all coating conditions, consistent with the dilution-driven compositional

gradients described in [14]. This region exhibited a refined dendritic morphology and a harder martensitic–ferritic mixture arising from rapid cooling and localised reheating. In the NHT coatings (both 410L (Figure 3) and MIX (Figure 4)), the PMZ displayed needle-like martensite with higher contrast carbide clusters, indicating strong thermal gradients and faster solidification rates. After heat treatment, this interface became more homogeneous: the martensitic needles were partially tempered, and the etched contrast decreased, suggesting reduced residual stresses and a more stable microstructure (HT 410L and HT MIX).

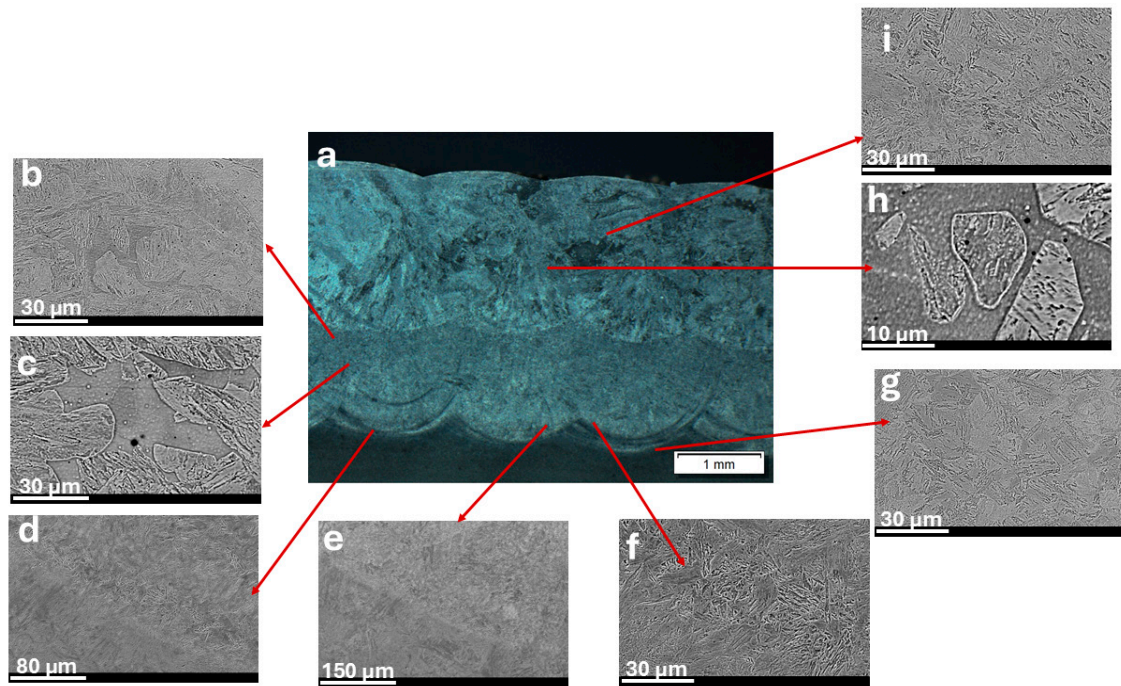


Figure 3. Optical micrographs of laser clad AISI 410L (NHT 410L) coating on EN 42CrMo4 steel. (a) overall coating, (b,c) magnification of 1st layer, (d–g) magnification of interface between 1st layer and substrate, (h,i) magnification of 2nd layer.

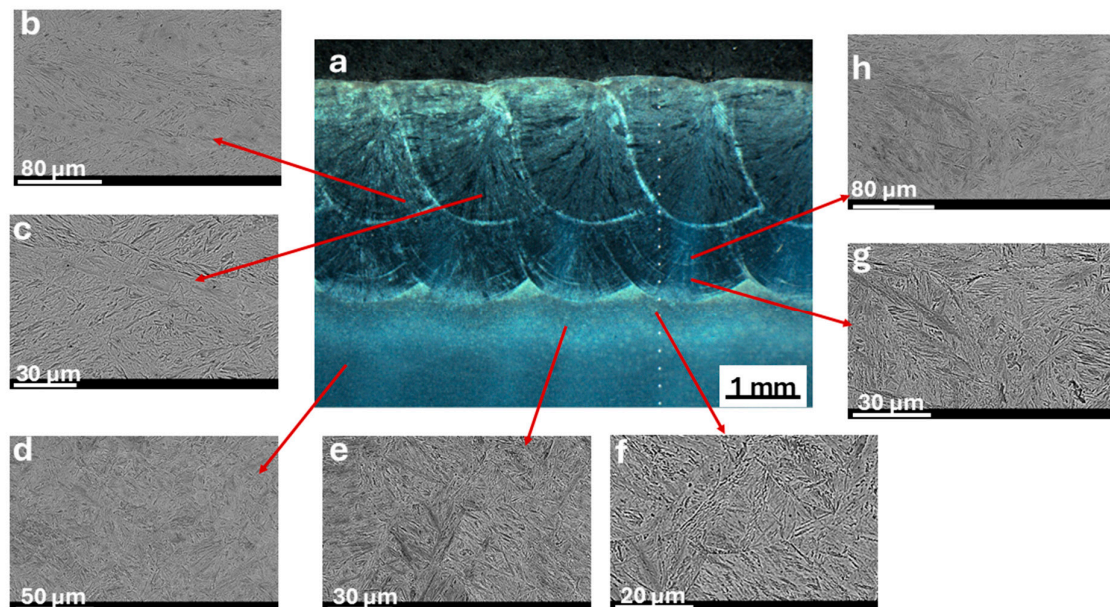


Figure 4. Optical micrographs of laser clad MIX (NHT MIX) coating on EN 42CrMo4 steel. (a) overall coating, (b,c) magnification of 2nd layer, (d–f) magnification of interface between 1st layer and substrate, (g,h) magnification of 1st layer.

The first clad layer exhibited the most pronounced solidification structures. In the NHT 410L coating, the microstructure consisted predominantly of fine cellular and columnar ferritic dendrites, with evidence of Widmanstätten ferrite, matching observations from the original study. The NHT MIX coating displayed a more complex dendritic network enriched in alloying elements from the 4140 fraction, producing locally harder martensitic regions embedded within a ferritic matrix. In HT specimens, both 410L (Figure 5) and MIX (Figure 6) coatings showed tempered microstructures with reduced dendrite contrast and partially decomposed martensite, indicating that the stress-relief heat treatment effectively softened the as-cladded deposits and improved structural stability.

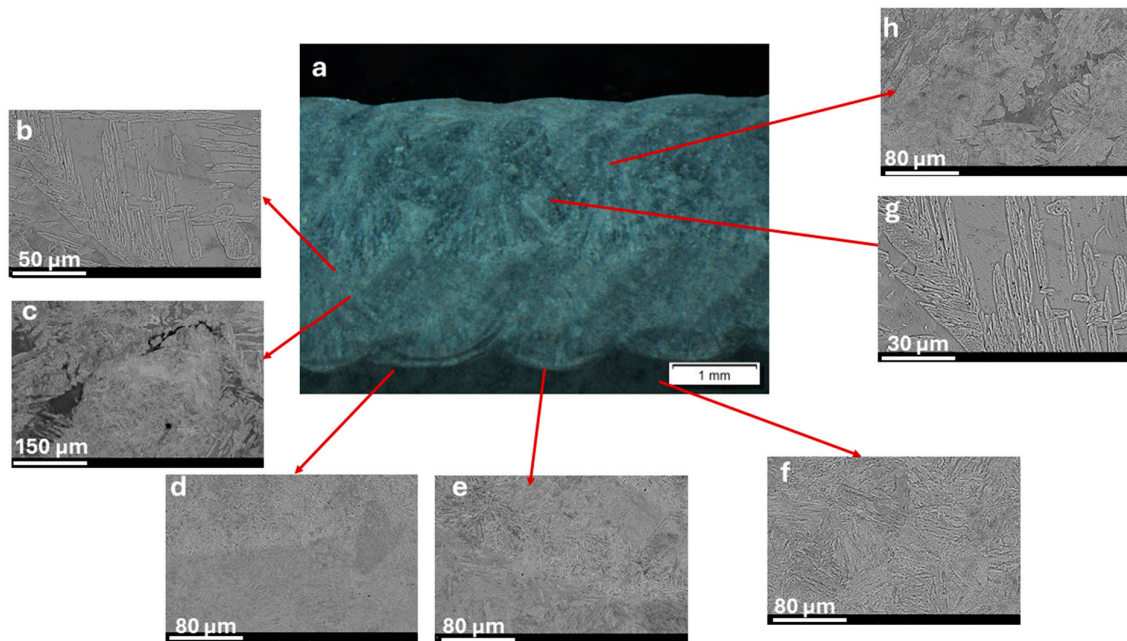


Figure 5. Optical micrographs of heat-treated laser clad HT 410L coating on EN 42CrMo4 steel. (a) overall coating, (b,c) magnification of 1st layer, (d–f) magnification of interface between 1st layer and substrate, (g,h) magnification of 2nd layer.

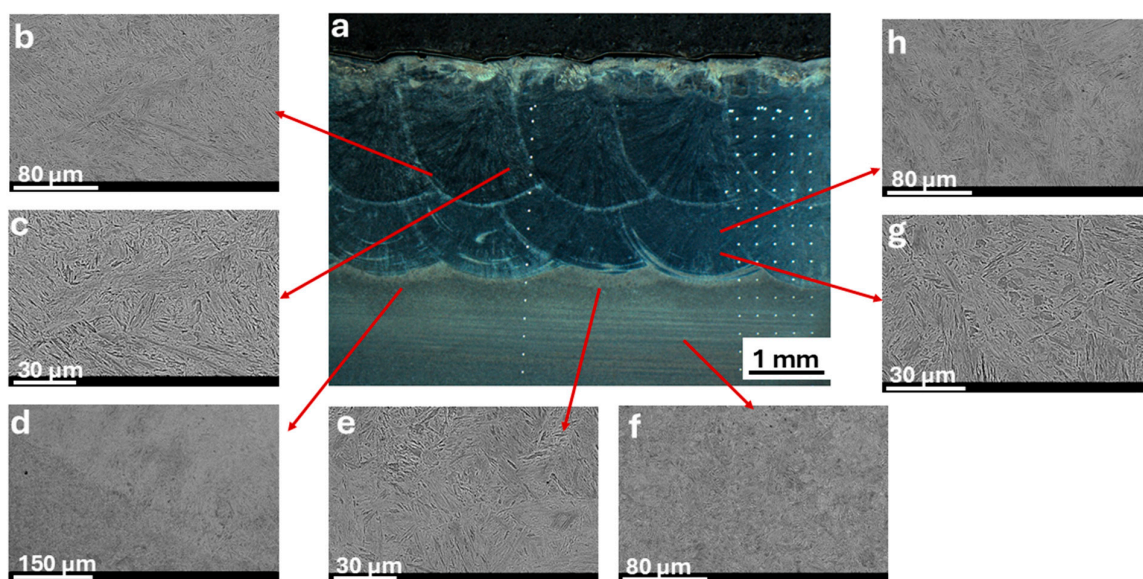


Figure 6. Optical micrographs of heat-treated laser clad HT MIX coating on EN 42CrMo4 steel. (a) overall coating, (b,c) magnification of 2nd layer, (d–f) magnification of interface between 1st layer and substrate, (g,h) magnification of 1st layer.

In the second layer, the morphology transitioned toward coarser dendrites, a characteristic attributed to the lower cooling rate away from the substrate. The NHT MIX coating exhibited more pronounced interdendritic carbide precipitation compared with 410L, reflecting differences in carbon content and solidification behaviour. Heat-treated specimens again demonstrated a more uniform microstructure, with coarsened but tempered dendritic regions and reduced segregation contrast.

Overall, the microstructural evolution across layers reflects the combined effects of melt pool dilution, thermal gradients, alloy composition, and post-heat treatment. The NHT coatings—especially the MIX variant—exhibited sharper dendritic features, higher martensite content, and more pronounced segregation, suggesting elevated hardness but lower toughness. Conversely, heat-treated coatings showed tempered martensite and homogenized dendritic structures, indicating reduced residual stresses and improved ductility. These microstructural distinctions play a central role in the subsequent tribological behaviour, influencing wear mechanisms, friction stability, and degradation resistance under sliding conditions.

The microstructural trends observed in the present coatings are consistent with the broader laser cladding literature on Fe-based martensitic systems, where rapid solidification promotes cellular/columnar morphologies and strong layer-to-layer gradients driven by cooling-rate changes and dilution. In particular, the mixed-alloy (410L/4140) condition exhibited increased martensitic fraction and more pronounced interdendritic strengthening features, which is expected when carbon and strong carbide-forming alloying elements are locally enriched during solidification. Similar microstructure–hardness linkages have been reported for martensitic stainless steel coatings deposited on 42CrMo4-type substrates via laser-based deposition, where the combination of solidification refinement and martensitic transformation yields marked hardness increments relative to the base steel [19].

From a comparative standpoint, the present hardness levels for the mixed coatings (first and second layer >500 HV) fall within the range commonly reported for laser-deposited martensitic stainless/low-alloy hybrid systems and mixed-powder strategies aimed at simultaneously increasing hardness and maintaining coating integrity. Studies investigating mixed 410L/4140-type powder systems report that compositional tuning is an effective route for increasing hardness while avoiding excessive brittleness associated with high-carbon deposits [9].

3.3. Microhardness Analysis

The microhardness profiles of the laser-cladded coatings for the four conditions—NHT 410L, HT 410L, NHT MIX, and HT MIX—are shown in Figure 7a–d, while Table 4 presents the average microhardness values, reported with associated measurement uncertainty, of distinct regions of specimens (substrate, HAZ + PMZ, first layer, and second layer of the four coating conditions—NHT 410L, HT 410L, NHT MIX, and HT MIX). All coatings exhibit higher hardness than the EN 42CrMo4 substrate, reflecting the formation of refined dendritic structures and martensitic transformations during rapid solidification, as described in detail in [14]. For the 410L coatings, the NHT and HT conditions display similar hardness in both the substrate region (≈ 332 – 338 HV) and the HAZ + PMZ (≈ 351 HV), suggesting that the stress-relief treatment induces only mild tempering in these zones. The most pronounced hardness difference occurs in the clad layers. In the first layer, hardness increases slightly after heat treatment (from 410.75 HV to 418.25 HV), suggesting that the heat-treatment cycle relieved residual stresses while preserving a predominantly martensitic structure. The second layer shows the opposite trend, with hardness decreasing from 327 HV in the NHT state to 306.75 HV after tempering, demonstrating that the upper region—subjected to lower cooling rates—responds more strongly to the tempering effect.

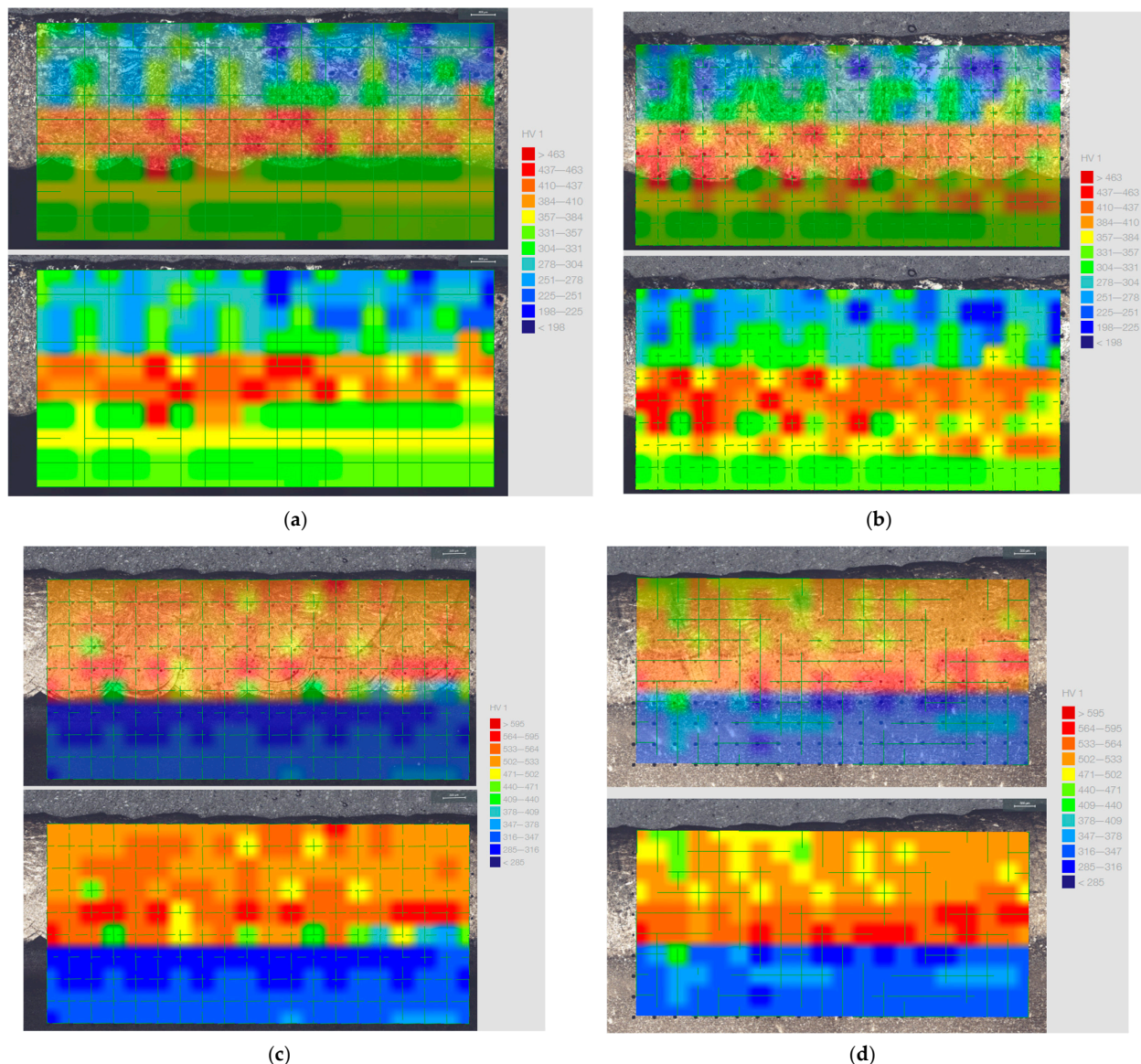


Figure 7. Microhardness profiles: (a) NHT 410L; (b) HT 410L; (c) NHT MIX; (d) HT MIX.

Table 4. Average microhardness values.

	NHT 410L	HT 410L	NHT MX	HT MIX
SUBSTRATE	331.75 ± 10	337.25 ± 12	332.75 ± 10	338 ± 11
HAZ + PMZ	350.75 ± 12	351.25 ± 12	318 ± 11	324.75 ± 15
1ST LAYER	410.75 ± 11	418.25 ± 11	555.25 ± 15	531.5 ± 15
2ND LAYER	327 ± 10	306.75 ± 10	537.5 ± 12	511.5 ± 15

The MIX coatings exhibit markedly higher hardness values compared to the 410L coatings, due to the higher carbon content and carbide-forming elements introduced by the 4140 fraction. In the NHT MIX, the first layer reaches 555.25 HV, significantly exceeding the NHT 410L first layer, while the second layer maintains a similarly high hardness of 537.5 HV. These elevated values reflect the presence of harder martensitic phases and increased carbide precipitation, as observed in the microstructural analysis. After heat treatment, both clad layers experience a moderate reduction in hardness—531.5 HV in the first layer and 511.5 HV in the second layer—indicating effective tempering of martensite

and partial homogenization of microsegregated phases. The HAZ + PMZ of the MIX coatings shows lower hardness values (318–324.75 HV) than the 410L coatings, suggesting that dilution effects and alloying interactions play a dominant role in this transition region.

Overall, the microhardness behaviour reveals three key trends: (i) MIX coatings are significantly harder than 410L coatings due to compositional enrichment and carbide formation; (ii) heat treatment reduces hardness more effectively in regions solidified at slower cooling rates, particularly the upper layer of the 410L coating; and (iii) the preserved high hardness of the MIX coating, even after tempering, suggests superior load-bearing capacity and potential improvements in wear resistance. These hardness gradients are expected to directly influence the tribological performance of the coatings, with the MIX clads likely exhibiting enhanced resistance to plastic deformation and abrasive wear during sliding contact.

The relatively modest hardness decrease after stress-relief heat treatment in the mixed coating, alongside improved frictional stability, is consistent with the role of tempering in reducing residual stresses and decreasing susceptibility to local brittle microfracture during repeated sliding. In laser cladding, residual stress magnitude and distribution are strongly governed by steep thermal gradients and transformation strains; post-processing strategies are routinely reported to stabilize near-surface response even when the average hardness reduction is limited [20].

Although XRD analysis was not conducted, the presence of martensitic structures and carbide-strengthened regions is supported by the observed dendritic and lath morphologies, hardness levels exceeding 500 HV in the mixed coatings, and the characteristic hardness gradients across the coating and HAZ, in agreement with previously reported laser-cladded 410L- and 4140-based systems.

3.4. Friction Coefficient

The evolution of the friction coefficient (μ) during dry sliding reflects the combined effects of surface roughness, real contact area, oxide formation, subsurface deformation, and microstructural stability of the cladded layers. As shown in Figure 8, all coatings exhibit a characteristic running-in stage during the first ~500 cycles, followed by a transition toward a steady-state friction regime. This behaviour is typical of metallic systems under dry sliding, where initial asperity interactions and debris generation progressively modify the contact conditions. During the initial sliding stage, a rapid increase in μ is observed for all coatings. This behaviour is associated with asperity fracture and plastic deformation in the near-surface region [21–23]. In the 410L coatings (NHT and HT), the relatively lower hardness and ferritic–martensitic matrix promote a larger real contact area, accelerating adhesive junction formation and increasing friction. The sharper rise in μ for HT 410L, which briefly exceeds 0.7, suggests enhanced adhesive interactions resulting from tempered martensite with reduced residual stresses but increased local ductility.

In contrast, both MIX coatings (NHT MIX and HT MIX) exhibit lower initial friction coefficients, with an average value of 0.62 ± 0.03 , indicating reduced adhesive contribution during running-in. This behaviour is primarily associated with the higher hardness and the presence of uniformly distributed carbides and hard martensitic regions introduced by the AISI 4140 fraction. These phases act as effective load-bearing constituents, limiting asperity deformation and suppressing early-stage adhesive junction growth.

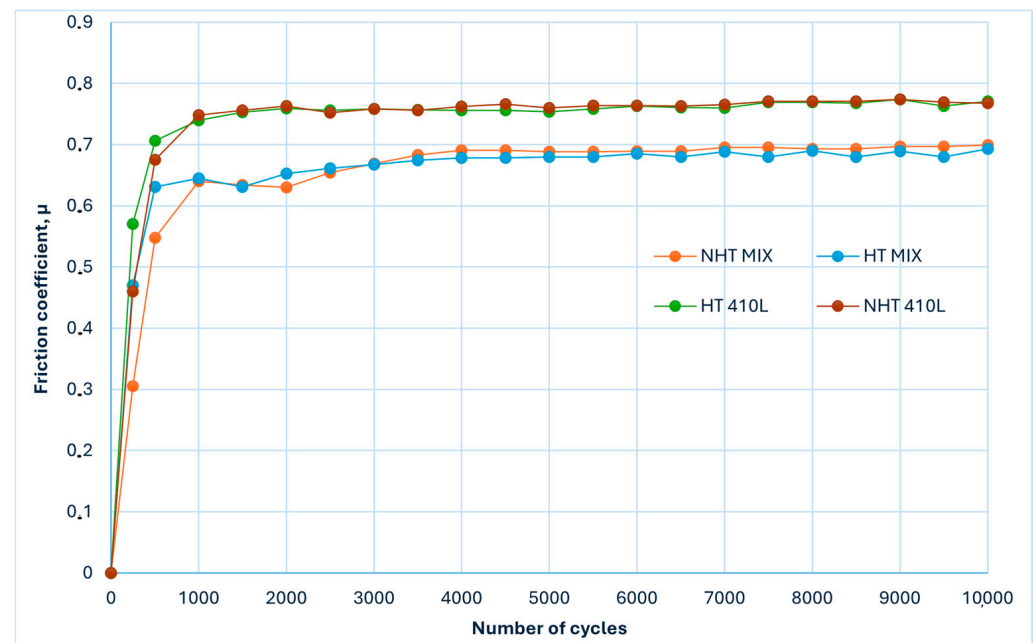


Figure 8. Friction coefficient (μ) as a function of number of cycles during pin on disc testing of coatings.

After the running-in period, all coatings reach a stable friction regime, although the plateau values differ significantly. The 410L coatings stabilize at higher friction coefficients, with an average value of 0.72 ± 0.03 , while the MIX coatings stabilize at lower average value of 0.67 ± 0.03 . This distinction is closely correlated with microhardness gradients and microstructural constitution. According to classical tribological models, such as the Bowden–Tabor adhesion theory, friction under dry sliding conditions is proportional to the real contact area and the shear strength of junctions formed at asperity contacts. In the present case, this framework explains the higher friction levels observed for the 410L coatings, where lower hardness promotes increased plastic deformation and enlargement of the real contact area. Conversely, the higher hardness of the MIX coatings restricts asperity flattening, reducing the effective contact area and limiting adhesive shear resistance. The friction behaviour is also influenced by the formation and stability of tribo-oxidative layers. SEM/EDS analysis of the wear tracks indicates mild oxidation in all coatings; however, its role differs between systems. In the 410L coatings, oxide fragments appear to be repeatedly fractured and removed, likely due to insufficient mechanical support from the softer matrix. This process promotes unstable third-body abrasion and contributes to sustained high friction levels. The friction levels measured here ($\mu \sim 0.65$ – 0.75 in steady-state dry sliding) are comparable to those reported for laser-cladded steel systems where adhesion–abrasion competition and tribo-oxide stability dominate the steady regime. In general, harder cladded layers tend to reduce the real area of contact and suppress adhesive junction growth, thereby lowering μ and stabilizing friction, provided that brittle fracture and debris generation are not dominant. This behaviour is consistent with published observations on laser-cladded carbon steels and martensitic stainless coatings where microstructural refinement and increased hardness promote lower and more stable friction under dry sliding [1].

In contrast, the MIX coatings appear to promote the formation of thinner and more stable oxide films during steady-state sliding. Wear track morphology and SEM/EDS observations suggest that these oxide layers may act as solid lubricating films. The harder martensitic–carbide matrix provides improved mechanical support, which helps to limit

premature oxide spallation and reduce direct metal-to-metal contact. Collectively, these effects contribute to lower friction coefficients and enhanced wear resistance.

Although post-cladding heat treatment significantly affects wear resistance, its influence on steady-state friction is comparatively modest. The friction curves of HT and NHT specimens for both 410L and MIX coatings converge toward similar plateau values, indicating that friction is less sensitive to residual stress relief than to intrinsic microstructural hardness and phase distribution. However, the HT MIX coating exhibits a smoother transition to steady-state friction, suggesting that stress relief and tempered martensite improve frictional stability by minimizing localised plasticity and micro-fracture events during sliding.

Overall, the friction behaviour of the laser-cladded coatings is governed by a synergistic interaction between microhardness, phase constitution, and tribo-layer stability. The mixed AISI 410L/AISI 4140 coatings demonstrate superior frictional performance due to their enhanced load-bearing capacity, reduced adhesive interaction, and more stable oxide-assisted sliding regime. These findings reinforce the conclusion that microstructural refinement and compositional tailoring are effective strategies for controlling frictional response in laser-cladded marine shaft coatings.

3.5. Wear Behaviour

Figure 9 and Table 5 present the specific wear rate of all coatings as determined by pin-on-disc testing. Mixing 410L and 4140 results in a coating that exhibits a significantly lower wear rate compared with the monolithic 410L coatings (Table 5). Both NHT MIX and HT MIX conditions show substantially improved wear resistance, with the heat-treated MIX coating demonstrating the lowest specific wear rate among all investigated conditions. In contrast, both NHT 410L and HT 410L exhibit considerably higher wear rates, indicating inferior wear resistance relative to the mixed coatings. All wear results are reported as mean $\pm$ standard deviation based on triplicate measurements. Weight loss of the counterbody was negligible in all cases and close to the balance resolution (10^{-4} g), as summarized in Table 5.

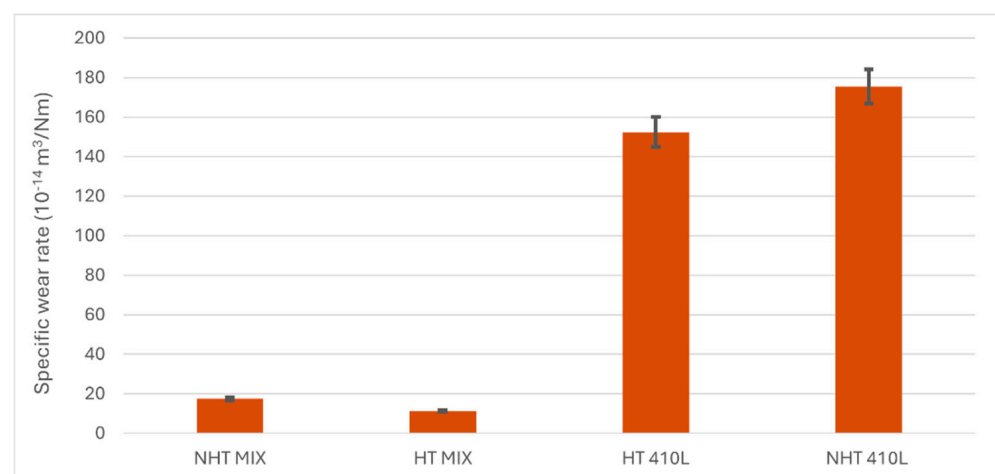


Figure 9. Specific wear rate (k) of coatings.

Table 5. Wear analysis results.

	HT MIX	NHT MIX	NHT 410L	HT 410L
Weight loss of specimen (gr)	0.0087 ± 0.0015	0.0078 ± 0.0012	0.0689 ± 0.0110	0.0613 ± 0.015
Weight loss of counter body (gr)	0.0001 ± 0.0001	0.0001 ± 0.0001	0.0007 ± 0.0001	0.001 ± 0.0001
Specific wear rate, k ($10^{-14} \text{ m}^3/\text{Nm}$)	17 ± 1	11 ± 1	175 ± 9	152 ± 8

The order-of-magnitude reduction in specific wear rate achieved by the mixed coating relative to 410L is consistent with the well-established dependence of wear volume loss on hardness and subsurface load-bearing capacity in dry sliding contacts. Comparable “step changes” in wear resistance have been reported in laser-cladded steels when the microstructure transitions from comparatively soft ferritic/mixed matrices to harder martensitic or carbide-strengthened matrices, which reduces ploughing depth, suppresses subsurface ratcheting, and limits third-body abrasion [1].

Notably, the literature on martensitic stainless laser deposition on 42CrMo4-type steels highlights that wear improvements are often maximized when the coating provides both (i) high hardness and (ii) sufficient microstructural stability to avoid brittle cracking and delamination. In this context, the mixed 410L/4140 approach acts as a practical compromise: the 410L fraction improves cladding stability and weldability, while the 4140 fraction increases hardenability and strengthening potential [19].

3.6. Wear Mechanisms

The dominant wear mechanisms observed in the laser-cladded coatings are strongly influenced by microstructural constitution, hardness distribution, and subsurface load-bearing capacity. SEM examination of the wear tracks, combined with microhardness data, reveals clear mechanistic differences between 410L and MIX coatings.

Both NHT 410L and HT 410L coatings (Figures 10 and 11, respectively) exhibit wide wear tracks ($\approx 2.1\text{--}2.2 \text{ mm}$) characterized by deep longitudinal grooves (Figure 10b), surface cracking, and localised delamination. These features indicate a wear regime dominated by abrasive wear accompanied by fatigue-assisted delamination. The ferritic–martensitic microstructure of the 410L coatings, together with their comparatively lower microhardness, limits their resistance to plastic deformation under sliding contact. During pin-on-disk testing, asperity interactions lead to repeated subsurface plastic strain accumulation, particularly within the upper cladded layer where hardness decreases toward the surface. This promotes the initiation of microcracks at dendrite boundaries and at the interface between softer ferritic regions and harder martensitic laths.

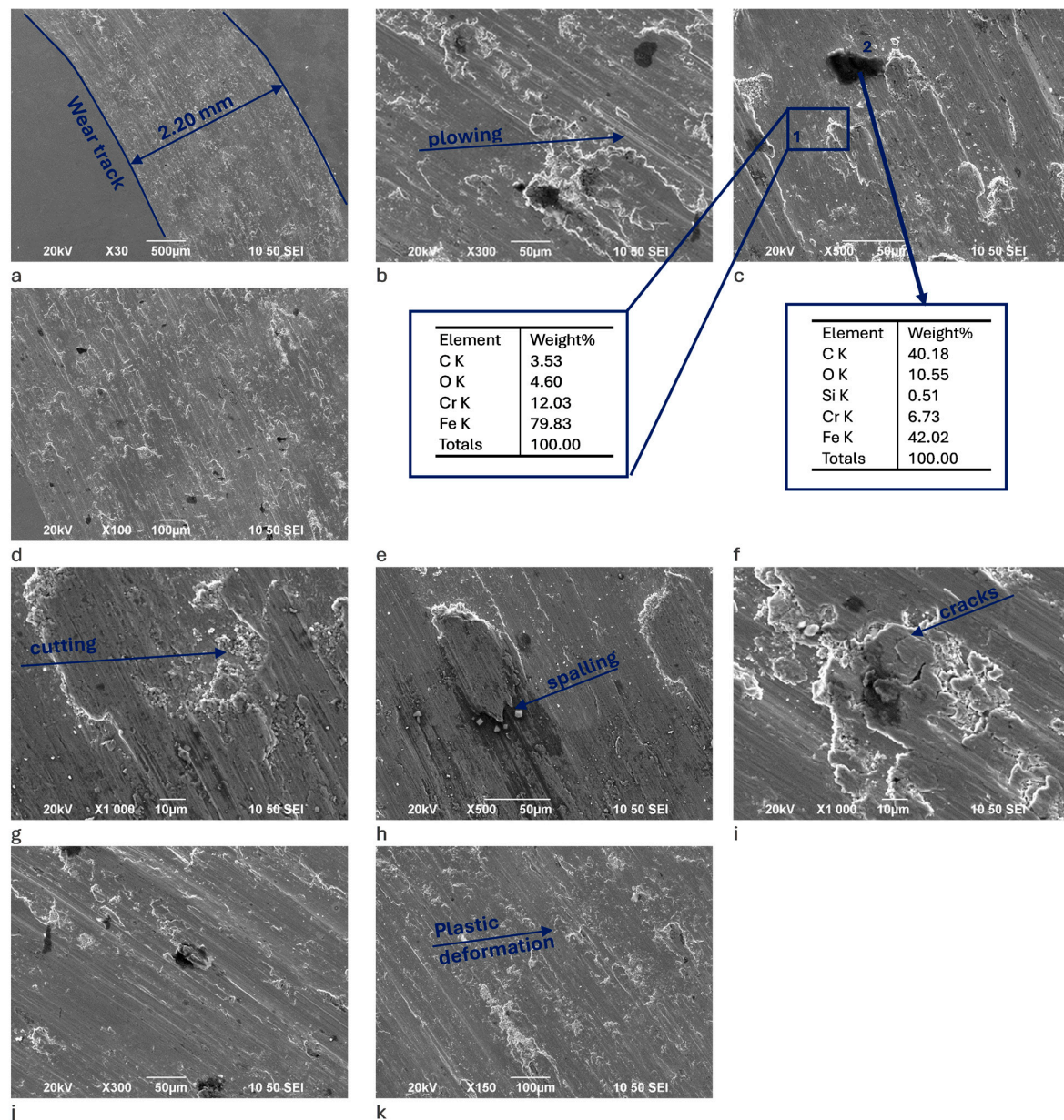


Figure 10. Wear track of NHT 410L coating. (a) overall wear track, (b) plowing marks, (c) plowing marks, (d) overview of wear track, (e,f) EDS analysis on points of (c), (g) cutting marks, (h) spalling marks, (i) cracking, (j,k) plastic deformation marks.

Crack propagation parallel to the sliding direction, as observed in SEM micrographs, is consistent with fatigue-controlled delamination. The presence of a partially mixed zone (PMZ) with steep hardness gradients further exacerbates stress localization, facilitating crack nucleation and spallation. Once detached, hard debris particles act as third-body abrasives, intensifying abrasion and ploughing and accelerating material removal.

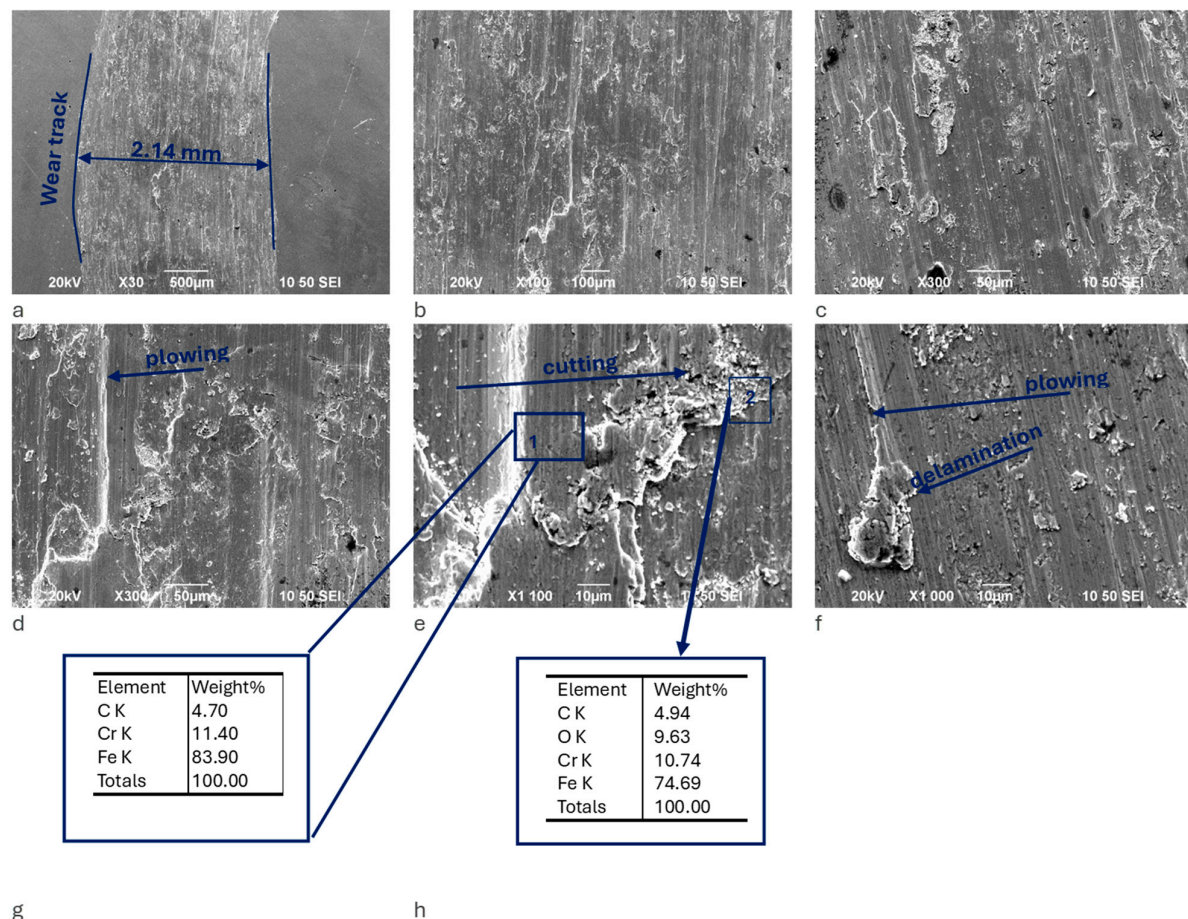


Figure 11. Wear track of HT 410L coating. (a) overall wear track, (b) plowing marks, (c) plowing marks, (d) plowing marks, (e) cutting marks, (f) plowing marks and deformation, (g,h) EDS analysis on points 1 and 2 of Figure 10e.

Although post-cladding heat treatment reduces residual stresses and partially tempers martensite, it does not fundamentally alter the phase balance or hardness of the 410L coatings. As a result, the dominant wear mechanisms remain largely unchanged, explaining the relatively high wear rates measured for both NHT and HT 410L specimens as confirmed by the wear rate diagram (Figure 9). A thorough examination of the surface revealed a significant number of cracks (Figure 10f), most likely caused by surface fatigue. In the case of contact in the running-in state, fatigue fracture is assumed to occur after multiple friction cycles. Material removal is governed by deformation and fracture in the contact region, which indicates fatigue fracture. Such deformation and fracture are caused by mechanically induced strains and residual tensile stresses in the coating. Repeated sliding leads to accumulation of subsurface plastic strain at stress concentration sites, promoting crack initiation after multiple friction cycles. In such a case, the mechanism of crack initiation and propagation is fatigue fracture, which is a rate process controlled by the inhomogeneity of a material's microstructure [15]. Furthermore, localized spallation occurred as fragmented material (Figure 10f,g and Figure 11) was removed from the surface by micro-cutting processes. In addition, mild oxidation was observed in both coatings, as confirmed by EDS analysis (Figure 10e,f and Figure 11g,h). The dominant wear mechanism is that of abrasion, but also adhesion and surface fatigue occurred in a synergistic manner, producing a greater rate of wear.

In contrast, the MIX coatings display substantially narrower wear tracks ($\approx 0.85\text{--}0.92\text{ mm}$) with smoother morphologies and significantly reduced material removal (Figures 12 and 13).

SEM analysis reveals shallow grooves aligned with the sliding direction (Figures 12h and 13b,e), limited delamination, and localised plastic deformation, indicating a transition toward mild abrasive wear.

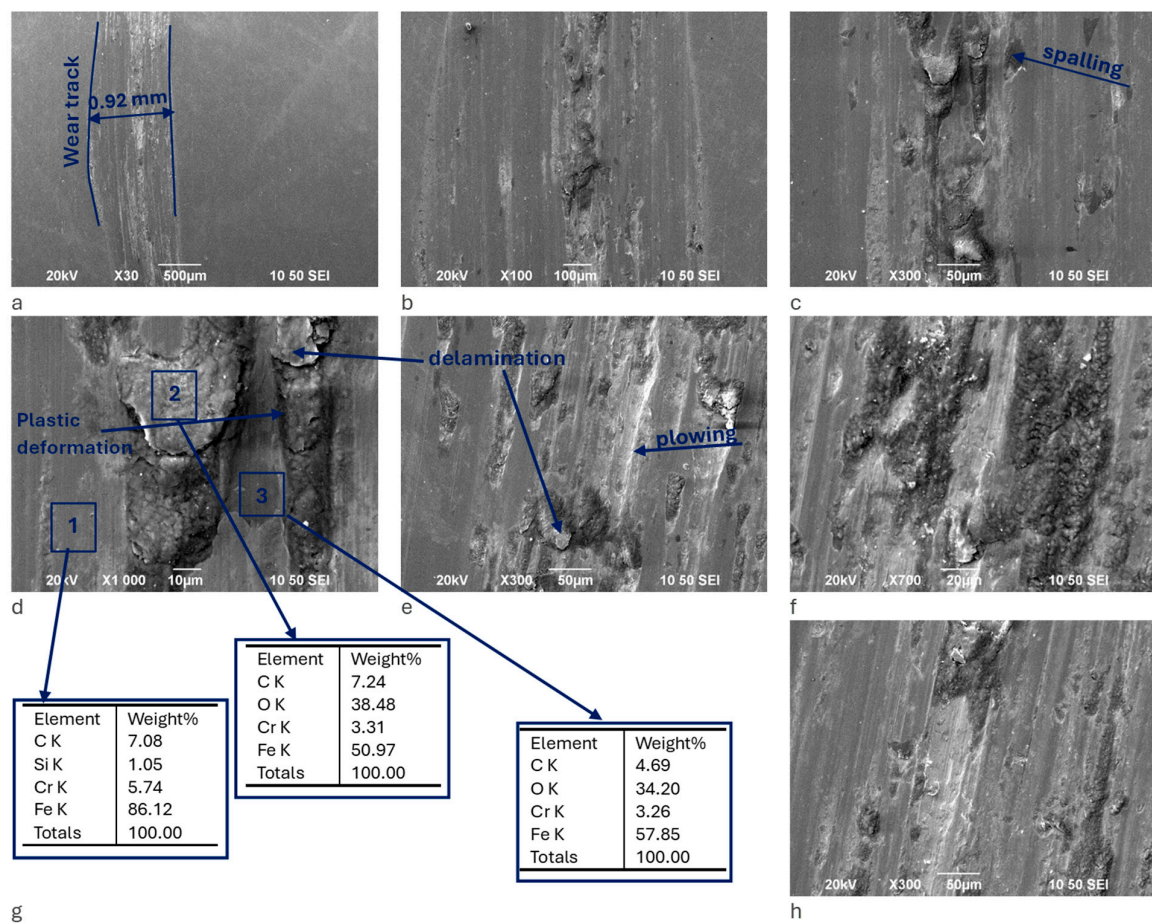


Figure 12. Wear track of NHT MIX coating. (a) overall wear track, (b) spalling marks, (c) spalling marks, (d) plastic deformation and delamination, (e) plowing marks and delamination, (f) plowing marks, (g,h) EDS analysis on points 1, 2 and 3 of Figure 10d, (h) plowing marks.

The superior wear resistance of the MIX coatings is directly linked to their refined martensitic microstructure and elevated hardness as described previously. The presence of uniformly distributed carbides and hard martensitic regions enhances the load-bearing capacity of the surface, restricting asperity penetration and minimizing subsurface plastic deformation.

Furthermore, the more homogeneous hardness profile across the clad layers reduces stress concentration at microstructural interfaces, suppressing crack initiation and propagation. Localised delamination observed in the MIX coatings (Figures 12c and 13b,d) is limited in extent and primarily associated with isolated microstructural heterogeneities rather than widespread fatigue damage.

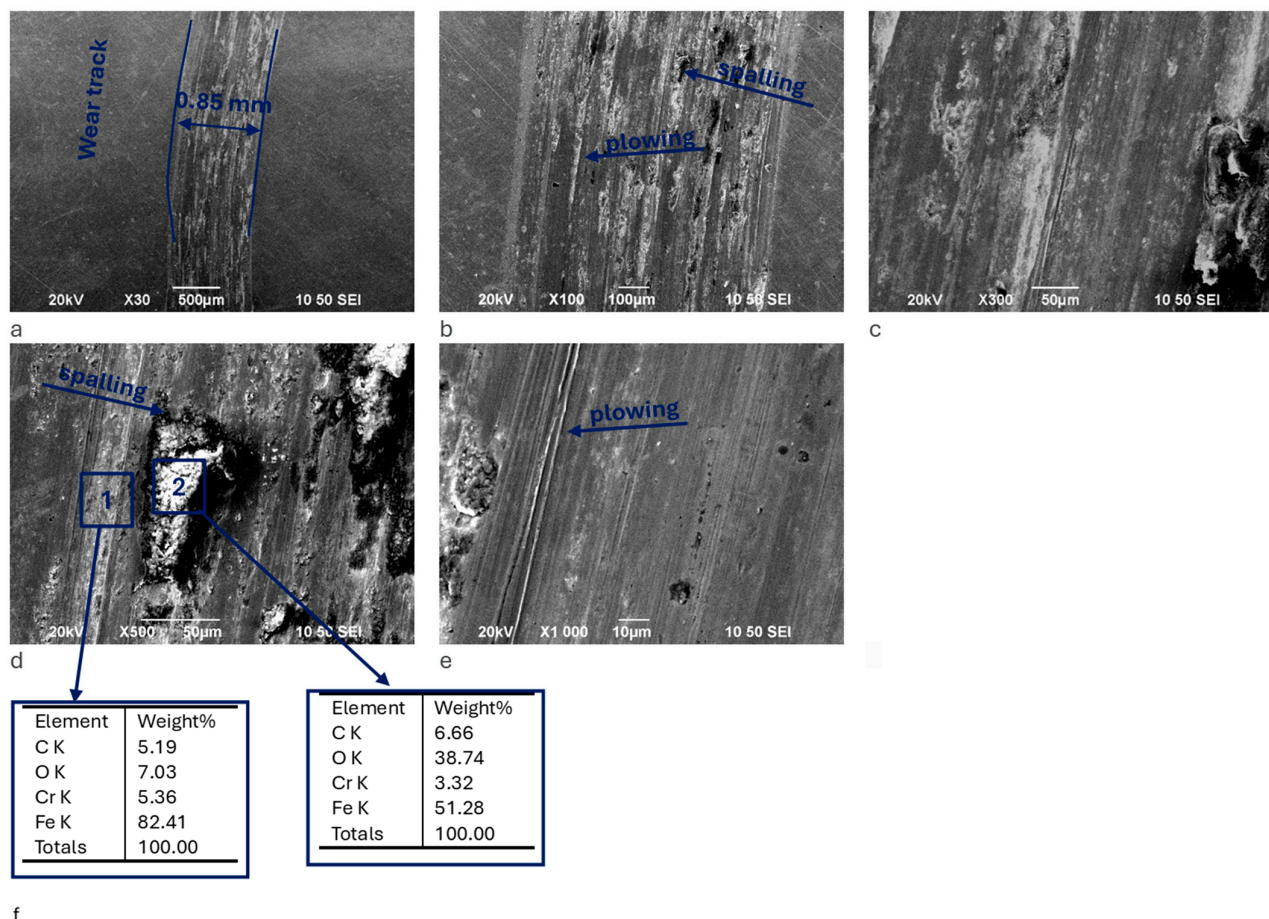


Figure 13. Wear track of HT MIX coating. (a) overall wear track, (b) plowing and spalling marks, (c) plowing marks, (d) spalling marks, (e) plowing marks, (f) EDS analysis on points 1 and 2 of Figure 10d.

EDS analysis confirms the presence of oxygen-rich regions within the wear tracks of all coatings, indicating mild oxidative wear (Figures 12g and 13f). However, the mechanical role of oxide layers differs markedly between coating systems. In the 410L coatings, oxide fragments are repeatedly fractured due to insufficient substrate support, contributing to unstable third-body abrasion and accelerated wear.

Conversely, in the MIX coatings, the harder martensitic–carbide matrix provides adequate support for thin oxide tribo-layers, allowing them to persist and act as protective barriers between the sliding surfaces. This stabilizes the wear process, reduces direct metal-to-metal contact, and limits adhesive transfer, contributing to the observed reduction in wear rate, as can be confirmed by the wear rate diagram (Figure 9).

Post-cladding heat treatment leads to a modest refinement of wear behaviour, particularly in the MIX coatings. Stress relief and martensite tempering reduce localised brittleness and improve microstructural stability, thereby limiting crack initiation during cyclic sliding. This effect is reflected in the slightly lower wear rate of HT MIX compared to NHT MIX.

In contrast, heat treatment has a limited influence on the wear mechanisms of the 410L coatings, as the fundamental microstructural characteristics governing wear—namely lower hardness and heterogeneous phase distribution—remain largely unchanged.

Overall, the dominant wear response transitions from severe abrasion with fatigue-assisted delamination in the 410L coatings to mild abrasion with limited plastic deformation in the MIX coatings. This transition is driven by increased hardness, refined microstructure, and improved hardness homogeneity in the mixed-alloy system. The results clearly demon-

strate that microstructural engineering through alloy blending is an effective strategy for suppressing deleterious wear mechanisms and enhancing the durability of laser-cladded coatings for marine shaft applications.

The wear-track morphology of the 410L coatings—deep grooves, cracking, and local delamination—corresponds to a mixed regime of abrasive wear and fatigue-assisted material removal, which has been frequently reported for comparatively softer or heterogeneous cladded layers where subsurface plastic strain accumulation leads to crack nucleation at microstructural interfaces. Conversely, the mixed coatings exhibit narrower tracks and shallow grooves consistent with mild abrasion and improved tribo-layer support, indicating that higher hardness and improved load support reduced both penetration depth and the severity of debris-driven microcutting. This mechanism shift is consistent with reports on laser-cladded martensitic/carbide-strengthened coatings where increasing hardness and strengthening the matrix changes the dominant wear mode from severe ploughing and delamination toward mild abrasion and polishing-like smoothing [24]. Table 6 summarizes dominant wear characteristics for 410L and MIX coatings.

Table 6. Summary of dominant wear characteristics for 410L and MIX coatings.

Coating System	Wear Track Width	Dominant Wear Mechanism	Delamination Tendency
410L (NHT & HT)	Wide	Abrasive wear + fatigue-assisted delamination	Pronounced
MIX (410L/4140)	Narrow	Mild abrasive wear	Limited

3.7. Wear Mechanism Model

Based on the combined analysis of friction behaviour, wear rates, microstructural observations, and hardness profiles, distinct wear mechanisms can be proposed for the investigated coatings. The proposed wear mechanism model is consistent with the quantitative results presented in Sections 3.4–3.6, where the 410L coatings exhibit higher friction coefficients and wear rates, whereas the MIX coatings show both lower friction levels and an order-of-magnitude reduction in wear rate.

For the AISI 410L coatings, the relatively lower hardness and heterogeneous microstructure promote a wear regime dominated by severe abrasive wear accompanied by subsurface plastic deformation and fatigue-assisted delamination. During sliding, repeated asperity interactions lead to localized plastic strain accumulation beneath the contact surface, resulting in crack initiation parallel to the surface and subsequent material removal in the form of delaminated fragments. This mechanism is consistent with the observed wide wear tracks, deep grooves, and unstable friction behaviour.

In contrast, the mixed AISI 410L/AISI 4140 coatings exhibit a transition toward a milder wear regime. The higher hardness and improved load-bearing capacity of the mixed microstructure reduce asperity penetration depth and suppress extensive plastic deformation. Wear is therefore dominated by mild abrasion with shallow grooves and limited material removal, resulting in significantly lower wear rates and more stable friction coefficients.

Post-cladding heat treatment further modifies the wear response by tempering the martensitic microstructure and relieving residual stresses. This treatment reduces crack susceptibility at the near-surface region and enhances tribological stability, leading to a reduction in fatigue-related damage and a more uniform wear track morphology.

The proposed wear model (Figure 14 and Table 7) highlights the role of microstructural strengthening and residual stress mitigation in shifting the dominant wear mechanism

from severe abrasive and delamination-controlled wear to mild abrasion with improved surface durability.

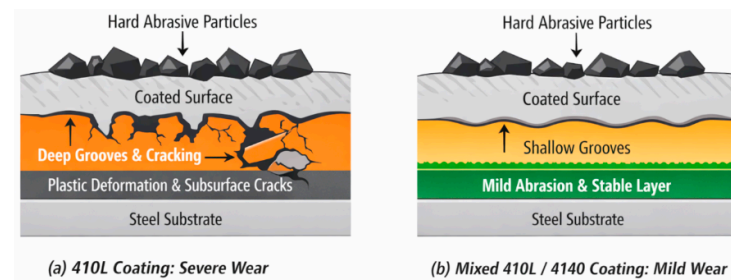


Figure 14. Proposed wear model.

Table 7. Summary of wear mechanism model for different coating conditions.

Coating	Hardness Influence	Dominant Wear Mechanism	Wear Response
410L (NHT & HT)	Lower hardness, steep gradients	Abrasion + fatigue-assisted delamination	High friction, high wear rate
MIX (NHT & HT)	Higher and more uniform hardness	Mild abrasion	Lower friction, low wear rate

4. Conclusions

In this study, laser cladding was successfully employed to enhance the tribological performance of EN 42CrMo4 steel substrates through the deposition of AISI 410L and mixed AISI 410L/AISI 4140 coatings. The combined experimental approach, involving microstructural characterization, mechanical assessment, and dry sliding tribological testing, enabled clear correlations to be established between coating composition, microstructure, hardness, and wear behaviour.

The MIX coatings exhibited significantly enhanced wear performance compared with the monolithic 410L coatings. This improvement is associated with a refined martensitic microstructure, higher and more homogeneous hardness (approximately 530–550 HV in the clad layers), and improved subsurface load-bearing capacity. As a result, the specific wear rate of the MIX coatings was reduced by approximately one order of magnitude relative to the 410L coatings under dry sliding conditions.

Post-cladding heat treatment contributed to improved tribological stability, particularly for the mixed coatings, by moderating hardness gradients and improving sliding stability. Wear mechanism analysis indicated a transition from severe abrasion with fatigue-assisted delamination in the 410L coatings to mild abrasion with limited plastic deformation in the MIX coatings. The proposed wear mechanisms and performance trends are valid within the experimental conditions investigated in this work, namely dry sliding pin-on-disc testing under the applied load and sliding speed. Extrapolation to other contact conditions should therefore be made with caution.

Overall, the findings highlight that mixed-alloy laser cladding offers a practical and industrially viable route for improving the surface durability of high-strength steels used in demanding applications, such as marine shaft components. By combining enhanced wear resistance with stable friction behaviour and good coating integrity, the proposed approach effectively addresses key limitations of single-alloy cladding systems.

Future research should focus on systematic variation in alloy ratios and multilayer coating architectures to refine the balance between hardness, toughness, and crack resistance. In addition, systematic studies on alternative post-cladding heat-treatment schedules, extended tribological testing under higher loads and aggressive environments, and detailed

direct phase identification and quantification would provide deeper insight into long-term coating durability and degradation mechanisms.

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