Development of High Wear Resistance Coating via High Speed Laser Cladding

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Abstract

The development of surface coatings with exceptional wear resistance is critical for prolonging the service life of components in demanding industrial applications. This study focuses on the fabrication of a high-carbon, vanadium-, and chromium-enriched precipitation-hardening martensitic steel coating via high-speed laser cladding (HSLC). Compared to conventional laser cladding, HSLC offers improved deposition quality, higher efficiency, minimal thermal distortion, and a smaller heat-affected zone.

Coatings were deposited on two substrate types: forged steel with a ferrite-pearlite microstructure and carburized steel with a martensitic microstructure-covering a wide range of industrial applications. A range of HSLC parameters—including laser power, travel speed, powder feed rate, and overlap distance—were explored. Microstructural analysis revealed the formation of solidification cracks, particularly on the carburized steel substrate, regardless of processing parameters. Preheating the substrates to 250°C effectively mitigated these cracks by reducing thermal gradients.

The resulting coatings exhibited a columnar dendritic microstructure, with coarser dendrites near the substrate-coating interface and finer dendrites near the surface. Hardness measurements aligned with this microstructural gradient, showing the highest hardness at the coating surface and a gradual decline toward the substrate. Notably, all hardness values exceeded the target of 60 HRC, even with preheating, which only marginally reduced the hardness. Finally, reciprocating sliding wear tests demonstrated that the defect-free coatings achieved superior wear resistance compared to the baseline steel substrates.

These findings underscore the potential of HSLC for producing high-performance, wear-resistant coatings tailored to meet the demands of industrial applications.

Keywords: High Speed laser Cladding, Heat affected zone, Cracking, Preheat, Wear Resistance.

1. Introduction and Motivation

Industrial components such as camshafts, CNC tooling, and die molds experience severe wear, leading to performance degradation and frequent replacements. Remanufacturing through wear-resistant coatings offers a cost-effective and sustainable alternative, reducing material consumption, energy use, and operational costs. Repairing worn parts requires significantly fewer processing steps than fabricating new ones, making it an efficient approach to extending service life [1].

Common coating techniques, including thermal spraying, plasma deposition, and conventional laser cladding (CLC), often suffer from weak adhesion, excessive dilution, and high heat input, which compromise repair quality. High-Speed Laser Cladding (HSLC), an advanced form of laser cladding, offers significant advantages, including higher deposition rates (up to 500 cm^2/min, nearly 10× faster than CLC), minimal dilution (<1%), and a reduced heat-affected zone (HAZ <100 µm). Unlike CLC, where the laser melts the powder on the substrate surface, HSLC injects the powder above the substrate, resulting in a smaller melt pool, lower heat input, and improved process efficiency [2][3][4].

Rockit® 606, a high-carbon, vanadium- and chromium-enriched martensitic steel, is an excellent candidate for wear-resistant coatings due to its high hardness, toughness, and superior wear resistance. However, the deposition of defect-free Rockit® 606 coatings via HSLC remains unexplored. Given the high solidification rate in HSLC, there is a potential risk of solidification cracking, particularly in high-strength coatings. This study aims to demonstrate that HSLC can produce crack-free, uniform-thickness, and highly wear-resistant coatings on industrial components sensitive to heat input. The selected substrate materials, identified in collaboration with industry partners, reflect real-world applications in the heavy machinery sector, ensuring the relevance of the developed repair methodology.

2. Review of related work

The adoption of High-Speed Laser Cladding (HSLC) as a replacement for traditional hard chrome plating (HCP) has been a key area of research due to the environmental and health concerns associated with hexavalent chromium. HCP, once widely used for wear-resistant coatings, has been phased out in many countries due to its toxic nature and strict environmental regulations, including the European Union's REACH directive, which prohibits its use. As a result, industries have been actively exploring alternative surface engineering techniques that offer similar or superior wear resistance while being environmentally sustainable [5][6][7].

HSLC was first developed at the Fraunhofer Institute for Laser Technology in Germany as a promising alternative to HCP [8]. Unlike CLC, HSLC utilizes a highly controlled powder injection system and a focused laser beam, leading to higher deposition speeds, minimal dilution, and significantly lower heat input. These advantages enable the formation of coatings with precise thickness control and enhanced mechanical properties while minimizing the heat-affected zone (HAZ), making HSLC particularly suitable for repairing high-performance industrial components.

In an earlier study, Schopphoven et al. investigated the feasibility of depositing Inconel 625 using HSLC techniques on chromium-nickel-steel substrates, demonstrating minimal HAZ formation and precise layer thickness control, making it a viable alternative for wear applications [7]. Similarly, Yuan et al. compared the Ni45 alloy coating produced by HSLC and CLC, reporting that HSLC achieved twice the cladding efficiency while producing finer, denser microstructures with narrower columnar crystal intervals. The cross-section microhardness of conventional LC coatings was relatively uniform at 337 HV, whereas HSLC coatings exhibited higher hardness (~543 HV)[9]. Additionally, HSLC coatings demonstrated superior wear and corrosion resistance, further showcasing the process's potential for high-performance applications [10]. Similar microstructural refinement and mechanical property improvements for various coating materials using HSLC have been consistently reported in the literature [11][12][13].

Despite these advantages, depositing high-hardness, wear-resistant coatings using HSLC presents significant challenges, particularly regarding crack sensitivity and process control. The high solidification rates and reduced heat input associated with HSLC increase susceptibility to solidification cracking, especially in alloys with high carbon content or carbide-forming elements [14]. Achieving defect-free coatings requires precise control over laser power, scanning speed, powder feed rate, and preheating conditions to manage thermal gradients and residual stresses. Furthermore, substrate properties play a critical role in crack formation, as harder or highly constrained materials are more prone to cracking.

To achieve enhanced wear resistance, Rockit® 606, a high-carbon, vanadium-, and chromium-enriched martensitic steel developed by Höganäs, has been explored as a potential alternative to M2 tool steel [15]. Rockit® 606 exhibits superior hardness and wear resistance, making it suitable for demanding applications. However, its high alloy content and rapid solidification increase its susceptibility to cracking, necessitating strict process optimization for defect-free coatings. A common strategy to mitigate cracking in high-hardness HSLC coatings is the use of high preheat temperatures (~500°C) to reduce thermal gradients and residual stresses. While preheating is effective in minimizing cracks, excessive preheating can degrade the mechanical properties of both the coating and substrate, limiting its industrial applicability [16][17].

This short review highlights the benefits of HSLC in depositing high-wear-resistant coatings with higher production rates, making it suitable for industrial applications. However, it also underscores the critical need for precise process control to achieve defect-free coatings across different substrate materials. To address these challenges, this study focuses on a set of unique process parameters developed in collaboration with industry partners for the specific material systems being considered. A key focus is to reduce the required preheat temperature while maintaining defect-free coatings, along with evaluating how substrate properties influence crack formation in HSLC coatings.

3. Technology Approach

3.1 Material

Commercial Rockit® 606 powder, with a particle size distribution of 53 to 180 µm, was deposited onto two different steel substrates representative of heavy machinery components. These substrates, supplied by an industry partner, included a carburized steel rod (Ø 60.3 mm, 60 HRC hardness) and a forged steel rod (Ø 25.4 mm, 40 HRC hardness). Rockit® 606 is a high-strength martensitic steel alloy, developed as a wear-resistant alternative to M2 tool steel. Its composition includes 2% carbon, 5% chromium, 6% vanadium, 0.6% silicon, and <4% additional alloying elements, contributing to its high hardness and wear resistance.

The microstructure of Rockit® 606, shown in Figure 1(a), consists of a martensitic matrix with eutectic interdendritic structures and uniformly dispersed hard particles. The carburized steel substrate, as seen in Figure 1(b), features a tempered martensitic microstructure, while the surface predominantly consists of untempered martensite. In contrast, the forged steel substrate exhibits a ferrite-pearlite microstructure, as shown in Figure 1(c).

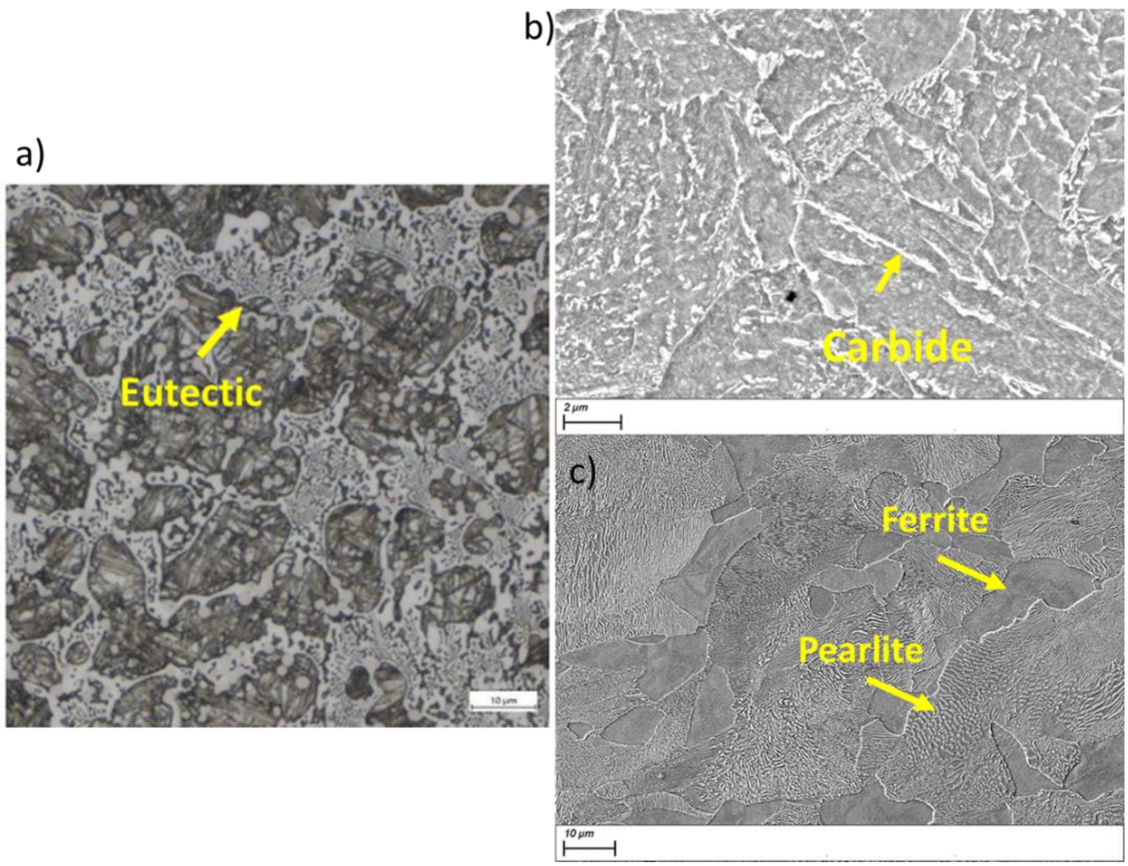

Figure 1: Micrographs of (a) the coating and substrate, (b) the carburized steel bar, and (c) the forged steel bar used in this study.

3.2 High Speed Laser Cladding

The laser cladding was performed by Synergy Additive Manufacturing LLC (Synergy), using a system with variable laser power in the range of 1000 to 3000 W, and equipped with a Fraunhofer high-precision coaxial laser cladding head. Argon was used as the carrier and shielding gas. The substrates were turned below the robotically-controlled cladding head using a rotary drivetrain, and the stand-off distance and heat input were controlled with non-contact laser distance sensors and pyrometers. The two rods were coated at various laser powers (1500W-2500W), surface traversal rates (30000 mm/min -50000 mm/min), pitch distances (0.12 mm-0.19 mm) and a fixed powder feed rates of 11g/min. For preheating experiment, both substrates were preheated using welding torch and temperature was measured using a pyrometer. Approximately 25 mm lengths of the sample rods was coated with each set of parameters.

3.3 Characterization

Magnetic particle inspection was performed to examine the rods for crack formation before samples were cut for microhardness testing and cross-sectional analysis. For microstructural analysis, the samples were initially sectioned using both a conventional band saw and a slow-speed diamond saw. They were then mounted in Polyfast, mechanically ground using 1200-grit silicon carbide paper, polished with 3 μm and 1 μm diamond pastes, and finally subjected to a final polishing step with 0.05 μm colloidal silica. Microstructural analysis was conducted using a Zeiss Sigma 300 scanning electron microscope (SEM) equipped with a field emission gun.

The Vickers microhardness test was conducted on the same cross-sectional samples used for SEM investigation to analyze depth-resolved hardness distributions. The test was performed using a LECO LM248 AT machine with an indentation load of 100 gf and a dwell time of 13 seconds.

Crack-free sections of the rod were evaluated for wear performance using a reciprocating sliding wear test fixture, employing a cylindrical indenter made of tool steel, as shown in Figure 2. The test followed the SAE 15W-40 standard under motor oil lubrication.

Figure 2: Fixture for the cylinder-on-cylinder wear test.

4. Results and discussion

4.1 Macroscopic Analysis

Cracking was observed in all HSLC deposits of Rockit® 606 applied to the carburized steel rod. To mitigate crack formation, a range of laser processing parameters—including laser power, travel speed, powder feed rate, and pitch distance—were systematically varied. However, despite these adjustments, the coatings consistently exhibited a high density of cracks, as evident in the magnetic particle inspection macrograph shown in Figure 3(a).

In contrast, while cracking was also present in the coatings deposited on the forged steel rod, the overall crack density was significantly lower (Figure 3(b)). This difference underscores the critical role of substrate properties in crack formation during HSLC deposition. The carburized steel rod, with its high hardness (60 HRC) and a case-hardened martensitic microstructure, likely induced higher residual stresses due to restricted thermal expansion and increased brittleness, making it more susceptible to cracking. In comparison, the forged steel rod (40 HRC), with its more ductile ferrite-pearlite microstructure, would have exhibited better stress accommodation and reduced susceptibility to solidification cracking.

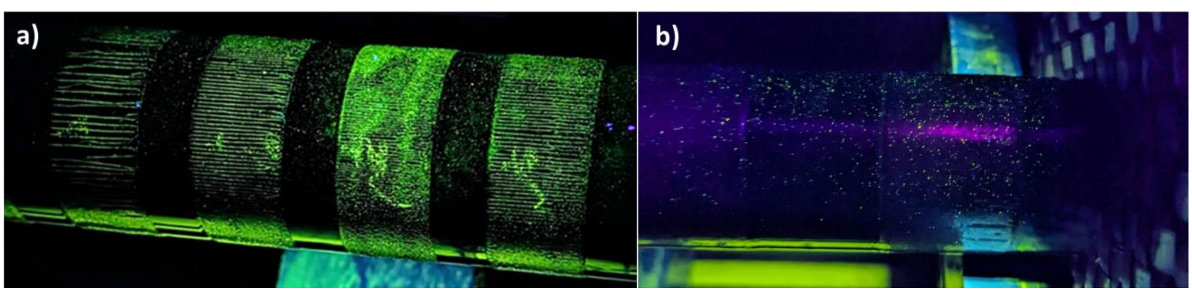

Figure 3: Magnetic particle analysis of HSLC-deposited Rockit® 606 coatings on (a) carburized and (b) forged steel rods, revealing cracking in the coating.

To mitigate thermal gradients and reduce crack formation, the substrate was preheated to 250°C before coating. Magnetic particle analysis confirmed that preheating successfully eliminated cracking in the coatings for both carburized and forged steel substrates. Figure 4 illustrates the absence of cracks in the carburized steel substrate, demonstrating the effectiveness of preheating in preventing defect formation.

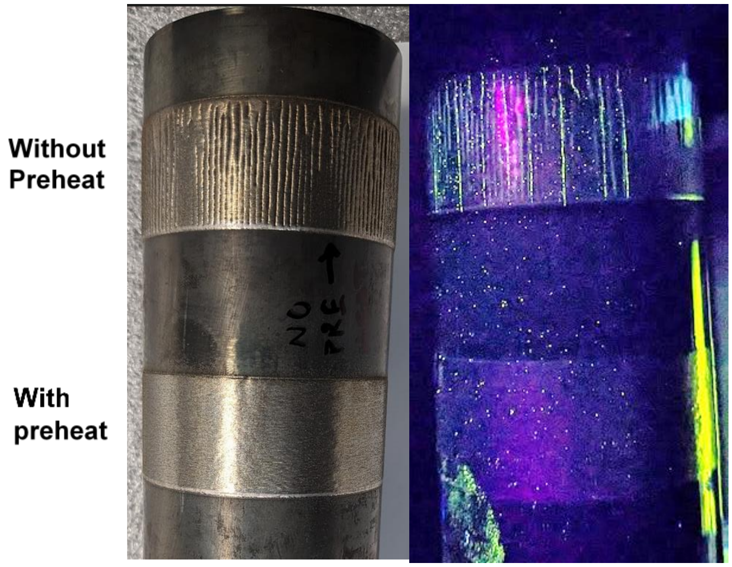

Figure 4: HSLC of Rockit® 606 on carburized rod with and without preheating

4.2 Microstructure Evolution

Figure 5 presents the microstructures of the coating and HAZ in HSLC-deposited Rockit® 606. Figure 5(a) confirms the formation of cracks in the overlapping regions between adjacent cladding tracks, consistent with the macrograph from magnetic particle inspection. This cracking is likely attributed to the rapid thermal cycling and localized residual stresses introduced during high-speed deposition. Additionally, Figure 5(b) reveals the presence of microcracks within the HAZ of the carburized steel substrate when no preheating was applied. The high hardness and limited ductility of the carburized steel likely contribute to the inability to accommodate thermal stresses, leading to crack formation.

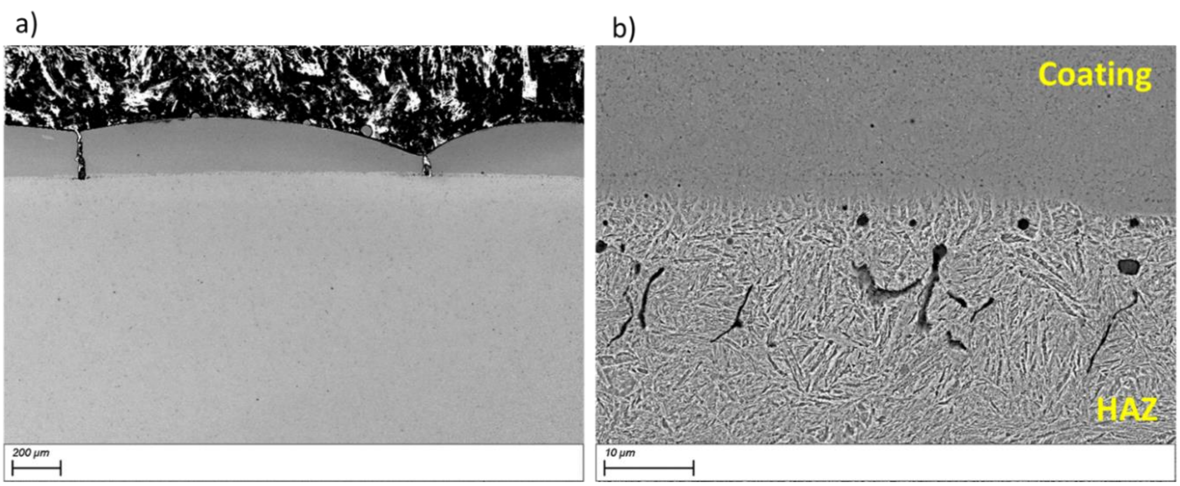

Figure 5: Microstructures of the (a) coating and (b) heat-affected zone (HAZ), showing crack formation in the absence of substrate preheating.

Cross-sectional analysis using SEM, as shown in Figure 6(a), confirms that preheating effectively eliminated crack formation in the carburized steel substrate. Compared to previously cracked samples, preheating did not significantly alter the coating thickness or the size of the heat-affected zone (HAZ). The coating maintained a uniform thickness, averaging approximately 200 µm, while the HAZ extended to approximately 250 µm, both of which fall within the acceptable thickness targets provided by industry partners for part repair feasibility. The high-magnification image in Figure 6(b) reveals a microstructural gradient, transitioning from a coarser, cellular morphology near the substrate to a finer, columnar dendritic structure toward the surface. Figure 6(c) and Figure 6(d) further highlight these variations, where the bottom region of the coating exhibits larger, equiaxed cellular structures, while the top region displays a refined, interconnected columnar morphology. This microstructural refinement at the surface is attributed to the rapid solidification inherent to the HSLC process, which enhances hardness and wear resistance. A similar microstructural trend was observed in the Rockit® 606 coating deposited on the preheated forged steel; however, in the interest of space, it is not included here.

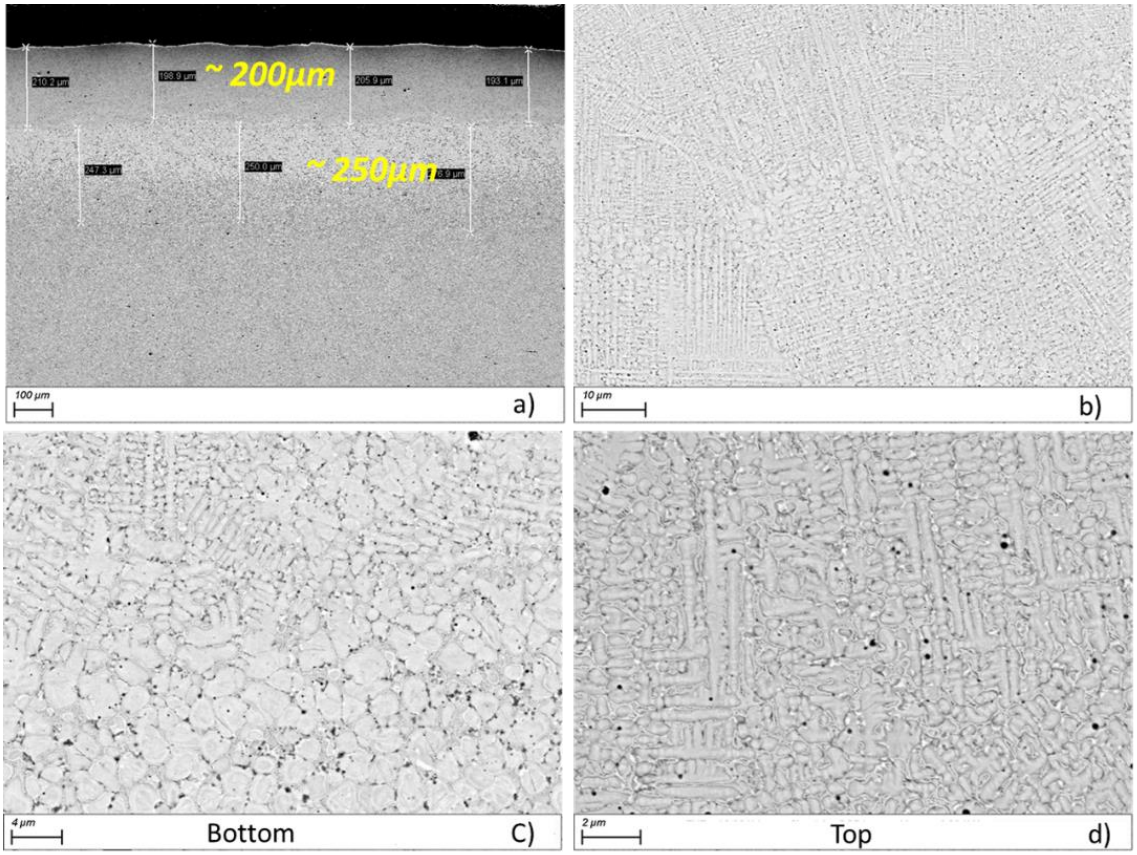

Figure 6: Microstructure of the coating deposited on preheated carburized rod.

3.3 Hardness

Figure 7 presents the microhardness distribution of the coating deposited on the carburized steel substrate, with and without preheating. In both cases, the microhardness is highest near the surface and gradually decreases along the coating depth. This trend is consistent with microstructural analysis, which indicates that the dendritic microstructure is more refined near the surface due to rapid solidification effects.

While the overall microhardness distribution exhibits a similar trend in both conditions, a slight reduction in hardness at all measured locations was observed in the preheated samples. The highest microhardness near the coating surface is approximately 975 HV for the non-preheated sample and around 930 HV for the preheated sample. This reduction correlates with microstructural observations showing a slightly coarser dendritic structure following preheating, likely resulting from a lower thermal gradient and slower solidification rate. Nevertheless, the coating hardness remained above the industry-specified minimum of 60 HRC (~690 HV) for carburized steel rods (see Figure 7), confirming its suitability for high wear-resistance applications.

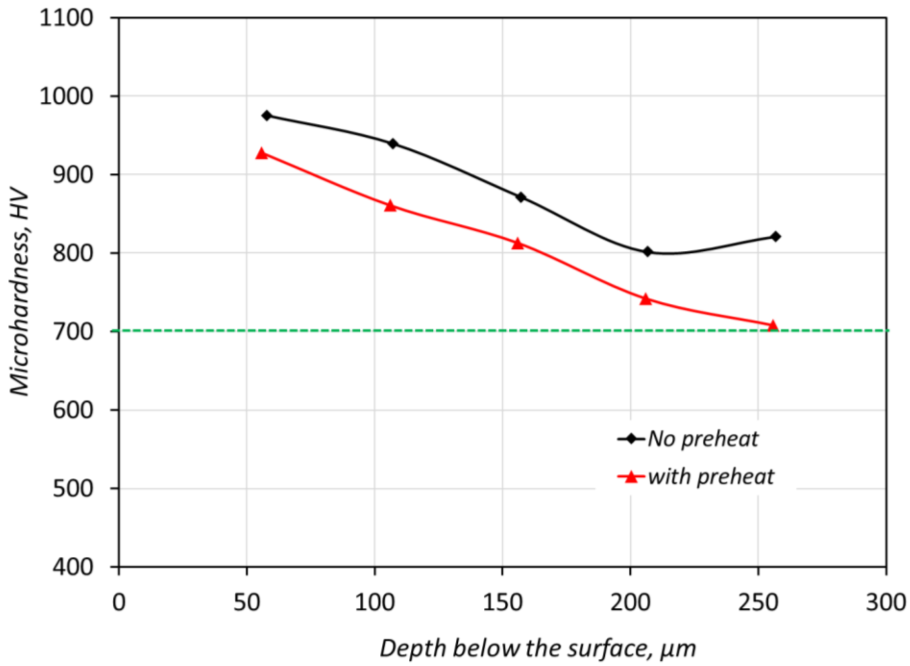

Figure 7: Distribution of the coating microhardness deposited on carburized rod with and without preheating

4.4 Wear Resistance

Figure 8 presents the worn surfaces of both coated and uncoated samples following the reciprocating sliding wear test, with the corresponding wear areas listed in Table 1. Visible wear tracks were observed on both uncoated forged and carburized steel, with the forged steel exhibiting a slightly larger wear area (14 mm²) compared to carburized steel (8.6 mm²), suggesting that carburization improves wear resistance.

For the coated samples, the wear tracks were smaller, with the coated forged steel showing a wear area of 6.0 mm² and the coated carburized steel having the smallest wear area (3.2 mm²). While these results indicate that the coating provides additional wear resistance, the overall wear was minimal for all samples, and no measurable weight loss was detected. Additionally, wear depth could not be measured, as it was not deep enough to be quantified.

Further investigation using higher cycle counts or a more aggressive wear test setup, such as a ball-on-cylinder test, would provide a more comprehensive assessment of wear performance.

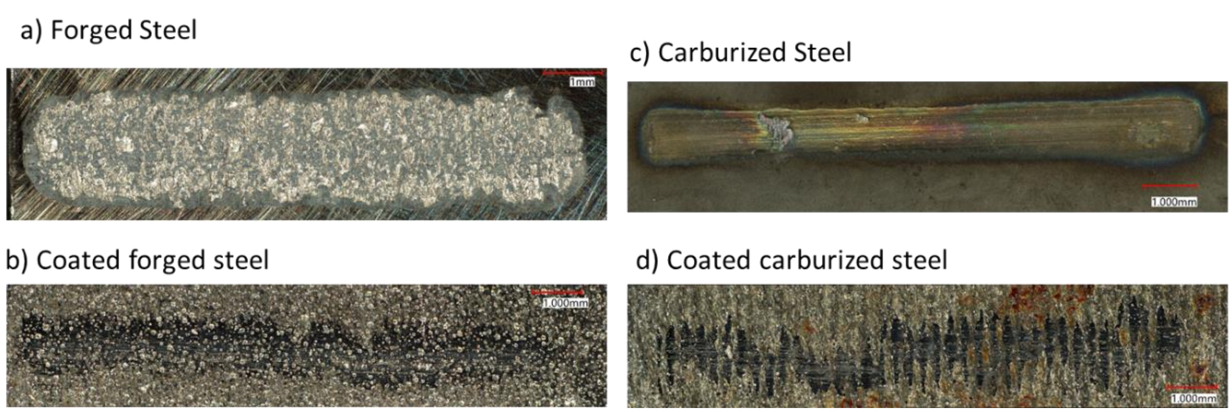

Figure 8: Wear marks on: a) forged steel, b) coated forged steel, c) carburized steel and d) coated carburized steel.

Table 1: Area of the wear marks

Samples	Area of the wear marks, mm^2
Forged steel	14
Carburized steel	8.6
Coated forged steel	6.0
Coated carburized steel	3.2

5. Conclusion and Recommendations

Rockit® 606 was successfully deposited onto forged and carburized steel rods using High-Speed Laser Cladding (HSLC) without inducing solidification cracking, as confirmed by SEM inspection. The implementation of a 250°C substrate preheat temperature, combined with optimized process parameters, effectively mitigated cracking while maintaining coating and heat-affected zone (HAZ) thicknesses within the acceptable range for industrial applications. Notably, the chosen preheat temperature was lower than those reported in prior literature and did not significantly alter the coating microstructure. Although a slight reduction in hardness was observed due to preheating, the coating maintained hardness values exceeding the industry requirement of 60 HRC, ensuring its suitability for wear-resistant applications. The consistency in coating thickness and microstructure across samples further demonstrates the reliability and repeatability of the optimized HSLC process.

Future work should focus on assessing the impact of preheating on residual stress and hardness distribution. Additionally, comprehensive fatigue testing should be conducted to evaluate the long-term mechanical integrity of the coatings under cyclic loading conditions. Investigating alternative process parameters or post-processing treatments, such as tempering or stress-relief annealing, may further enhance coating properties. Finally, expanding the study to include more extensive wear testing methods, such as high-cycle ball-on-disk or abrasive slurry wear tests, would provide a more comprehensive evaluation of the coating's durability across various operational environments.

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