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A Comprehensive Review of Optimization Techniques and Wear Analysis in Sugar Mill Roller Hardfacing

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Abstract
"Wear is a widespread problem across many industries, severely shortening component life. Consequently, wear-resistant coatings are commonly applied to these components. Enhancing the effectiveness of the deposition process and the quality of coatings is essential. This paper investigates the use of optimization algorithms in the hardfacing process to attain optimal outcomes. These algorithms are particularly effective in addressing intricate engineering challenges, achieving precise objectives, reducing errors, and enhancing results in diverse areas. In conclusion, this study delves into the use of these algorithms for material hardfacing and describes the procedures for conducting wear testing.

Keywords: hardfacing, welding patterns, Taguchi method, hardness, optimization.

1. Introduction:

Many industries use mechanical components. The most common issue seen in many industries, especially in the sugar industry, sugarcane crushing rollers, is wear and tear from constant friction and impurities that come with sugarcane. This can result in lower efficiency, higher maintenance costs, and possible safety risks. To tackle this problem, the hardfacing method is used to treat surfaces so that parts can have different properties, especially designed to handle tough conditions like wear, impact, corrosion, or high heat. Wire arc spraying is a technique used to harden surfaces. Studies have looked into wear-resistant weld overlays and how materials like Fe-Cr-C hardfacing perform on sugarcane mill rollers. These studies also tried to find the best settings for electric wire arc-spraying, such as voltage, current, air pressure, and spray distance, for coatings like FeCrB and other iron-based ones. The goal was to get the least amount of abrasive wear and good hardness, so these coatings could replace existing ones on sugar mill roller shells and be used in other industrial applications. This research has been studied further in papers [6 [7], and [8]. In some cases, adding different alloying elements with various heat inputs can affect the impact toughness and mechanical strength of hardfaced high-strength steels [6], [7], [8]. It has been observed how normal load and temperature (20°C vs. 500°C) influence mild abrasive wear in Fe-Cr-C and complex Fe-Cr-Mo-Nb-W-C hardfacings, and to check if the HT-CATrw method is reliable for high-temperature wear testing. Research also looked at surface changes, microstructural development, amorphization processes, and better tribological performance of cobalt-based hardfacing alloys through advanced energy beam techniques.

The study aimed to understand how processing settings, surface features, and wear resistance are related for tough engineering uses. [6], [10], [11], [12]. Based on the type of hardfacing material, there is a need to properly evaluate and compare the tensile properties, high-cycle fatigue behavior, and how the interface cracks or separates in 316L(N) austenitic stainless steel that has been hardfaced with a Ni–Cr–B–Si alloy (Colmonoy 5). This work will compare all types of hardfacing methods, for example,, Gas Tungsten Arc (GTA) cladding and Laser Cladding (LC), to see how they affect mechanical performance, how the interface holds together, and how reliable they are over time. [12], [13], [14], [15], [16], [17]. Optimizing the hardfacing process is important for making the process more efficient, cutting down on material and operating costs, avoiding mixing with the base material, and improving wear resistance and how long the parts last. A well-optimized process gives better performance, better use of resources, and more economic benefits. [5] This study aims to find the most commonly used hardfacing methods and check how well they improve wear resistance and durability of engineering parts. It also reviews and looks at the optimization techniques used in hardfacing to improve performance, cut costs, and make the parts last longer.

2. Comprehensive review of Methods

Group 1: Sugar Mill Industry Applications & Wear Mechanics

This group focuses explicitly on components, materials, and simulated environments unique to sugarcane processing (rollers, shafts, and corrosive/abrasive environments).

The study looks at how hypereutectic and hypoeutectic Fe-Cr-C hardfacings wear down. These hardfacings were put on grey cast iron using shielded metal arc welding. They were tested with sand and bagasse board to see what happens when they are used in sugarcane milling. This testing was done in two ways: with conditions and with cane-juice slurry. The hypereutectic coating is very hard. When a lot of force is applied to it, it wears down at the same rate as the hypoeutectic coating. When we look closely at the coating, we see that it gets worn down by tiny scratches. The hypereutectic coating gets worn down by cracks in the carbides.[1]. The Taguchi fractional-factorial L9 design was used to find the settings for four spray parameters. Current voltage, air pressure, and spray distance. For FeCrB arc-sprayed coatings on sugar mill rollers. These FeCrB arc-sprayed coatings on sugar mill rollers were looked at in terms of hardness, microstructure, and abrasive wear. The goal was to find the settings for these FeCrB arc-sprayed coatings on sugar mill rollers. The best wear rate with hardness was found. This meant that the best process parameters for these FeCrB arc-sprayed coatings on sugar mill rollers were the ones that resulted in the least mass loss over a two-hour wear test. The FeCrB arc-sprayed coatings on sugar mill rollers are a choice for sugar mill rollers.[2] Laboratory tests found that cracks on the surface of sugar mill shafts happen because of the way things rub together at the sliding interface. This interface gets contaminated with sugar cane juice and bagasse. A special kind of film called a tribofilm forms, and it controls how things slide. The study looked at what happens when EN8 and E52100 rub against each other under certain conditions. It used tools like FTIR and TGA to see what was going on. When sugar mill shafts rub against each other, they make debris. The study found that the debris from sugar mill shafts changes the way sugar mill shafts wear down. This means that the debris from sugar mill shafts makes them wear down faster. The study looked at the debris from sugar mill shafts to see what was happening to the sugar mill shafts.[3]

Group 2: Iron-Based Fe-Cr-C Systems & Elemental Modifications.
The research is conducted to determine the effect Molybdenum content on the properties of hard-face coating made of Fe-Cr-C-V that resists wear, corrosion, and cavitation. The metal arc welding method is used for hardfacing on S235JR Steel. Apart from chromium-rich carbides, the presence of Molybdenum does not alter hardness or resistance, but it does have direct effects on Cavitation and corrosion. Cavitation resistance is increased compared to the coating without Molybdenum content[4].

This tungsten-free approach focuses on developing and applying powder electrodes for flux-cored arc welding to strengthen and repair parts while prioritizing mechanical durability and wear resistance. The surface hardening process involves filling an 08 kp steel casing with a mixture of base materials (Mo-Ti-B-C). We fabricated electrodes with different titanium-to-molybdenum ratios. Electron microscopy and X-ray diffraction revealed a high content of the Fe(Mo, B)2 strengthening phase in the hardfaced layers. Hardness measurements showed values up to 64 HRC. Wear resistance was evaluated under a variety of loading conditions, and for benchmarking, commercial electrodes from various countries were tested. The experimental hardfaced layers demonstrated better wear resistance than the imported alternatives. One specimen displayed a flawless structure and strong adhesion between the hardfaced layer and the base metal, while the sample with increased molybdenum content exhibited structural and fusion zone defects.[5]

In the realm of industrial manufacturing, tackling wear caused by friction is a major area of research. Scientists are working to improve resistance to wear by incorporating cost-effective Boron (B) into hypereutectic hardfacing alloys. This research examines the impact of different B concentrations (B-Free, 0.39 wt%, 1.03 wt%, 1.43 wt%) on the microstructure and wear resistance of Fe-Cr-C-Mo-xB hardfacing alloys. The findings indicate that as B content rises, the size of primary M7C3 carbides decreases from 36.9 µm to 15.5 µm, and the hardness of the alloy significantly increases from 690 HV to 1033 HV. EDS and TEM analyses reveal that B partially replaces carbon (C) in M7C3 and Mo2C carbides, resulting in the formation of M7C3-xBx and Mo2(C1-xBx) carbides. Remarkably, at 0.39 wt% B, the alloy demonstrates enhanced wear resistance, characterized by a smoother surface after abrasion, the absence of long furrows, and minimal abrasive penetration. Examination of abrasive wear micromechanisms underscores the significance of the hard phase's shear resistance in wear resistance. Quantitative evaluations using first-principle calculations show a consistent decline in the mechanical modulus of the hard phase with increased B doping, which accounts for the reduced wear resistance at higher B levels. These insights are promising for the development of hardfacing alloys in the industrial sector.[6]

Alloys within the Fe–Cr–C–B–Ti system are known for their brittleness, which can be mitigated by incorporating copper, though this reduces both corrosion and abrasive wear resistance. This article presents a detailed examination of the microstructure and mechanical characteristics of the high-copper boron-containing alloy 110Cr4Cu7Ti1VB. The study includes both theoretical and experimental approaches, such as thermodynamic modeling using ThermoCALC, the creation of flux-cored wires for hardfacing and welding, capturing SEM images, and obtaining load and unload diagrams through instrumental indentation on different phases of the deposited metal. Additionally, the chemical composition at indentation points was analyzed locally. The mechanical properties of certain phases, including the γ–Fe phase (austenite), hemioboride Fe2(B, C), boron cementite Fe3(B, C), and titanium carbide TiC in the Fe–Cr–C–B–Ti–Cr alloy, were assessed using density functional theory (DFT) as implemented in the CASTEP code. These properties were also compared with those of other commercial compounds when available. Based on the calculated elastic constants, predictions and discussions were made regarding the moduli, Pugh's modulus ratio G/B, Poisson's ratio v, and the hardness of the phases in 110Cr4Cu7Ti1VB [7]. A

A novel impact-sliding wear test apparatus was created to explore the tribological and wear behavior of iron-based hardfacings with manganese (Mn) additives. The investigation focused on how varying Mn content from 0 to 13 wt% influenced wear characteristics under a constant load of 200 N, with 1000 impacts and a speed of 50 strokes per minute. Hardness tests indicated an increase in hardness following the impact-sliding wear tests. The worn surfaces of hardfacings containing 0 and 8 wt% Mn exhibited a similar micro-abrasion mechanism; however, the abrasion damage in hardfacings with 8 wt% Mn was less pronounced compared to those with 0 wt% Mn. When Mn content exceeded 8 wt%, oxidative wear became the primary wear mechanism, leading to the formation of protective tribo-oxide layers and an improvement in wear resistance. Conversely, subsurface analysis revealed significant damage beneath the tribo-oxide layer, indicating that the wear trend alone does not accurately reflect the material's wear resistance. The wear behavior of the hardfacings was effectively linked to hardness, as well as the morphology of the worn surfaces and subsurfaces.[8]

Metal inert gas (MIG) hardfacing technology has advanced the development of high-performance materials on carbon steel, which demonstrate excellent thermal wear resistance due to their Cr and C content. In this research, 12Cr-xC (x = 0.3, 0.4) hardfacings were produced using the MIG technique, and their wear behavior was assessed under varying loads and temperatures. The findings indicated that the 12Cr-xC hardfacings had good forming quality, with a microstructure comprising a martensite matrix, retained austenite, different shapes of the martensite-austenite constituent (M/A), and a small amount of carbides. The hardness values reached 483.1 and 520.3 HV0.2. The coefficient of friction (COF) for the 12Cr-xC hardfacings ranged from 0.27 to 0.43 and decreased as the temperature rose from 150 °C to 300 °C at 200 N. The 12Cr-xC hardfacings showed excellent wear resistance, with wear loss rates remaining low (10-5 mm3/(N·m)). The worn morphology of SiC balls was irregular, featuring abrasive wear and embedded oxide debris. Adhesive wear occurred under certain conditions, with a lower wear loss rate compared to the hardfacings. At 150 °C, 12Cr-xC hardfacings displayed low Whardfacing/Wball ratios (4–11), with abrasive mechanisms. Higher loads resulted in a more significant sacrifice of SiC balls, with abrasive wear and oxides covering the worn surface at 300 °C, where tribochemical reactions were the primary mechanism.[9]

Creating Fe-based non-magnetic wear-resistant hardfacing coatings for reinforcing drill collars through flux-cored arc welding (FCAW) with multiple components. The study thoroughly examined how B4C additions affect the coatings' microstructure, magnetic properties, and wear resistance. Findings indicate that B4C additions facilitate the in-situ formation of multi-boro-carbides within the austenitic matrix, greatly improving the coating's performance. As the boron content rises from 0 to 3.0 wt%, the volume fraction of retained austenite drops from 93.2 vol% to 13.8 vol%, while the fraction of borocarbides increases. This change enhances the non-magnetic properties, as evidenced by a decrease in relative permeability from 4.534 to 1.006, attributed to the formation of paramagnetic and antiferromagnetic boro-carbides, as confirmed by density functional theory (DFT) calculations. The coatings' microstructure evolves from a network eutectic structure to a fine-grained eutectic composed of lath-M2(BC), lamellar-M23(BC)6, and dispersed Nb(BC) as % B content slightly increases

from 0 to 1.5 wt%. At a B content of 3.0 wt%, the ductility index (H·E 1) and plastic deformation index (H3·E 2) of Nb(BC) reach their highest values, measuring 0.0559 and 0.0516 GPa, respectively. The abrasion damage tolerance index (1/(E2·H)) of M23(BC)6 is the highest, reaching 3.45 × 10 6 GPa 3. M23(BC)6 plays a significant role in enhancing the coating's wear resistance. This fine-grained eutectic structure of boro-carbides ensures superior macro hardness (49.8 HRC) and excellent wear resistance (8.29 × 10 4 mm3/ (N·m)). The study underscores the potential of B4C additions in developing boro-carbide-reinforced, non-magnetic Fe-based coatings with enhanced wear resistance, presenting a promising solution for non-magnetic drilling tools.[10]

In sodium-cooled fast reactors (SFRs), the 316L(N) stainless steel grid plates are protected with a Ni-Cr-B-Si alloy coating to boost their wear resistance. The junction between the substrate and the coating, however, is exposed to tensile and fatigue stresses stemming from differences in thermal expansion, which can cause cracking or delamination during reactor operation. Selecting a hardfacing process that ensures strong tensile and fatigue properties is therefore essential to prevent such interface failures. This work evaluates two hardfacing methods—Gas Tungsten Arc (GTA) welding and Laser Cladding (LC). After applying both techniques, the coated samples underwent tensile and high-cycle fatigue testing. The mechanical responses were assessed using stress-strain curves and S-N diagrams, providing insight into the materials' tensile and fatigue behaviour. Fractographic analysis was performed to examine how and where fatigue cracks initiated and spread. Results indicated that LC-coated specimens displayed approximately 11% lower tensile strength and 17% lower fatigue strength than those coated by GTA, most likely due to increased brittleness. Consequently, GTA welding is recommended as the superior hardfacing technique for SFR grid plate applications.[11]

Group 3: Non-Ferrous Alloys, Cobalt/Nickel Systems & Advanced Surface Treatments

Additive manufacturing (AM) has become a well-established, efficient, and economical method for restoring components suffering from localized damage, such as that caused by wear or corrosion. However, using AM techniques to repair hardfacing coatings presents several difficulties, largely due to the complexity of part geometries and the heightened risk of crack development from process-induced stresses. This study focuses on the restoration of a cobalt-based Stellite 6 hardfacing coating on an AISI 316L steel substrate using Laser Powder Directed Energy Deposition (LP-DED). It explores the effects of key process variables and their influence on repair quality. Through meticulous initial machining, induction heating of a broader section during laser deposition, and an optimized scanning approach, the process effectively eliminates the formation of cracks during and after the repair. High-quality metallurgical bonding and repair integrity are confirmed through non-destructive evaluation, Vickers hardness testing, and detailed microstructural analysis using scanning electron microscopy (SEM). Furthermore, the study introduces an innovative qualification test—Absence of Crack Attraction by the Repair (ACAR1)—which assesses repair quality by monitoring the system's response to deliberately introduced cracks. The ACAR results reveal only a slight difference in mechanical behavior between the repaired region and the original coating, suggesting additional investigation is needed to achieve a repair that is completely indistinguishable from the initial surface.[12]

The interaction between the valve and seat insert is essential to the proper functioning of an engine, making its durability and performance a subject of considerable interest. This research compares two seat insert varieties: conventional industry-tempered inserts and inserts enhanced with a hardfacing layer, referred to as the tempered and hardfacing groups. Impact wear experiments were conducted at a temperature of 650 °C, under a 30 kN load, at a frequency of 12 Hz, with a stroke length of 1 mm. The wear regions were analyzed using a suite of advanced tools, including 3D scanning, optical microscopy, SEM, and XPS, to assess both macro and micro wear characteristics. The analysis revealed that, following impact testing, an oxide film formed on the surface of the hardfacing seat insert, effectively preventing direct metal-to-metal contact and greatly enhancing wear resistance. Additionally, the hardfacing seat insert exhibited higher hardness than the tempered variant, leading to significantly reduced mass loss during testing. The hardfacing group experienced just 0.36 g of weight loss, in contrast to 1.62 g for the tempered group—a reduction of 77.78%. These results demonstrate that the hardfacing seat insert outperforms the tempered insert in resisting impact wear. [13]

Stellite 12 hardfacing alloy was subjected to high-current pulsed electron beam treatment to evaluate its influence on surface structure and mechanical properties. The treatment generated a carbide-free surface layer, composed of an outer amorphous zone atop a nanocrystalline α-Co region beneath. This layered structure results from rapid melting, solidification, and the dissolution of existing carbides during the process. The treated alloy showed marked mechanical improvements, with surface hardness more than doubling and a reduction in wear rate of over 60% compared to the original, untreated state. These results highlight the effectiveness of pulsed electron beam treatment as a method to significantly enhance Co-based hardfacing alloys, providing substantial strengthening without requiring changes to the alloy composition or the use of composite structures.[14]

Group 4: Processing Methods, Process Parameters & Thermal Cycling (HAZ / Buffer Layers)

Electric arc spraying utilizing dual wires is a cost-effective coating technique with a wide range of applications. Electrode phenomena, including oxidation and turbulence, significantly influence droplet formation and, consequently, the properties of the coating. A low turbulence intensity in the atomizing gas flow is associated with a higher frequency and smaller amplitude of arc voltage fluctuations. The use of nitrogen mitigates oxidation and turbulence in the electrode region. A converging-diverging nozzle achieves higher gas velocity with reduced turbulence. These processes result in coatings characterized by lower oxidation and reduced porosity.[15]

The effects of flux-cored arc welding (FCAW) under varying conditions, including preheating, gas-shielding, and buffering, on the microstructure and wear resistance of Fe-Cr-C hardfacing alloy. Flux-cored wires composed of austenitic nickel and Fe-Cr-C alloyed steel were employed as buffer and hardfacing layers. Welding quality was assessed using visual testing (VT) and penetrant testing (PT). Structural characteristics were analyzed using optical microscopy (OM), X-ray diffraction (XRD), and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS). The findings indicated that preheating, gas-shielding, and buffering enhanced the quality, dilution, and weldability of the hardfacing weld. The structural phase of the hardfacing weld was identified as (Fe, Cr)7C3 combined with a martensite-austenite matrix (MA matrix). Buffering facilitated the integration of the hardfacing layer with the structural steel base, reducing crack formation and carbide precipitation (Fe3C) at the fusion line due to elemental dilution. The combination of buffer and hardfacing layers influenced the crystallite size and fraction ratio of (Fe, Cr)7C3 to the MA matrix, increasing elemental diffusion. Wear testing results, including hardness, impact, and abrasion tests, demonstrated that FCAW with preheating, gas-shielding, and buffering significantly improved the wear resistance of the Fe-Cr-C hardfacing alloy. This improvement was attributed to the presence of (Fe, Cr)7C3 eutectic carbide in a high fraction of the MA matrix, resulting in a favorable toughness-hardness balance. Furthermore, the optimal FCAW conditions identified in this study could be applied to the hardfacing of the tooth plate of crushing rollers used in the biomass energy industry, offering a longer service life compared to traditional FCAW methods.[16]

The study examined the interfaces between substrate and high-chromium cast iron (HCCI) hardfacing layers, as well as those between substrate, buffer layer, and HCCI hardfacing layers. In substrate-HCCI configurations, distinct interfacial regions formed, marked by carbon-rich layers with sharp concentration gradients and limited diffusion. Conversely, systems incorporating a buffer layer between the substrate and HCCI exhibited improved interfacial characteristics. At these interfaces, austenite bands replaced the carbon-rich zones, with the austenite band measuring around 35 μm at the buffer-hypoeutectic HCCI junction and about 13 μm at the buffer-hypereutectic HCCI interface. The junction between the substrate and buffer layer showed minimal elemental differences and a wide diffusion zone. Overall, the presence of a buffer layer significantly improved the bonding strength at the interface. Shear testing revealed that adding a buffer layer increased the interfacial bonding strength by 57.2% and 40.1% for hypoeutectic and hypereutectic HCCI, respectively, compared to direct cladding onto the substrate.17]

Hardfacing is frequently employed to enhance the wear resistance of surfaces, but it can lead to a decrease in the toughness of the substrate due to alterations in the microstructure within the heat-affected zone. To counteract this drawback, a layer of austenitic stainless steel is typically inserted between the high-strength steel substrate and the hardfacing layer. This research examined how the butter layer and heat input affect the impact behavior of S690QL, S960QL, and S1100QL steels through instrumented Charpy impact tests. Generally, a rise in heat input led to a decrease in impact energy and an increase in peak impact force. The optimal outcome was achieved with S960QL when processed with minimal heat input, resulting in a 132% boost in impact energy. In contrast, S1100QL showed the least impact energy under the same conditions; however, with the maximum heat input, S1100QL's impact energy rose by 113%. These results are especially significant for demolition shears, where components often face dynamic loading, emphasizing the need to optimize the combinations of substrate and butter layers along with hardfacing parameters.[18]
The hardfacing process made use of Hardface HC-O cored wire (classified as T Fe15 under EN 14700), which contains high levels of carburizing elements—approximately 4% carbon, 5% silicon, and 25% chromium by weight. Several layers were applied to an S355MC steel base, and both macro- and microscopic examinations were conducted on the resulting structure. Samples from various locations were digitally sectioned using X-ray tomography to identify and separate any defects. Each layer was then analyzed for its chemical makeup, microstructure, and crystallographic orientation, with these findings compared to tomography and hardness results. The research showed that the use of an over-alloyed cored wire notably increased the hardness from 140 HV (±5 HV) in the base material to 700 HV (±152 HV)

throughout the welded surface. Formation of primary M(Fe,Cr)$_7$C$_3$ chromium carbides within a carbon-enriched austenitic structure resulted in a maximum surface hardness of 888 HV (±25 HV) at the outermost layer. The study determined that the wire's chemical composition, the multi-layer build-up, and the cladding process all contributed to the observed microstructural characteristics. These encouraging findings point to a wider range of applications for hardfacing alloys, especially in situations where improved energy absorption is required.19]

The hardfacing process employed Hardface HC-O cored wire (also known as T Fe15 under EN 14700), which contains high amounts of carburizing elements—approximately 4% carbon, 5% silicon, and 25% chromium by weight. Several hardfacing layers were applied to an S355MC steel base, and the final deposit was analyzed at both the macro and micro scales. Samples were collected from various locations and initially underwent digital sectioning using X-ray tomography to identify and segment any defects. Each layer's chemical composition, microstructure, and crystallographic orientation were examined and then correlated with tomographic and hardness findings. The results revealed that the use of an over-alloyed cored wire greatly boosted the hardness from 140 HV (±5 HV) in the original substrate to 700 HV (±152 HV) across the welded build-up. The development of primary M(Fe,Cr)$_7$C$_3$ chromium carbides within a carbon-enriched austenitic matrix resulted in a maximum surface hardness of 888 HV (±25 HV) at the outermost layer. The mechanisms behind the formation of these microstructures were found to depend on the wire's chemical composition, the multi-layer structure of the deposit, and the kinetics of the cladding process. These encouraging results indicate that hardfacing materials could see expanded use in applications requiring improved energy absorption.[20]

Fe–Cr–C martensitic stainless steels are important hardfacing alloys for components that must withstand significant abrasion. This study used a multi-track, multi-layer wire-arc directed energy deposition (WA-DED) approach to apply ER420 martensitic stainless steel onto an AISI 4140 substrate. The research explored how the microstructure of the deposited layer relates to its hardness, tensile strength, impact toughness, and wear characteristics during dry sand rubber wheel testing. Results showed that post-deposition tempering greatly enhanced the abrasion resistance of the hardfacing layer, even though it led to reduced hardness. In the as-deposited condition, the upper layer exhibited both untempered and tempered martensite, with δ-ferrite forming along sub-solidification boundaries. This configuration resulted in high surface hardness but lower toughness, causing the layer to experience more abrasion wear due to microcutting and microcracking. By introducing post-deposition tempering to improve toughness, the dominant wear mechanism shifted from microcutting/microcracking to microploughing, yielding a marked increase in wear resistance. The findings emphasize that achieving the right balance between fracture toughness and hardness is crucial for optimizing the performance of abrasion-resistant hardfacing alloys.21]

Shaft-shaped parts are designed to perform well in demanding, wear-prone environments, but over extended use, they may suffer from wear that compromises their size and effectiveness. This study examines the effectiveness of hardfacing layers deposited on worn steel shafts restored using resistance welding techniques. Researchers implemented nine different welding setups based on Taguchi's methodology and experimentally applied them to steel shaft specimens. The welding process was conducted with a recovery system that combined a resistance seam welding machine and a specially engineered fixture. Findings revealed that the resulting weld surfaces were smooth and defect-free. Macrostructural analysis confirmed strong bonding between the hardfacing material and the original shaft. Tests of hardness and resistance to wear showed that the repaired surface properties were similar to those of new shafts subjected to high-frequency quenching. The study also assessed how different welding parameters influence the resulting hardness and wear resistance, ultimately recommending the best welding conditions for achieving optimal hardness and the least possible metal loss. These insights are valuable for mechanical workshops focused on shaft refurbishment, supporting more time- and cost-efficient repair processes.[22]

Group 5: Component Reclamation & Specific Structural Applications

Addressing surface defects in thermite welds on operational railway lines is essential for preserving rail quality and safety. Repair strategies for these imperfections must be practical, cost-effective, and viable for on-site implementation. Hardfacing stands out as the most reliable approach for restoring the rail head in thermite-welded rails. In this research, four different repair scenarios were evaluated using two types of hardfacing alloys with distinct shielding gas environments during the Flux-Cored Arc Welding (FCAW) process: a single martensitic layer paired with an austenitic buffer (used in both self-shielded and Ar + CO_2 mixed gas settings), and a two-layer pearlitic hardfacing (without a buffer) under pure CO_2 and Ar + CO_2 shielding. The resulting microstructures were analyzed using both optical and scanning electron microscopy (SEM). To assess the mechanical and wear properties, microVickers hardness, Charpy V-notch impact, and ball-on-disc sliding wear tests were conducted. It was found that the martensitic structure significantly enhanced resistance to wear, while the presence of an austenitic buffer layer boosted impact toughness. Hardness testing indicated that the martensitic sample with an austenitic buffer layer exhibited values comparable to those of the original pearlitic rail and thermite weld. Overall, in terms of impact toughness, hardness, microstructural characteristics, and sliding wear resistance, the martensitic electrode combined with a mixed gas-shielded buffer layer delivered the best performance among all tested configurations.[23]

This research outlines the combined fabrication of Fe-Cr-C-Si hardfacing layers using gas metal arc welding (GMAW), followed by a two-step laser heat treatment that involves sequential water and air cooling. This approach enabled a thorough investigation of the layers' intermittent wear response under various temperature settings. Results demonstrate that Fe-Cr-C-Si hardfacing layers possess strong interfacial bonding and intricate microstructural features, both of which are further improved by laser heat treatment (LHT), leading to enhanced hardness. Wear tests conducted in two different modes and across multiple temperatures revealed unique Coefficient of Friction (COF) patterns, with the SiC counterpart showing outstanding wear resistance. Post-wear examination of the Fe-Cr-C-Si layers highlighted the roles of tribochemical reactions, adhesion, and abrasion in the wear process. Both the hardfaced and LHT-treated samples displayed remarkable wear resistance, evidenced by very low wear loss rates ($\times 10^7$). Specifically, the wear loss rate of the hardfacing was 65.7% higher at 400 °C and 39.71% higher at 500 °C compared to the LHT samples, underscoring the complex influence of temperature on oxide development and wear performance. At 400 °C, the running-in period was prolonged, while significant formation of Cr_2O_3 and SiO_2 oxides was observed at 500 °C. Early in the wear process, decreased oxide debris indicated a shorter running-in stage, but as wear continued, the expulsion of fine debris increased due to three-body abrasion from oxide particles. [24]

This research presents the integrated production of Fe-Cr-C-Si hardfacing layers using gas metal arc welding (GMAW), followed by a double-stage laser heat treatment that involves both water and air cooling. This methodology enabled a detailed study of the intermittent wear characteristics of these layers at different temperatures. Results show that Fe-Cr-C-Si hardfacing layers exhibit strong interfacial bonding and a complex microstructure, attributes that are further improved by laser heat treatment (LHT), leading to greater hardness. Wear evaluations, performed under two different test modes and temperature ranges, produced varied Coefficient of Friction (COF) responses, with the SiC counterface showing superior wear resistance. Examination of worn Fe-Cr-C-Si surfaces revealed the contributions of tribochemical interactions, adhesion, and abrasion to the wear process. Both the hardfaced and LHT-treated samples displayed excellent wear resistance, reflected in very low wear loss rates ($\times 10^7$). Hardfacing wear loss rates were 65.7% higher at 400°C and 39.71% higher at 500°C than those of LHT samples, highlighting the complex effect of temperature on oxide formation and wear mechanisms. At 400°C, the running-in stage lasted longer, while at 500°C, significant amounts of Cr_2O_3 and SiO_2 oxides were found. Initially, less oxide debris indicated a shorter running-in period, but with prolonged wear, the ejection of fine debris increased due to three-body abrasive effects.[25]

Surface hardening methods for steel are essential in producing parts that must withstand wear. Hardfacing is frequently chosen due to its cost-effectiveness and efficiency. In this study, multiple-pass MIG welding was used to deposit a martensitic stainless steel coating onto Q345 steel, resulting in marked enhancements in surface wear and corrosion resistance. The adhesion between the coating and substrate surpassed the tensile strength of the base steel. The microstructure of the coating featured lath martensite intermixed with (Cr, Fe)7C3 particles. The development of martensite in the layer is crucial for boosting both wear resistance and bonding strength. Elevated chromium levels in the alloy provide superior resistance to corrosion. Among the X12Cr13, X20Cr13, and X30Cr13 coatings, wear resistance increased while corrosion resistance decreased in this order. X30Cr13 was found to offer the highest protection against wear, establishing it as the most suitable option. These outcomes highlight new possibilities for steel surface hardening. [26]

Addressing mild abrasive wear at elevated temperatures is a critical challenge for industries like hot sieving and bulk material handling. To meet this challenge, a novel high-temperature rubber wheel abrasion test (HT-CATrw) was developed to evaluate wear resistance. This approach enabled direct comparison of a Fe-Cr-C-based hardfacing with a complex Fe-Cr-Mo-Nb-W-C alloy, both at ambient and 500 °C, under different load conditions to simulate various real-world operations. Thorough material characterization was performed before and after testing, including 3D and scanning electron microscopy, X-ray diffraction, measurements of hot hardness, and electron backscatter diffraction (EBSD).[27]

PEEK Polymer Composites (Outliers)

Modern industrial applications increasingly rely on polymer-based composites for tribological components. To evaluate these capabilities, an empirical investigation examined the friction and wear behavior of polyetheretherketone (PEEK) matrix composites loaded with various filler types and concentrations. Using a Taguchi design of experiments on a pin-on-disc apparatus, the study assessed how key operating conditions—specifically sliding velocity, contact pressure, and duration—influenced material degradation. Analysis of variance (ANOVA) was conducted to quantify the statistical significance of each operational factor, and linear regression models were formulated to predict wear response across all composite formulations. Results indicated that sliding speed, applied load, and test time heavily govern tribological behavior by dictating frictional heating at the sliding interface. Notably, incorporating a combined reinforcement of carbon fiber (CF), polytetrafluoroethylene (PTFE), and graphite significantly enhanced the overall wear resistance of the PEEK matrix [28].

This study investigated the tribological behavior of two polyetheretherketone (PEEK) material systems: a standard micro-composite reinforced with short carbon fibers (SCF) and a nanocomposite incorporating SiO2 nanoparticles. Rather than combining the fillers internally, the two distinct composites were joined side-by-side using an adhesive bonding method. Tribological characterization via a pin-on-disc configuration—where both composite surfaces engaged a steel counterpart along a shared friction track—revealed a marked performance improvement over the individual component tests. This enhancement points to a strong synergistic interaction between the SCF and SiO2 filled matrices. Crucially, the side-by-side assembly matched the friction and wear performance of a fully integrated hybrid nanocomposite containing both SCF and SiO2 additives. Analysis of the resulting tribofilm morphologies clarified the active mechanisms driving this synergistic effect, establishing a novel strategy for engineering tribological components through the functional assembly of discrete composite materials [29].

Comprehensive Review Papers

Hardfacing serves as an essential surface modification technique designed to extend the operational longevity of critical structural parts across diverse sectors, including nuclear energy, petrochemical processing, mining operations, sugar refining, and agricultural machinery, where components face combined degradation from impact, abrasion, and corrosion. Among standard surfacing consumables—namely Fe-, Co-, and Ni-based alloys—nickel-based formulations are often favored for their capacity to retain elevated-temperature hardness. Specifically, Colmonoy alloys are heavily utilized in nuclear reactor applications because their radiological dose rate is roughly 1/265 that of cobalt-based alternatives. Deposition methods such as Gas Tungsten Arc (GTA), Plasma Transferred Arc (PTA), and laser cladding directly govern four key overlay characteristics: microstructural development, base metal dilution, tribological wear behavior, and mechanical integrity. This review delivers a thorough evaluation of nickel alloy hardfacing literature, assessing various deposition processes across different substrate alloys within these four performance domains to guide ongoing research and industrial practice [30].

Hardfacing serves as an economical and versatile surface modification method widely implemented across heavy industrial sectors to restore damaged parts or proactively improve wear performance prior to operational service. Successfully engineering a hardfacing layer requires comprehensive insight into the chosen deposition technique, filler alloy chemistry, and base metal characteristics. Crucially, operators must control key processing parameters and mitigate inherent deposition challenges, such as excessive dilution and residual stress–driven cracking. Over recent decades, extensive research has evaluated hardfacing systems, concentrating primarily on tribological wear, corrosion resistance, and impact behavior across varied welding techniques and alloy formulations. This review systematically synthesizes the current literature to establish selection frameworks for hardfacing processes and materials. It examines critical processing variables—including heat input, travel parameters, and multi-pass layer count—and evaluates their direct impact on coating integrity. Furthermore, major technical hurdles like elemental dilution, cracking, and thermal degradation of high-strength steel substrates are examined, highlighting damage characterization techniques. Ultimately, this work explores optimization strategies for high-strength steel hardfacing while outlining emerging research directions and industrial prospects [31].

As a critical surface engineering technique, hardfacing improves component longevity and performance by depositing a resilient protective coating onto metallic substrates through diverse application methods. This process significantly enhances functional properties—such as resistance to abrasion, chemical corrosion, erosive wear, and high-temperature oxidation—thereby minimizing operational downtime and maintenance expenses in severe working environments. This review systematically evaluates current hardfacing methodologies and their associated feedstock materials across various industrial sectors. Furthermore, it discusses recent innovations in deposition technology, material strengthening mechanisms, and emerging developmental trends. Key avenues for future progress include optimizing process parameters, engineering advanced material systems, and leveraging computational simulations to refine overall deposit quality [32, 33].

Summary of the outcomes

1. Fe-Cr-C Hardfacings in Sugarcane Industry:
   Hypereutectic Fe-Cr-C hardfacings exhibit a microstructure dominated by primary M7C3 carbides embedded in an austenitic matrix, resulting in significantly higher surface hardness (~800 HV) and a large carbide volume fraction (~43%). However, these coatings suffer from carbide fracture and spallation under higher load conditions (120–150 N), leading to increased wear. In contrast, hypoeutectic coatings, characterized by a cellular austenite/ferrite matrix with fewer carbides (~7%), show lower hardness (~520→337 HV) but improved wear resistance at higher loads due to microploughing and microcutting mechanisms. The presence of cane-juice slurry influences wear behavior differently for these coatings: it promotes corrosion wear in hypereutectic coatings at low loads but reduces wear in hypoeutectic coatings by providing lubrication.

2. Electric Wire Arc-Spraying Optimization for Sugar Mill Rollers:
   Optimization of parameters such as voltage, current, air pressure, and spray distance through Taguchi analysis led to coatings with superior wear resistance and hardness. The optimized settings (35 V, 150 A, 4.5 bar air pressure, 120 mm spray distance) produced FeCrB coatings with hardness values between 963 and 993 HV0.2, minimal porosity (~0.8–1.2%), and very low mass loss during wear testing. Contrary to conventional wisdom, hardness alone was not the primary determinant of wear resistance, air pressure notably influenced coating quality and wear performance.

3. Tribochemistry of Sugar Mill Shafts:
   Wear and tribofilm formation on EN8 steel sliding against E52100 steel are significantly affected by environmental contaminants such as sucrose and water. Dry sliding produces stable oxide debris with oxidational wear dominating, while lubricated conditions generate hydrocarbon-rich tribofilms. Contaminated environments accelerate oil decomposition and spoil lubrication, resulting in mixed tribofilms that exacerbate wear. Tribochemical reactions and the evolving composition of the mechanically mixed tribofilm layer are critical factors controlling friction and wear rates.

4. Mo-Added Fe-Cr-C-V Hardfacings:
Incorporating molybdenum into Fe-Cr-C-V hardfacing alloys introduces complex M2C carbides and alters the microstructure from hypoeutectic near the substrate to hypereutectic at the surface. While macrohardness and wear rates remain relatively unchanged, molybdenum significantly enhances cavitation resistance (up to 20 times) and corrosion resistance (up to 4.5 times), attributed to solid solution strengthening and fine carbide precipitation, which impede dislocation motion and improve surface durability.

5. Fe-Ti-Mo-B-C FCAW Hardfacing:
Flux-cored arc welding with varying Mo content reveals that moderate Mo levels (Sample 3) yield the most uniform microstructure with prolonged polygonal Fe(Mo,B)2 crystals, resulting in the highest hardness (64 HRC) and superior wear resistance across multiple abrasive conditions. Excessive Mo (Sample 4) induces arc instability and structural defects such as cracks, reducing performance, while low Mo content (Sample 1) lacks the beneficial carbide phases necessary for optimal hardness and wear resistance.

6. Boron Influence on Fe-Cr-C-Mo Hardfacing:
Low boron additions refine primary M7C3 carbides by approximately 60% in size and promote the formation of M2B borides, which collectively increase hardness substantially (up to 1033 HV at 1.43 wt% B). However, the abrasive wear resistance peaks at a low boron content (~0.39 wt%) because higher boron levels increase brittleness, leading to carbide flaking and surface cracking despite further hardness gains. First-principles calculations indicate boron substitution weakens certain metal-boron bonds, reducing intrinsic carbide hardness and shear resistance.

7. Fe-Cr-C-B-Ti-Cu Alloy Modeling:
A modeling-experimental workflow predicts phase formation sequences and mechanical properties at the phase level, revealing a multi-phase microstructure consisting of TiC, austenite, borides, and copper-rich phases. Mechanical property simulations identify the Fe2(B,C) phase as optimally balancing hardness and ductility for abrasion resistance, while TiC is the hardest but most brittle phase. Indentation tests confirm that microstructural groups combining ductile and hard phases provide the best wear resistance by mitigating brittle cracking.

8. Mn-Added Iron-Based Hardfacings:
Increasing Mn content stabilizes retained austenite, increases hardness slightly through solid solution strengthening, and enhances wear resistance by promoting the formation of protective tribo-oxide layers. However, excessive oxide layer thickness can cause subsurface cracking, compromising structural integrity despite reduced surface wear. Wear mechanisms shift from micro-abrasion with carbide pull-out to mild oxidative wear with smoother surfaces and lower roughness.

9. MIG 12Cr-xC Hardfacings:
Higher carbon content (0.4 wt%) in 12Cr hardfacings increases hardness and reduces temperature sensitivity of wear rates compared to 0.3 wt% C alloys. Wear is dominated by abrasive mechanisms involving embedded oxide debris, whose formation and stability depend on load and temperature.

Thick oxide layers can spall, generating debris that simultaneously lubricates and accelerates fatigue wear, affecting long-term durability.

10. Fe-Based Hardfacing with Multi-Boro-Carbides:
Boron additions lead to a highly refined multi-component eutectic microstructure containing various boro-carbides (M2(BC), M23(BC)6, Nb(BC)), which dramatically reduce magnetic permeability from 4.534 to near unity (1.006), essential for directional drilling applications. The dense distribution of these hard phases enhances wear resistance significantly, achieving low volumetric wear coefficients and high hardness (~49.8 HRC).

11. 316L(N) SS Hardfacing via GTA and Laser Cladding:
Gas Tungsten Arc (GTA) cladding yields coarser grains with lower hardness (~447 VHN) but superior tensile strength (595 MPa), ductility, and fatigue life compared to Laser Cladding (LC), which produces finer grains, higher hardness (~596 VHN), but brittle martensitic microstructures prone to cracking and delamination. GTA specimens exhibit ductile fracture modes, while LC coatings fail prematurely with brittle fractures and reduced fatigue strength.

12. Laser Metal Deposition Repair of Stellite™ 6:
A crack-free repair method combining EDM groove design, preheating, and optimized laser scanning was developed for brittle Stellite 6 hardfacing layers. Non-destructive testing confirmed defect-free metallurgical bonding with minimal dilution. Mechanical testing validated the repaired zone's structural integrity, showing no weak points for crack propagation, although subtle mechanical differences compared to the original layer were observed.

13. STL12 Hardfacing for Valve Seats:
STL12 hardfacing significantly improves deformation resistance and wear performance under high-temperature, heavy-load conditions. The formation of continuous oxide films (Fe, Ni, Co oxides, carbides) on valve and seat surfaces acts as a protective, lubricating barrier, reducing wear by approximately 3.7 times compared to tempered inserts. Wear mechanisms shift from severe adhesive and fatigue wear in tempered seats to mild abrasive and oxidation wear in hardfaced components.

14. HCPEB Treatment on Co-Based Alloy:
High-current pulsed electron beam irradiation induces surface amorphization and nanocrystallization in Stellite 12 alloys, doubling surface hardness from ~495 HV to over 1076 HV. The amorphous layer is primarily responsible for this enhancement. High-temperature wear tests reveal over 60% reduction in wear rate due to the dislocation-free amorphous surface, with stabilized surface roughness achieved after initial melting and smoothing cycles.

15. FCAW Effects on Fe-Cr-C Hardfacing:
Preheating, gas shielding, and buffering during flux-cored arc welding reduce defects such as cracks and porosity, modify microstructure by increasing martensite-austenite matrix fraction, and optimize carbide size. These effects improve toughness and wear resistance, extending service life of industrial components by roughly 80%. Buffered and gas-shielded welds demonstrate superior impact and abrasion resistance compared to non-buffered or self-shielded counterparts.

16. Buffer Layers in Q235-HCCI Hardfacing:
Buffer layers between Q235 steel and hardfacing alloy eliminate brittle, carbon-enriched zones at the interface, preventing crack formation and improving bonding strength by 40–57%. They create graded hardness transitions from substrate (~150 HV) through buffer (~200–390 HV) to hardfacing (~308–755 HV), enhancing toughness and interface durability by promoting wide diffusion zones and austenite band formation.

17. Austenitic Buffer Layers on High-Strength Steel: To enhance the interfacial properties of heterogeneous materials, multilayer structures consisting of substrate, buffer layer, and HCCI hardfacing layer were applied. The influence of the buffer layer on the microstructure, alloy element distribution, hardness gradient, and interfacial bonding strength was systematically investigated. The key findings are summarized as follows.

1) Across all evaluated interfaces, the base metal microstructure consistently revealed a combination of ferrite, pearlite, and Widmanstätten structures. Direct substrate–HCCI junctions exhibited notable structural shortcomings, including abrupt, well-defined boundaries and strong carbon accumulation—particularly prominent at the hypereutectic HCCI interface. Additionally, these unbuffered regions suffered from significant elemental disparities, marked by sharp concentration gradients and restricted solute diffusion lengths.

2) Incorporating a buffer layer into the substrate–HCCI system significantly enhanced interfacial performance. At the substrate–buffer interface, compositional discrepancies were minimized alongside the formation of a broad elemental diffusion zone. Simultaneously, the buffer layer–HCCI boundaries developed a ductile, high-toughness austenitic band measuring approximately **35 µm** for hypoeutectic HCCI and **13 µm** for hypereutectic HCCI.

3) Microhardness testing showed that the substrate had a baseline value of **150 HV0.2**. In contrast, the initial buffer layer registered a higher hardness of approximately **390 HV0.2**, whereas the second buffer layer measured **200 HV0.2**. This variation stems from differences in phase distribution, as the first layer was rich in martensite, while the second was dominated by austenite. Furthermore, as deposit thickness increased, the microhardness of the hypoeutectic HCCI layer climbed from **308 HV0.2** to **585 HV0.2**, while the hypereutectic HCCI layer experienced a more pronounced increase from **324 HV0.2** to **755 HV0.2**.

4) The buffer layers enhanced the interface microstructure, facilitated element distribution across the interface, and resulted in a marked increase in interfacial bonding strength.

18. Multiple Heating of HAZ in High-Strength Steel:

1. Thermal Input & Penetration Dynamics

- **Penetration Depth:** In high-strength steel hardfacing, heat input directly dictates penetration depth, which subsequently impacts dynamic load capability.
- **Buffer Layer Comparison:** Depositing an **austenitic stainless steel buffer layer** results in substantially shallower penetration than using a carbon steel buffer layer.

2. Microstructural Response & HAZ Softening across Substrates

Heat-affected zone (HAZ) hardness responses vary significantly across high-strength substrate grades:

- **S690QL:** Demonstrates localized hardening within the coarse-grained HAZ (UCHAZ), accompanied by minor softening in the intercritical (ICHAZ) and subcritical (SCHAZ) regions.
- **S960QL:** Maintains hardness in the UCHAZ similar to S690QL, but exhibits pronounced softening across the ICHAZ and SCHAZ.
- **S1100QL:** Experiences the most severe degradation, suffering dramatic hardness loss within the ICHAZ and SCHAZ.
- **Austenitic Buffer Behavior:** Across all grades, the austenitic butter layer maintains a consistent, uniform hardness profile of approximately **200 HV**.

3. Substrate-Specific Impact Performance

S690QL

- Hardfacing reduces impact energy relative to the base metal across all test conditions.
- Lower heat inputs preserve impact energy better, whereas higher heat inputs degrade energy absorption despite increasing maximum impact force.
- Impact force is superior when using an austenitic buffer layer compared to a carbon steel buffer layer, as confirmed by force–time response curves and fractography.

S960QL

- Yielded the highest overall impact energy values among the tested alloys.
- Applying minimal heat input generated **more than double** the impact energy of the un-welded base metal, whereas high heat input caused a severe drop.
- Maximum impact force peaked at higher heat inputs (though remaining below base metal levels) and performed better with an austenitic buffer layer.

S1100QL

- Exhibited the lowest baseline and hardfaced impact energy levels overall.
- Unlike other grades, increasing heat input to **1284 J/mm** improved impact energy to **more than twice** that of the base material.
- While buffer material selection did not noticeably change impact energy, the carbon steel buffer layer caused a steep drop in maximum impact force compared to the austenitic layer.

4. Key Engineering Takeaways & Process Optimization

- **Optimal vs. Worst Configurations:**
  - **Best overall toughness:** S960QL substrate paired with an austenitic buffer layer processed at **low heat input**.
  - **Worst overall toughness:** S1100QL substrate with an austenitic buffer layer processed at **low heat input**.
- **Heat Input Customization:** Steel grades cannot be treated uniformly; heat input parameters must be tailored individually to match the specific metallurgy of the base metal.

- **Design & Repair Implications:** To maximize component lifespan and ensure reliable repair welding, design criteria must jointly optimize the **substrate grade**, **butter layer chemistry**, and **welding process parameters** rather than evaluating the substrate in isolation.

19. Multi-Layer High-Cr Hardfacing:
Repeated thermal cycling during multi-layer hardfacing increases hardness up to 888 HV by promoting dense precipitation of primary M7C3 carbides. Thermal stresses induce macro-cracks correlated with porosity, but crucially, the substrate-hardfacing interface remains crack-free. Anisotropic heat profiles influence carbide morphology and thermal impact zone thickness, affecting overall microstructural stability.

20. The main objective of hardfacing is to extend the lifespan of parts exposed to complex
Hardfacing aims to prolong the service life of components operating under severe surface degradation (abrasion, wear, and corrosion) by depositing a protective, high-durability alloy overlay. In a recent investigation, an 8 mm thick high-chromium/carbon coating (5 wt.% C, 27 wt.% Cr) was applied via flux-cored arc welding (FCAW) in three sequential passes over an 8 mm S355MC steel substrate (200 × 200 mm section). Characterization of the as-welded bilayer revealed critical relationships between macro-level deposition dynamics and post-cooling microstructural evolution:

    1. **Hardness Enhancement:** High C and Cr concentrations in the filler metal promoted the precipitation of primary carbides within an austenitic matrix. This microstructural phase yielded an approximate 530% surge in surface hardness relative to the S355MC substrate, making it highly suitable for high-stress mechanical environments [31].
    2. **Interfacial Elemental Gradient:** Interfacial diffusion of Cr and C during solidification created a pronounced composition and microstructural transition across the overlay depth. Notably, element carburization was suppressed in the initial pass, initiating only within the second deposited layer.
    3. **Defect Distribution:** Although the base metal/coating interface remained free of void defects, porosity selectively formed at carburized sites near the interface between the first and second passes. This localized region also acted as an initiation site for thermal hot cracking.
    4. **Anisotropic Cooling & Crack Orientation:** Microstructural features, chemical distribution, and cooling behavior demonstrated distinct anisotropy. Crystallographic texture analysis revealed heightened crack susceptibility normal to the welding trajectory, which explains how thermal residual stresses are relieved during ambient air cooling—manifesting as a transverse crack network across the weld beads.

21. WA-DED Martensitic Stainless Steel:
Wire-arc directed energy deposition (WA-DED) produces an as-deposited microstructure with brittle untempered martensite and residual δ-ferrite, resulting in high hardness (~500 HV) but poor tensile behavior. Tempering at 610°C transforms the matrix to tempered martensite/ferrite with fine carbides, reducing hardness (~280 HV) but significantly improving tensile strength (up to

1150 MPa), ductility, impact toughness, and wear resistance. The tempered coating shifts wear mechanisms from destructive micro-cutting to milder micro-ploughing.

22. Resistance Seam Welding for Hardfacing:
    Resistance seam welding produces uniform, crack-free hardfacing layers on C45 steel shafts with minimal dilution and narrow HAZ due to solid-state bonding below melting temperatures. Welding parameters influence surface morphology, with lower current and higher cooling rates yielding smoother surfaces. The resulting coatings match the wear resistance and mechanical properties of new, high-frequency quenched steel shafts.

23. .FCAW Hardfacing on Thermite Welded Rail:

Flux-cored arc welding with an austenitic buffer layer on thermite welded rails improves metallurgical soundness and mechanical performance. Gas-shielded martensitic hardfacing layers with buffers show optimal hardness (~345 HV), toughness, and wear resistance, whereas self-shielded specimens suffer porosity and slag inclusions. The buffer layer cushions structural transitions, enhancing impact toughness and sliding wear behavior.

24. Hardfacing for Ballistic Protection:
    Arc-welded Fe-Cr-C hardfacing on S355JR steel achieves armor-grade hardness (~905 HV) and ballistic limits sufficient to stop 7.62×51 mm AP rounds. Layered structures incorporating austenitic buttering improve ductility and energy absorption, mitigating brittleness and carbide cracking seen in hypereutectic coatings. Practical armor plates produced are low-cost, repairable, and lighter than monolithic armor steels.

25. Fe-Cr-C-Si Hardfacing with Laser Heat Treatment:
    Laser heat treatment (LHT) following hardfacing refines microstructure by reducing retained austenite and secondary dendrite arm spacing, promoting acicular tempered martensite. Silicon segregation at carbide interfaces inhibits carbide coarsening, enhancing toughness. LHT specimens exhibit significantly lower wear loss rates (up to 65.7% reduction at 400°C) compared to untreated layers, with dense Cr2O3 and SiO2 oxide barriers forming at elevated temperatures to protect surfaces.

26. Martensitic Stainless Steel Coatings on Q345:
    Multiple-pass MIG welding deposits martensitic stainless steel coatings with lath martensite and chromium-rich carbides. Hardness increases with carbon content: X30Cr13 (523 HV) > X20Cr13 > X12Cr13. Coatings bond strongly with the substrate, failing in the base metal during tensile tests. Wear resistance improves with carbon, but corrosion resistance declines due to chromium carbide precipitation causing galvanic corrosion. X30Cr13 offers the best wear-corrosion balance for industrial roller applications.

27. Load and Temperature Effects on Fe-Cr-C Wear:
    Wear rates of Fe-Cr-C hardfacings increase with load at room temperature but decrease at elevated temperatures (~500°C) due to enhanced matrix ductility. Complex Fe-Cr-Mo-Nb-W-C alloys show more stable wear behavior with less load sensitivity. Carbide cracking and plastic

deformation occur under load, while abrasive particle fracture contributes to wear mechanisms, influenced by temperature and load conditions.

28. PEEK Composite Wear Behavior:
Dry sliding wear of PEEK composites is primarily influenced by test duration, followed by applied pressure and sliding velocity. Fillers such as carbon fiber (CF), polytetrafluoroethylene (PTFE), and graphite significantly reduce wear rates by improving load distribution and reducing friction. Regression models effectively predict wear rates based on these parameters.

29. PEEK Composite Assembly:
Side-by-side assembly of SCF-reinforced and nano-SiO2-filled PEEK composites achieves low friction coefficients (<0.10 at high PV) and wear rates comparable to hybrid SCF+SiO2 composites. This approach mitigates processing difficulties associated with multi-filler melts, while tribofilm analysis shows formation of thin, nanostructured silica-rich films that reduce direct surface contact and wear.

30. Ni-Alloy Hardfacing Review:
Ni-based hardfacing alloys exhibit microstructures with dendritic carbides and eutectics whose morphology and dilution levels critically influence hardness and wear resistance. Laser cladding offers the lowest dilution, preserving coating properties. Alloying elements and process parameters are optimized to enhance toughness, reduce cracking, and improve performance at elevated temperatures. Emerging techniques include low-intensity high current (LIHC) and ultrasonic nanocrystal surface modification (UNSM).

31. Hardfacing Review Summary:
Welding process selection, consumable composition, and parameters such as heat input, travel speed, and preheating critically influence hardfacing quality. Main challenges include cracking (embrittlement, hydrogen-assisted), dilution-induced hardness loss, thermal distortion, and HAZ softening, particularly in high-strength steels. Buffer layers and multi-layer builds improve bonding and wear resistance. Advanced processes like laser cladding and PTAW reduce dilution and improve microstructural control. Alloying with elements such as C, Cr, Mo, Nb, V, W, Ti, and B tailors carbide morphology and mechanical properties to balance wear resistance and toughness.

32. Hardfacing of metals: A review of consumables, properties and strengthening processes:
1. Fe-based, Ni-based, and Co-based alloys are the primary materials used for hardfacing. To meet increasing industrial needs, innovative materials like high entropy alloys have been created. (a) hardfacing without interlayers; (b) hardfacing using ASS as an interlayer; and (c) hardfacing with ASS serving as both an interlayer and a capping layer. Y. Ning et al. Journal of Materials Research and Technology (2025)

2. Although conventional hardfacing methods like gas tungsten arc welding and submerged arc welding continue to be prevalent, newer techniques such as hybrid welding, double electrode welding, and arc oscillation are gaining traction. These innovative methods allow for improved

management of heat distribution during the welding process, modification of dilution rates, and changes in the material's microstructure, collectively boosting the materials' performance.
3. Innovations in hardfacing technologies are closely tied to the exploration and creation of novel materials. The progress in these areas is mutually dependent, as breakthroughs in material science propel advancements in process techniques, and the reverse is also true. This collaborative relationship is anticipated to hasten the evolution of hardfacing technologies, allowing them to address the increasingly intricate demands of industrial production. To improve fabrication quality, it is essential to develop new feedstock with superior mechanical properties. Moreover, welding processes require optimization, which involves designing structures and implementing in-situ operations like magnetic oscillation to even out microstructures and reduce heat input, while employing automation and hybrid welding to maintain consistency. Furthermore, simulations can be employed to forecast the structure and properties of the resulting materials.

33. The effect of heat treatment temperature on the wear resistance of 42CrMo steel hardfacing with Fe–Cr–C alloy
(1) Residual stress generated during hardfacing significantly impacts the operational performance of welded components. To mitigate this stress, post-weld heat treatment (PWHT) was applied to a 42CrMo plate. Using a finite element simulation of the combined hardfacing and PWHT processes, residual stress levels were assessed across three heat treatment temperatures: 400°C, 600°C, and 800°C. Results indicated that treating the component at 600°C successfully lowered peak residual stress from 1,040 MPa down to 30–50 MPa. This simulation methodology offers a reliable framework for determining optimal post-hardfacing heat treatment temperatures.

(2) Following the hardfacing process on 42CrMo steel, the resulting alloy composition comprised an iron matrix (α-Fe), solid solutions ([Fe,Ni] and [Fe,Cr]), along with various carbides, Synergistic contributions from both solid-solution and secondary-phase strengthening elevated the surface microhardness to an average of 551.3 HV, significantly improving the wear resistance of the hardfaced coating.

(3) Following hardfacing and subsequent heat treatment, the friction coefficient of 42CrMo steel progressively dropped, whereas its wear rate increased. A comparison revealed that the hardfacing alloy treated at 600 °C demonstrated outstanding wear resistance, with a 74.6% enhancement in friction coefficient and a 26.1% reduction in volumetric wear loss.

(4) After wear testing, all samples displayed parallel grooves on the wear scar surfaces, indicating abrasive wear as the primary mechanism. The presence of plastic deformation on the 42CrMo steel's wear scars pointed to adhesive wear, while pits observed on the hardfacing alloy's wear scars confirmed fatigue wear as a contributing factor.

3. Existing research gaps:

Implementing successful hardfacing demands a deep appreciation of the specific industrial environment, its unique operational demands, and overarching economic factors to accurately match methods with materials. Although the industry offers an extensive catalog of hardfacing alloys and deposition techniques, the current literature lacks a unified framework to guide engineers through these selection criteria. Furthermore, existing research rarely provides a comprehensive map of how shifting individual process variables directly alters the ultimate quality and integrity of the surface deposits. Developing a clearer, more systemic insight into these relationships is essential for engineering proactive deposition strategies and avoiding costly, recurring mistakes during application.

1	1.The study shows that excessive carbide volume (~43%) can reduce wear resistance, suggesting an optimal carbide fraction (~30–35%) but does not map performance across a wide range of compositions or carbide morphologies systematically 1.20 2.Only two commercial electrodes and specific test conditions were examined; further work could explore different alloy designs, load ranges, sand morphologies, and full-scale mill validation.
2	1.The study uses one FeCrB wire composition only; it does not compare alternative chemistries or coating materials for sugar mill rollers 1.27. 2.Only short-duration (2 h), lab-scale abrasive wear tests with bagasse and cane juice are reported; long-term field performance and other wear modes (e.g., impact, corrosion–wear interactions) are not addressed 1.28. 3.The work shows hardness is not the primary control of wear but does not deeply model or separate the roles of microstructure, crack formation, and porosity in governing wear loss beyond qualitative discussion of cracks and voids 1.29. 4.Parameter optimization is based on a single Taguchi L9 array; more extensive designs or response-surface methods could refine the process window and explore parameter interactions quantitatively, which are only qualitatively mentioned as making interpretation "more difficult" 1.30.
3	1.The work characterizes debris chemistry and thermal behavior but does not quantify wear rates, friction coefficients, or crack growth for each condition, limiting direct design implications.2. Only one shaft material pair (EN8/E52100) and specific contaminant combinations are studied; other steels, coatings, and sugar mill operating regimes are not explored. 3.Microstructural details of the mixed layer (e.g., thickness, phase distribution) are not deeply correlated with mechanical response, suggesting need for combined tribology–mechanics modeling.
4	While the literature extensively details the wear and corrosion performance of nickel, cobalt, and standard iron-based hardfacing alloys, comprehensive investigations into the ultrasonic cavitation behavior of iron-based hypereutectic systems—specifically regarding how alloying elements like Mo affect microconstituent hardness and structural variations along the cross-section—remained limited. This study bridges that gap by directly correlating microstructure changes, dislocation densities, and microhardness to cavitation performance in FeCrCVMo systems.
5	Standard industrial hardfacing heavily relies on expensive tungsten-based systems or traditional FeCrC alloy groups. However, FeCrC configurations inherently develop coarse, brittle M7C3 carbides that cause low crack resistance and structural defects during industrial application. While prior research touched upon Fe-Ti-B-C

	frameworks, a critical gap existed in systematically assessing how varying the precise stoichiometric ratio between Ti and Mo affects modifier phase distribution, matrix defects, and performance across multiple discrete abrasive regimes simultaneously (fixed, non-fixed, and impact). This paper successfully mapped that relationship, proving that proper Ti-to-Mo balancing eliminates the structural cracking typically associated with high-molybdenum ferrous deposits.
6	1.Only one base alloy system (Fe-~25Cr-~5Mo-~4.5C) and one wear mode (room-temperature dry-sand abrasion) are studied; effects of B under impact-abrasive, corrosive, or high-temperature wear are not addressed. 2.Focus is on B content; interactions with other carbide-forming elements (Ti, Nb, V, etc.) in similar Fe-Cr-C-Mo-B hardfacings remain unexplored. 3.DFT links B doping to hard-phase modulus, but there is no continuum or life-prediction model quantitatively connecting these properties to macroscopic wear rates for different service conditions.
7	1.No direct abrasive or tribocorrosion wear tests on 110Cr4Cu7Ti1VB are reported here; wear resistance is inferred from mechanical indices and indentation, not measured under ASTM wear tests 1.28. 2.Only one composition (fixed B, Cu, Cr, Ti, V) is experimentally built; systematic variation of Cu and B in this multicomponent Fe–Cr–C–B–Ti–Cu system is not explored. 3.Modeling uses equilibrium Thermo-Calc and DFT on ideal phases; the link between welding thermal cycles, real non-equilibrium microstructures, residual stresses, and in-service fatigue/wear life remains only qualitatively addressed. 4.Effect of exothermic additions (CuO–Al) on long-term coating performance and on defect populations (porosity, cracking) is not deeply quantified beyond microstructure and local indentation behavior.
8	Wear tests are limited to dry sand abrasion and room-temperature impact; no systematic study of impact-abrasive, corrosive, or high-temperature wear, though such conditions are relevant in industry.
9	1.Study is limited to two carbon levels (0.3, 0.4 % C) at fixed ~12 %Cr and one substrate; no exploration of broader alloying (Mo, Nb, V) or other base steels. 2.Wear environment is dry sliding with SiC balls; corrosive media, lubrication, multi-particle abrasion, or impact-sliding typical of real valves are not tested, and authors note liquid corrosion and HAZ cracking may change performance 1.19. 3.Oxide inclusions from shielding gas are observed but not systematically varied; their effect on long-term wear is unknown and flagged for future work 1.20. 4.Field validation on actual H61Y check valves is absent; link between laboratory tribosystem metrics (Whardfacing/Wball, oxide behavior) and in-service life is not quantified.

10	Conventional non-magnetic drilling tools rely on soft austenitic substrates that wear out prematurely. While high-wear-resistance hardfacings exist, they usually contain ferromagnetic phases or utilize nickel-based matrices that create material compatibility issues and introduce high manufacturing costs when applied to iron-based components.This paper bridges the gap by developing an economically viable, iron-based non-magnetic hardfacing system. It successfully uses B_4C additions to concurrently drive down magnetic permeability to near-vacuum levels ($\mu_r \approx 1$) while creating an in-situ network of refined boro-carbides that deliver industrial-grade wear protection.
11	While existing literature thoroughly documents the microhardness, dilution parameters, thermal wear, and self-welding characteristics of Ni-Cr-B-Si / Colmonoy overlays on stainless steel substrates, there was no prior published work tracking the exact tensile behavior, high-cycle fatigue thresholds (S-N curves), and accompanying interfacial failure mechanisms of these specific hardfaced structures when comparing traditional Gas Tungsten Arc welding directly against modern Laser Cladding. This study addresses that gap, providing quantitative data needed to ensure structural reliability in the design of critical components like sodium-cooled fast reactor grid plates.
12	While existing industrial standards provide robust guidelines for standard additive manufacturing, specialized procedures for repairing inherently brittle hardfacing overlays (like Stellite™) remain limited due to severe thermal shock and process-induced cracking. Furthermore, standard welding inspection techniques rely on localized, static metrics such as microhardness and tensile bars. This paper bridges the gap by establishing a scalable repair methodology that uses volumetric induction preheating to prevent cracks in large components. Additionally, it introduces the ACAR test, filling a critical void in quality assurance by providing a global, dynamic inspection method that explicitly assesses crack propagation risks across complex repaired boundaries in high-consequence industries like nuclear energy.
13	1.Only one engine material system is studied: Ni30/STL1 valves and T128/STL12 seats; other steels, hardfacing alloys, geometries or lubrication conditions are not explored. 2.Testing uses a single, very severe condition (65 °C, 30 kN, dry, 2 million cycles); effects of varying temperature, load, frequency, or lubricated operation remain unknown. 3.Subsurface stresses, crack initiation and life prediction are interpreted qualitatively from microstructures; no quantitative mechanical or tribo-mechanical modeling links oxide film evolution, hardness gradients and fatigue life. 4.Results are from a laboratory impact rig; direct in-engine validation or long-term field data are not provided, so translation to diverse real engines needs further study.

14	While laser surface melting and conventional electron beam melting have been explored to improve the surface properties of Stellite 12 alloys, HCPEB-based surface modification had not yet been reported or achieved for Co-based alloys. Additionally, Stellite 12 normally does not form amorphous structures under conventional rapid solidification methods (like melt spinning) due to its low carbon content. This paper bridges that gap by demonstrating that the ultra-high cooling rate of HCPEB (10^8 K s^{-1}) forces the surface of a standard, low-carbon industrial Co-alloy into a beneficial amorphous state.
15	1.The work identifies a correlation framework but does not yet provide a full predictive model linking voltage spectra quantitatively to coating properties. 2.It is limited to aluminum and specific nozzle/gas configurations; other materials, geometries, and industrial conditions are not explored. 3.The conclusion suggests the need for nozzle configurations that achieve high velocity with minimal turbulence, implying further design optimization and validation remain open
16	1.Only one Fe-Cr-C composition and one structural steel (SM490YA) are studied; effects of different base steels, other alloying additions (Mo, Nb, etc.) or alternative buffers are not explored. 2.Wear tests are limited to dry sand abrasion and room-temperature impact; no systematic study of impact-abrasive, corrosive, or high-temperature wear, though such conditions are relevant in industry. 3.Microstructural quantification focuses on XRD-based phase fractions and crystallite size; there is limited quantitative fracture mechanics or modeling to link local microstructure (carbide morphology, MA matrix properties) to crack initiation and delamination under service loads. 4.Field validation is reported for a single plant and duty (12 TCD, 45 days); broader industrial statistics and economic analysis (cost vs life extension across different mills) are not provided.
17	Long-term wear performance of buffer-layer systems under industrial operating conditions (e.g., mining, cement, agriculture) remains unexplored. Influence of different buffer layer compositions and thicknesses on fatigue resistance and thermal cycling stability needs further study. Limited focus on cost-effectiveness and scalability of buffer-layer deposition for large-scale applications.

18	Limited understanding of cyclic impact loading and long-term service performance in demolition shears. Need for drop-weight and cyclic impact tests to complement Charpy results. Influence of dilution effects and microstructural evolution under varying heat inputs requires deeper study. Cost-effectiveness and scalability of austenitic butter layers compared to carbon steel alternatives remain underexplored.
19	While traditional joint-welding research thoroughly evaluates single thermal cycles (like UCHAZ or ICHAZ) and occasional double thermal cycles (like ICCGHAZ), hardfacing creates a far more complex, multi-layered HAZ matrix because beads are deposited side by side and layer upon layer. Prior to this study, subzones subjected to three successive thermal cycles had not been comprehensively isolated or investigated. This paper bridges that gap, showing that the softest triple-heated regions do not automatically act as brittle failure points under dynamic impact conditions, offering a new foundation for industrial hardfacing safety margins.
20	While traditional hardfacing studies extensively document microstructural outcomes for single-pass configurations or low-to-moderate carbide alloy contents, minimal research has isolated the combined effects of multi-layer configurations combined with extreme, over-alloyed carbon-chromium filler chemistry over a large surface area. This paper bridges that gap by establishing a clear relationship between layer-by-layer composition dilution, spatial carbide alignment (texture), and volumetric defect locations. This provides a blueprint for adapting extremely hard, over-alloyed surface treatments for advanced structural or ballistic defense components requiring optimized surface energy absorption.
21	Prior academic research on the wire-arc directed energy deposition (or wire arc additive manufacturing—WAAM) of 420 martensitic stainless steel has been strictly restricted to multi-layer single-wall (single-track) thin structures. However, using WA-DED for actual industrial component restoration requires a complex multi-layer, multi-track layout. This paper bridges the gap by evaluating the complex overlapping thermal history inherent to multi-track WA-DED overlays. Furthermore, it challenges the traditional "higher hardness equals better wear resistance" paradigm by providing empirical proof that balancing structural fracture toughness against macro-hardness is necessary to prevent micro-cracking and optimize performance under low-stress abrasive conditions.

22	Traditional shaft reconditioning predominantly relies on fusion welding methods such as Flux-Cored Wire Arc Welding (FCAW) or Shielded Metal Arc Welding (SMAW). While effective at depositing alloy elements, fusion processes induce significant thermal stress, severe shaft warping/distortion, structural residual stresses, and harmful element vaporization due to excessive melting temperatures.This paper bridges the gap by providing systematic empirical data on solid-state reconditioning via resistance seam welding. Specifically, it fills a critical information void regarding how the triad relationship of intense localized current, electrode compression force, and direct water-quench cooling rates collectively dictate surface topology, macrostructural boundaries, and hardfaced layer purity on large-diameter industrial carbon steel shafts.
23	Prior to this study, numerous research attempts focused on utilizing fusion welding processes (such as SMAW, GMAW, SAW, and laser cladding) exclusively to repair damaged rail heads on standard, un-welded base rails. No prior published literature had specifically evaluated or established a hardfacing/repair schema targeting the localized softened zones and material disparities unique to thermite weld joints in track infrastructure.
	1.Field validation is reported for a single plant and duty (120 TCD, 45 days); broader industrial statistics and economic analysis (cost vs life extension across different mills) are not provided.Only one base steel (S355JR), one plate thickness (10 mm), and a fixed welding parameter set are used; effects of heat input, preheat, and thickness on ballistic response are not mapped. 2.The study considers only Fe14, Fe16, and 307 electrodes; other alloying systems (e.g., Ni-, Nb-modified Fe-Cr-C, different buttering sequences) are not explored. 3.Ballistic tests are limited to normal impact with 7.62×51 mm AP at room conditions; oblique impacts, multiple-hit performance, fatigue from repeated shots, and environmental effects (temperature, corrosion) remain unaddressed. 4.Microstructural–ballistic links are qualitative; there is no detailed fracture mechanics or modeling to quantitatively relate carbide morphology, residual stresses, and failure modes to ballistic limit and damage patterns.
24	Traditional repair and manufacturing methods for high-temperature carbon steel valve bodies face severe limitations. Standard heat treatments struggle to modify the surface microstructure without changing the bulk mechanical properties of the underlying substrate, frequently leading to high residual stress, stress-cracking defects, and premature component failure. Furthermore, conventional studies often evaluate tribological properties under uniform, continuous wear modes at room temperature. This paper directly bridges these gaps by: Engineered a localized, eco-friendly two-step LHT process that dramatically boosts surface hardness and refines grain microstructure without compromising the 16Mn substrate bulk. Unveiling the exact microstructural and oxide-debris mechanics governing Fe-Cr-C-Si alloy performance under complex short-interval intermittent high-temperature configurations

25	Industrial components operating under high-temperature abrasive loads, such as rock wool production rollers, have traditionally depended on expensive cobalt-based special alloys (e.g., Stellite 6) for wear resistance. However, cobalt is scarce, expensive, and complex to process. This paper bridges the gap by proving that common, low-cost martensitic stainless steels can serve as viable industrial alternatives. Furthermore, it clarifies the exact compromise between wear resistance and corrosion performance across the X12/X20/X30 steel grade spectrum when applied specifically via multiple-pass, robotic automated MIG welding.
26	Long-term performance of these hardfacings under industrial service conditions (e.g., mining, sieves, cement plants) remains untested. Need for deeper study on microstructural evolution under cyclic loading and oxidation at elevated temperatures. Limited exploration of cost-effectiveness and scalability of complex alloy deposition compared to conventional Fe-Cr-C hardfacings.
27	1.Only three specific PEEK composite formulations and a limited P–V–T range under dry sliding on cast iron are studied; other filler ratios, counterface materials, and lubricated or elevated-temperature conditions are not explored 1.20 2.Microstructural wear mechanisms (e.g., transfer film formation, surface damage characterization) are not detailed, suggesting a gap in linking quantitative Taguchi/ANOVA results to microscale wear processes.
28	1.Tests are limited to lab-scale dry sliding against one steel and surface finish; other counterface materials, lubricated environments, and complex loading (impact, fretting) remain unexplored. 2.Only one SCF and one nano-SiO_2 content (10 vol% and 2 vol%) and one assembly geometry were studied; optimal filler ratios, spatial arrangements, and scale-up designs are not mapped. 3.The proposed mechanistic model (flash temperature, particle release, tribo-sintering) is qualitative; no quantitative temperature, stress, or tribofilm property measurements (thickness, modulus) are provided to fully validate it.
29	1.Need for new Ni–W or tungsten–Ni alloys achieving very high hardness (80–90 HRC) without cracking, suitable for thick overlays in nuclear service 1.15. 2.Limited quantitative models linking dilution, microstructure, and property gradients; recent dilution-coefficient work suggests scope for predictive design. 3.More work needed on fatigue, long-term corrosion/irradiation effects, and in-service performance of modern processes (laser, CMT, LIHC, UNSM-treated coatings).

30	1.Lack of a framework for selecting processes and consumables; few works integrate application conditions, economics and process variables into unified guidelines 1.28. 2.Limited systematic studies linking deposition strategy, residual stress, distortion and cracking to in-service performance; cracking, distortion and stress distribution remain poorly quantified 1.29. 3.Few investigations on high-strength and thermomechanically treated steels as substrates; HAZ behaviour and thermal damage in these advanced steels are under-explored 1.30. 4.Research is heavily concentrated on abrasion; high-velocity impact resistance and weight-efficient hardfacing are emerging but sparsely studied areas ation under service loads.
31	While past literature separately addresses individual welding parameters or specific alloy behaviors, this review bridges a critical gap by providing a unified comparative analysis that links chemical consumable designs, multi-energy process selection, and post-deposition performance metrics. Furthermore, it highlights existing voids in current research, such as the need for standardizing high-entropy alloy hardfacing formulas, establishing predictive machine-learning simulations for weld-pool solidification, and optimizing the automated structural path design of multi-layer buffer coatings to completely prevent stress-induced cracking in heavy industrial applications.

4. Future scope

1. Flux-Cored Wire Arc Welding (FCAW) or Shielded Metal Arc Welding (SMAW). Needs to be optimized by using optimization technique.
2. Welding electrode Composition, Deposition (nickel molybdenum), Welding Pattern combination needs to be varied to obtained better result.
3. Hardafced material needs to be tested in actual working conditions in laboratory in presence of impurities, corrosive medium, and other environmental parameters.
4. Wear analysis needs to be done in software with the introduction of new material properties matching the hardfaced material properties.
5. Field Validation needs to be done for results.

5. Conclusion

Heart facing is very effective surface treatment process to improve performance and surface hardness of machine parts that are generally subjected to wear impact and corrosion had facing provides low cost alternative to one components and enhance they are life it is also suitable for Complex components.

As deposition technologies and material sciences advance, the hardfacing industry is entering a new era of growth, bringing forward a wealth of fresh development opportunities. While extensive literature has historically mapped out various hardfacing processes, material formulations, and basic metallurgical behaviors, several critical areas still demand deeper academic and industrial investigation. Specifically, future research must shift focus toward optimizing complex hardfacing deposition strategies, mitigating thermal damage in sensitive high-strength steel substrates, mapping exact residual stress distributions, and uncovering the underlying mechanisms of stress-induced cracking. By addressing these foundational gaps, upcoming studies can significantly push the boundaries of industrial wear protection.

6. Research Gaps in Hardfacing

Hardfacing requires a comprehensive understanding of the industrial application, operating condition, and economics to select suitable methods and materials. While there are wide range of choices for hardfacing alloys and processes, there is a lack of work in the literature that provide a framework for understanding the selection criteria of such materials and processes. Additionally, there is a gap in the literature when it comes to forming a comprehensive understanding of the relationship between various process variables and their influence on the quality of surface deposits. A thorough understanding in these aspects can help develop strategies to address issues during depositions and avoid common mistakes in hardfacing processes.

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