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REVIEW

Enhancing the Tribo-Mechanical Properties of AISI 304 Steel Using Cladding Techniques: A Review

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ABSTRACT

AISI 304 steel has limited use in several applications because of its high friction coefficient, insufficient hardness, and inadequate resistance. To wear. Enhancing the tribological and mechanical characteristics of the material can be enhanced by applying a coating to its surface. Cladding, a surface modification method, is employed to form layers on the substrate with improved biocompatibility, durability, resistance to high-temperature oxidation, and mechanical strength. Proper material selection, along with appropriate cladding techniques and process parameters, is crucial for achieving these enhanced properties. Hard transition metals, metal matrix composites, alloys, ceramics, high-entropy alloys, nano-composites, rare earth oxides, and solid lubricants are frequently used to coat AISI 304 steel. The application of these coatings is to boost the hardness, wear resistance, corrosion-resistance, and extend the lifespan of steel. This study reviews the results of widely-used wear-resistant cladding methods applied to AISI 304 steel surfaces, while examining key functional claddings in detail. Contemporary problems and future perspectives are also reviewed, with a particular emphasis on identifying facts and technological gaps and proposing future research possibilities. It is recommended that future advancements in wear-resistant cladding should emphasize smart manufacturing techniques, optimize microstructural configurations, and develop numerical simulations for cladding processes to enhance toughness and hardness.

1. INTRODUCTION

Cladding is an efficient method for enhancing the surface properties of metallic and non-metallic parts by forming a high-quality coating of materials [1–3]. Heat sources with high energy, such as lasers, electron beams, and electric-arc welding techniques, have been successfully used to achieve strong metallurgical bonds between the cladding and substrate materials [4–5]. Common cladding techniques such as laser cladding (LC), tungsten inert gas (TIG) cladding, plasma transferred arc (PTA) cladding, and high-velocity oxygen-fuel (HVOF) cladding, are widely applied in industry to coat surfaces with metals, ceramics, or a combination of both [6–9].

Stainless steel AISI 304 is frequently selected for producing machine parts, utensils, and structural elements due to its durability and excellent resistance to corrosion [10]. Its mechanical properties and durability in harsh environments make it suitable for use in variety of industries, such as nuclear and chemical industries, food processing equipment, petrochemical industries, condenser tubing, vapor lines, and heat exchangers [11-13]. However, the use of austenitic steel like AISI 304 is limited in applications where components face adhesive and abrasive wear, such as in agricultural and mining equipment, rock excavation tools, and dies used in manufacturing. Carbon may be added to stainless steels to boost their hardness, but doing so often decreases their ductility and degrades their overall performance [14]. Heat treatment also proves ineffective in hardening austenitic steel, as the process leads to the formation of chromium carbide (Cr23C6) along grain boundaries, depleting the steel of chromium and reducing its corrosion resistance [15]. Hard ceramic granules such as tungsten carbide (WC), titanium carbide (TiC), and silicon carbide (SiC) can be added to the surface of austenitic steel to improve wear resistance by forming a composite clad layer that increases hardness. Various coating techniques have been explored to apply hard, wear-resistant coatings to steel substrates [16-18].

Various surface modification techniques have been employed for producing claddings on AISI 304 steel surfaces, as illustrated in Fig. 1. These techniques include metal inert gas (MIG) cladding, tungsten inert gas (TIG) cladding, laser cladding, and plasma arc cladding. The entire cladding process is presented in a flow chart format, with Fig. 2 providing a step-by-step breakdown of how the cladding layer is created on the substrate [18]. Initially, the surfaces were ground using sandpaper, and any organic residues were cleaned off with alcohol. Following that, a paste made of cladding powders and polyvinyl alcohol was applied onto the substrate with appropriate thickness to generate a green coating layer. Heat is then applied using different ways (as indicated in Fig. 1) to melt the powder; produce cladding with improved tribo-mechanical properties.

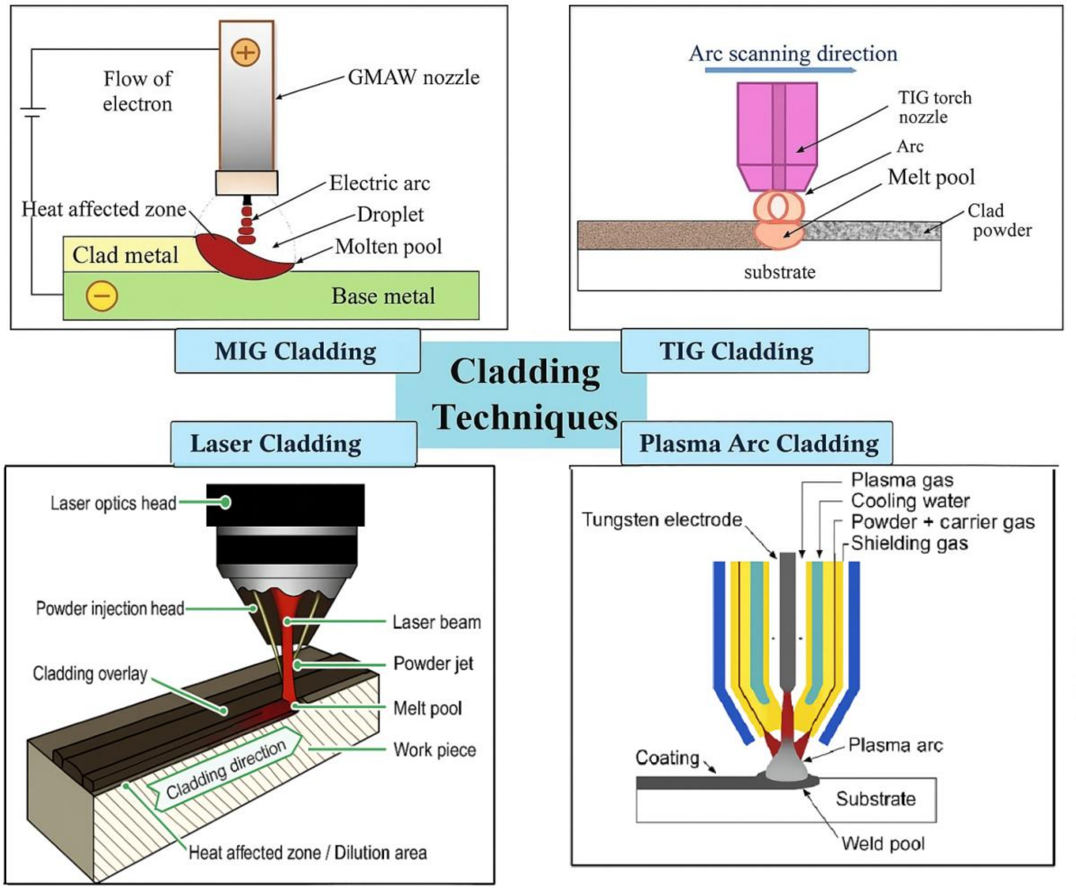

Fig. 1. Cladding techniques for AISI 304 steel substrate.

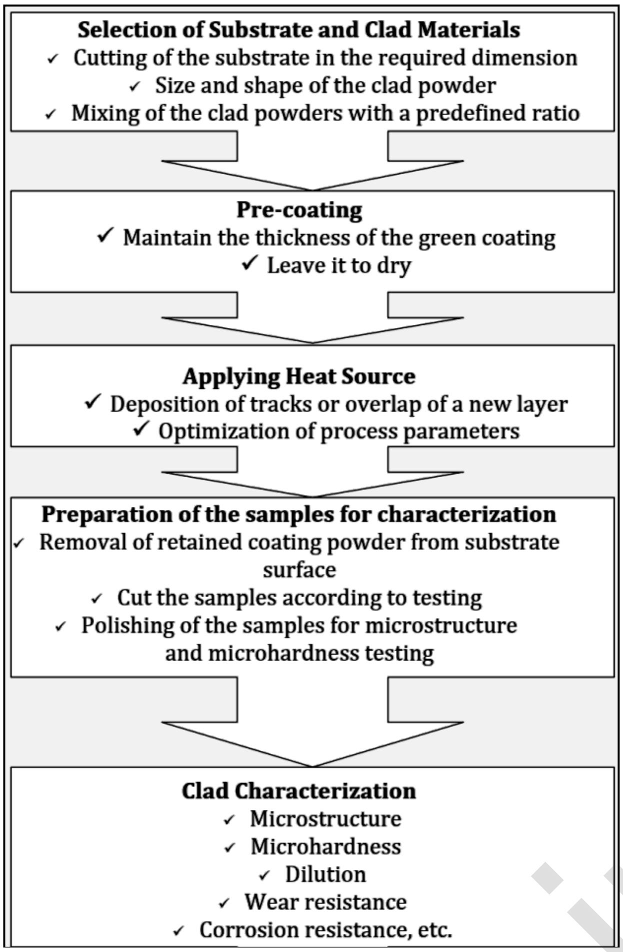

Fig. 2. Flow diagram illustrates the techniques used to create the cladding layer on a substrate.

Table 1 presents the various cladding techniques for AISI 304 steel investigated by earlier researchers. It also lists their corresponding coating methods, key outcomes and research limitations of the studies. Among these, laser cladding has been identified as particularly advantageous for creating dense microstructures and strong metallurgical bonds with substrates. Researchers have extensively investigated the effects of laser cladding on AISI 304 steel to enhance its resistance to wear, high-temperature oxidation resistance, and biocompatibility. Recent progress in this field has focused on optimizing process parameters, refining cladding materials, and achieving specific material properties. However, challenges remain in the cladding of AISI 304 steel.

This article presents a comprehensive overview of surface modification techniques for AISI 304 steel using cladding techniques. It focuses on the benefits and uses of various cladding methods, as well as how different process parameters affect the microstructure and surface properties of the final clad layer. Additionally, the study discusses how optimizing process variables can improve the overall quality of cladding. This review serves as a useful resource for researchers in choosing appropriate coating powders and process parameters for thick cladding applications, and it also outlines potential future trends in this field of study.

Table 1. An overview of the cladding techniques used on AISI 304 steel.

Cladding Method	Coating/ Clad materials	Findings/ Results	Limitations	Authors (Ref.)
Laser Cladding	Titanium boride	Significantly enhancing wear resistance. Hardness improved up to 900HV (≈4.5 times increased)	Corrosion performance not analyzed	Majumdar et al. [11]
Plasma Arc Cladding	Ni–Cr–Si–B	Significantly enhancing micro-hardness (≈3.5 times increased)	Wear and corrosion performance not analyzed	Sudha et al. [19]
Laser Cladding	TiB2–TiC–Al2O3	Wear-rate reduced by 60% with respect to the substrate	Oxidation resistance not explored	Masanta et al. [16]
Laser Cladding	WC + Ni + NiCr	Produced fine-grained stainless steel with significantly enhancing micro-hardness (≈6 times increased)	Wear and corrosion behavior not studied	Anandan et al. [20]
Plasma sprayed	WC–Co	Wear-resistance improved nearly five times with respect to the substrate	Corrosion behavior unaddressed	Balamurugan et al. [21]
Plasma Arc Cladding	Ti–N–O	Hardness improved up to 1600HV (≈8 times increased)	Wear behavior unaddressed	Hsu et al. [22]

Thermal Spray	Ni-Base	Corrosion rate decreased by 50% in HCl solution	Wear behavior unaddressed	Sharma et al. [23]
Plasma sprayed	Hydroxyapatite-silicon oxide	Corrosion rate decreased by 60%	Mechanical strength and bonding strength unaddressed	Singh et al. [24]
Plasma Arc Cladding	TiAlN	Erosion rate reduced by 40% compared to the substrate	Wear behavior unaddressed	Grewal et al. [25]
Laser Cladding	Al2O3	Hardness increased to 600HV (≈3times over the substrate)	Effect of coating thickness on adhesion not examined	Xu 2014 [26]
Laser Cladding	TiC	Micro-hardness increased from 210HV to 1100HV	Did not explore resistance to wear	Sahoo et al. [27]
Laser Cladding	TiC	Hardness improved by 10 times as compared to the substrate	wear resistance not analyzed	Ushashri et al. [14]
Electrical discharge coating	TiC-Fe cermets	Hardness improved by 10 times as compared to the substrate	Tribological performance not investigated	Algodi et al. [28]
TIG cladding	TiC-Ni	Wear rate decreased by 70 times and hardness improved by 4.5 times	Oxidation and corrosion resistance not investigated	Sahoo et al. [29]
TIG cladding	TiC-Inconel825	Wear rate decreased by seven times and hardness improved by 5.5 times	Oxidation and corrosion resistance not investigated	Saroj et al. [30]
Thermal Spray	WC-CrC	Wear rate decreased by 65% compared to the substrate	Corrosion resistance not studied	Hajare et al. [31]
Laser Cladding	Tribaloy 400	Significantly enhancing wear resistance. Hardness improved up to 850HV (≈4 times increased)	Corrosion resistance not studied	Lin et al. [32]
Plasma Arc Cladding	TiC/CaF2/γ-Ni	Hardness improved by 5.5 times and friction coefficient reduced by 40%	Corrosion resistance not studied	Liu et al. [33]
Plasma Arc Cladding	Al2O3	The findings indicated that the porous coating increased and hence damping capacity improved by 35% over the substrate	Corelation of damping with coating thickness or porosity not investigated	Sachidananda et al. [34]
TIG cladding	Ni-201	Hardness improved by 1.5 times and corrosion rate decreased by 50%	Tribological performance not investigated	Shi et al. [35]
Magnetron sputtering	TiN	Hardness improved by 8 times and friction coefficient reduced to 0.35	Corrosion resistance not studied	Xi et al. [36]
Laser Cladding	AISI316	Dilution ratio reduced to 10%	Mechanical and corrosion performance not quantitatively analyzed	Apolinario et al. [37]
Laser Cladding	Ti and W	Resistance to wear of the coating was enhanced and hardness improved from 230HV to 900HV	The effect of multi-layer deposition not discussed	Dong et al. [38]
Sandblasting	Ni	Corrosion rate decreased by 45% in hydrochloric acid	Mechanical performance not quantitatively analyzed	Li et al. [39]
Laser Cladding	AlCrFeNi2W0.2Nbx	The microhardness improved by 4.5 times and wear rate reduced by 70%	Tribological behavior at elevated temperatures not studied	Liang et al. [40]
HVOF Spraying	NiCrSiB and Al2O3	Wear resistance improved by 1.6 times and erosion rate reduced by 25%	Adhesion and fatigue properties not investigated	Praveen et al. [41]
Laser Cladding	NiCrBSi	Microhardness of coating 780HV (≈4 times improvement)	Corrosion aspects not investigated	zhang et al. [42]

Thermal Spray	Ti/TiN/TiSiN	Coefficiat of Friction reduced by 80% and wear resistance by 18.7 times	Long-term oxidation and fatigue behavior not studied	Alanagh et al. [43]
TIG cladding	Ni-Cr-B-Si	The microhardness improved by 4.5 times with dilution less than 8%	Tribological behavior not studied	Balaguru et al. [44]
HVOF-sprayed	Ni-20Cr2O3	Wear loss decreased by 55%	Oxidation and corrosion resistance not analyzed	Bansal et al. [45]
Laser Cladding	Stellite 12 and Ti/B4C	Microhardness increased upto 650HV and wear rate decreased by 50%	Oxidation and corrosion resistance not analyzed	Cheng et al. [46]
Plasma Arc Cladding	NiAl-Al2O3 + TiB2	Microstructure analysis revealed strong bonding between coating and the substrate, achieving hardness four times greater than the substrate	No corrosion or thermal cycling studies reported.	Imak et al. [47]
Laser Cladding	Ni60-TiC-WS2	Hardness increased to 302HV and COF reduced by 30%	Oxidation and corrosion resistance not analyzed	OuYang et al. [48]
Laser Cladding	Hastelloy C276TM alloy	Hardness increased to 850HV and wear loss reduced by 40%	Oxidation and corrosion resistance not analyzed	Rivero et al. [49]
TIG cladding	TiC–Ni	Hardness increased to 950HV and wear rate 70 times lower than the substrate	Corrosion and fatigue studies were not included.	sahu et al. [50]
TIG cladding	Inconel 825	Hardness increased by 5 times compared to the substrate	High-temperature wear and corrosion not examined	Saroj et al. [51]
TIG cladding	WC-10Co-4Cr	Hardness improved by 1200HV and wear-rate reduced by 60%	The effect of multilayer or overlapping tracks not analyzed	Singh et al. [52]
Cold Metal Transfer	Nickel-based	Hardness increased by 3 times and wear loss decreased by 50%	Corrosion and erosion resistance not explored.	Tang [53]
Magnetron Sputtering	AlFeCrNiMo	Friction coefficient reduced by 40% and corrosion rate dropped 50%	Mechanical performance not quantitatively analyzed	Zeng et al. [54]
Laser Cladding	WC	Hardness enhanced to 1100HV and COF reduced from 0.65 to 0.25	Fatigue and corrosion performance not reported	Chakraborty et al. [55]
Laser Cladding	Colmonoy-6 and Stellite-6	Wear resistance improved by 49 times and hardness incresed to 950 HV	Corrosion and thermal fatigue behavior not discussed	Jeyaprakash et al. [56]
Laser Cladding	Ni60-Ti3SiC2	COF decreased from 0.6 to 0.3 and hardness increased to 900HV	Oxidation resistance not evaluated	Liu et al. [57]
Laser Cladding	CoCrMoSi	Hardness increased from 220HV to 850HV and wear-rate reduced by 60%	Corrosion and fatigue behavior unaddressed	lu et al. [58]
Laser Cladding	Tribaloy T-700, PAC 718 and MEC 41- C	Hardness improved to 1000HV (≈5 times that of the substrate)	Corrosion and fatigue behavior unaddressed	More et al. [59]
Laser Cladding	NiCoCrAlY	Oxidation rate reduced by 35%	Long-term cyclic oxidation tests unaddressed	Nie et al. [60]
HVOF spraying	WC–CoCr, WC–Ni, WC–Cr3C2–Ni	Abrasive wear resistance increased by 4 to 90 times and hardness improved to 1200HV	Corrosion and fatigue behavior unaddressed	Qiao et al. [61]
TIG cladding	WC-10Co-4Cr	Hardness increased to 1150HV and wear rate reduced by 60%	Fatigue and corrosion performance not analyzed	Singh et al. [62]

Laser Cladding	WC-Cr	Hardness increased to 1050HV and dilution minimized to less than 8%	Coating porosity and bonding strength not analyzed	singh et al. [63]
Laser Cladding	AISI 316	Dilution controlled below 10% with formation of cellular-dendritic structure	Mechanical and wear not analyzed	Torres et al. [64]
Laser Cladding	Al2O3@Ni	Hardness increased to 917HV and wear rate reduced by 65%	Corrosion behavior not analyzed	Zhang et al. [65]
MIG Cladding	Ni–Cr–Si–B	Wear resistance increased by 20 times and microhardness increased by 3 times	Long-term oxidation and corrosion tests not performed	Zunake et al. [66]
Laser Cladding	FeCrAlNbNi	Hardness increased to 950HV and wear rate reduced by 70%	Corrosion and oxidation resistance not analyzed.	Cui et al. [67]
Plasma Arc Cladding	Ni-WC	Hardness increased to 1200HV and wear resistance improved by 2.5 times	Corrosion and oxidation resistance not analyzed	Fan et al. [68]
Laser Cladding	CoCrNiMo and CoCrNiMoBC	Hardness increased to 1000HV, wear rate decreased by 60% and corrosion rate decreased by 50%	Fatigue and oxidation properties not examined	Jiang et al. [69]
Plasma Arc Cladding	NiCrBSi and NiCrBSi-WC	Slurry abrasive resiatance to wear increased by 65% and hardness increased to 850HV	High-temperature wear behavior not assessed	Kalyankar et al. [70]
Laser Cladding	NiCoCrAlY	Oxidation resistance decreased by 30%	Mechanical performance not quantitatively analyzed	Li et al. [71]
Laser Cladding	stellite-6	Hardness increased to 950HVand wear rate decreased by 45%	Thermal fatigue and corrosion not investigated	Singh et al. [72]
Laser Cladding	TiN	Hardness increased by 6 times that of the substrate	Thermal fatigue and corrosion not investigated	Tyagi et al. [73]
Microwave Cladding	Ni-CrC	Micro-hardness increased by approximately 47.6%	Thermal fatigue and corrosion not investigated	Dwivedi et al. [74]
Microwave Cladding	Ni-Si-La2O3	COF reduced from 0.6 to 0.3 and wear rate decreased by 40%	Oxidation and corrosion behavior not investigated	Dwivedi et al. [75]
Plasma Arc Cladding	Stellite 6	Hardness increased to 900HVand corrosion decreased by 50%	Adhesion strength and wear under elevated temperatures not evaluated	Sarangi et al. [76]
Laser Cladding	FeCoCrNiTi (High-Entropy Alloy)	Hardness improved to 780HV (≈3.5times that of the substrate) and corrosion decreased by 60% with refined microstructure	Long-term corrosion–wear behavior not investigated	Zheng et al. [77]
Laser Cladding	Fe60	Hardness increased from 420HV to 720HV and wear-rate decreased by 45%	Wear and corrosion mechanisms post-heat treatment not investigated	Du et al. [78]
Gas Tungsten Arc (TIG) Cladding	CoCrFeMoNi	Hardness increased to 950HV (≈4 times that of the substrate) and corrosion resistance increased by 50%	Effect of multi-pass overlapping and residual stress not analyzed	Liu et al. [79]
Laser Cladding	Stellite 12	Hardness increased to 880HV, friction coefficient reduced by 35% and wear rate decreased by 55%	Oxidation and fatigue life under cyclic loads not evaluated	Wang et al. [80]
Argon Arc Cladding	TiB2–CoTi Composite	Hardness increased to 1200HV, wear rate reduced by 60% and COF reduced by 40%.	High-temperature oxidation and corrosion not evaluated	Kumar et al. [81]

Gas Tungsten Arc Cladding	CoCrFeNi + Sn/Ti	Hardness increased to 1000HV and wear resistance increased by 65%	Tribocorrosion and oxidation behavior not studied	Jaturapronperm et al. [82]
Microwave Cladding	Ni + TiO2	Hardness increased to 750HV (i.e. 3.5 times that of the substrate) and COF reduced by 40%	Corrosion-oxidation behavior not studied	Sharma et al. [83]
Microwave Cladding	Ni + 15% SiC	Hardness enhanced by 60% and wear resistance increased by 45%	Adhesion strength and oxidation not studied	Dwivedi et al. [84]
Microwave Cladding	Si + Ni + TiO2	Hardness increased by 720HV and wear resistance increased by 50%	Thermal fatigue and corrosion behaviour not explored	Dwivedi et al. [85]
Laser Cladding (Magnetic Field-Assisted)	Nickel Alloy GH3625	Hardness increased by 400%, friction coefficient reduced by 30% and wear-rate decreased by 50%	Thermal fatigue and corrosion behaviour not explored	Shi et al. [86]

2. SELECTION OF CLADDING MATERIALS FOR OPTIMAL COATING PERFORMANCE

An important part of the coating process is selecting the right cladding materials. Insufficient adhesion to the substrate and failure might be caused by improper material selection. Assessing how closely the coating's chemical and physical characteristics match those of the substrate is crucial when choosing coating materials. The elasticity modulus, melting temperature, wettability, and coefficient of thermal expansion are important physical properties that affect coating performance. These characteristics should be comparable or closely aligned between the coating materials and the substrate. Problems including delamination, high thermal residual stress, poor bonding, cracking, void formation, segregation, uneven coating, and substrate evaporation from overheating might arise if there is a significant mismatch. Therefore, careful material selection is critical to ensuring optimal hardness, wear resistance, and corrosion protection in surface engineering. The following sections will cover various approaches to designing and selecting coating materials.

2.1 Applying metallic, ceramic, and composite coatings to enhance mechanical performance

Metal coatings and alloy layers are often applied to enhance the characteristics of materials like austenitic stainless steel. Combinations of two or more metallic elements, known as alloys, usually have better qualities than the individual metals. Common coatings for austenitic stainless steel include transition metal alloys, Ni-Ti (Nickel-Titanium) alloys, and other hard metal alloys. For example, Saroj et al. [51] applied the gas tungsten arc (GTA) coating method combined with a pre-placed powder technique to deposit an Inconel 825 cladding on AISI 304 steel. The upper and central regions of the cladding exhibited a consistent cellular microstructure, while the interface displayed a columnar dendritic pattern. The cladding layer achieved hardness between 300 and 350 HV, which is significantly higher than the base material's 220 HV. This enhancement also led to improved wear resistance against a hardened steel ball. Similarly, Zeng et al. [87] coated AISI 304 steel with a layer of Ni-Ti alloy by GTA cladding. This layer enhanced the corrosion and cavitation-resistance of the material, particularly in marine environments. Two thicknesses, 2 mm and 1.2 mm, were examined, with the thicker layer showing better performance. The development of an oxide film contributed to enhanced resistance to both wear and corrosion, with the Ni-Ti coating outperforming the uncoated stainless steel. In another experiment, Krishnakumar and Saravanan [88] used GTA surfacing on AISI 304 coated with Ti-W alloy layer under argon and nitrogen atmospheres. The hardness of the cladding reached 1968 HV in argon and increased to 2139 HV in nitrogen, both significantly higher than the 277 HV of the base material. The development of intermetallic compounds and a refined microstructure was associated with this increase in hardness. Additionally, both layers showed better wear and corrosion-resistance than the stainless steel substrate, particularly in Hank's salt solution, and the wear-rate in nitrogen was lower than in argon. Lastly, Shi et al. [89] fabricated Ni-Ti alloy layers on stainless steel using the TIG surfacing technique, with and without a Ni interlayer. The Ni interlayer improved cavitations erosion resistance by reducing the formation of brittle Fe2Ti phases and limiting crack propagation. As a result, the Ni-Ti alloy with the interlayer had better resistance to cavitations-erosion compared to the alloy layer without the interlayer, due to its enhanced elasticity and ability to suppress crack growth.

Ceramic materials are known for their extreme hardness due to their covalent bonding properties. When applied as a coating on stainless steel substrates, they enhance both the micro-hardness and resistance to wear of the surface. Ceramics used for such coatings include oxides, carbides, nitrides, and borides, with common materials being SiC, TiC, WC, TiB, TiN, TiO2, and Al2O3. A TIG torch-assisted coating approach was used in research by Buytoz and Ulutan [90] to apply SiC ceramic powder to AISI 304 austenitic steel. They found that at lower powder concentrations, surface hardness ranged between 550 and 750 HV, which was connected to the formation of dendrites. With increased powder content, a hypereutectic microstructure developed, resulting in hardness values between 890 and 1210 HV due to the formation of M7C3 carbide. Rasool and Stack [91] used the GTA surfacing process to coat austenitic stainless steel with a TiC ceramic layer, observing improved micro-hardness and resistance to wear over the base material. Similarly, Sahoo et al. [92] applied a TiC coating on AISI 304 SS through the GTA method. In comparison to the substrate, they found that a TiC layer with improved hardness and resistance to wear was created at a lower current and higher scanning speed. Slower scanning and greater currents, however, diminished these characteristics.

Composite materials are made up of two distinct components: the matrix and the reinforcement. By combining a softer reinforcement phase with a harder one, the resulting composite material can display superior characteristics such as improved hardness, wear resistance, and stiffness. Generally, ceramics like oxides, carbides, nitrides, and borides are used as reinforcements, while metals like nickel, cobalt, iron, aluminum, titanium, copper, molybdenum, chromium, and zirconium act as matrix elements, particularly for forming composite coatings on stainless steel. In their study, Kumar and Das [93] employed a gas tungsten arc (GTA) torch to coat AISI 304 SS with a mixture of cobalt and silicon carbide powders. The resulting coating featured phases including FeSi, SiC, CoSi2, CoSi, Fe2Si, and cobalt, achieving hardness values between 374 HV and 650 HV, significantly higher than the hardness of the substrate (i.e. 190 HV). Additionally, the coated layer exhibited much better resistance to wear than the stainless steel base material. Singh et al. [52, 94] created a composite coating using tungsten carbide (WC) as the reinforcement within a cobalt-chromium matrix, applied via a tungsten inert gas (TIG) cladding method on AISI 304. The findings demonstrated that the hard WC phase in the Co-Cr matrix was responsible for the better surface hardness and resistance to wear of the coated layer when compared to the original material. Kilic et al. [95] created a surface layer reinforced with silicon carbide in a nickel-boron-silicon matrix on AISI 304 SS using the GTA coating technique. This coating exhibited increased surface hardness and wear resistance due to the presence of dissolved silicon carbide within its dendritic microstructure. Hard metal carbides and borides were added to the SiC-reinforced nickel-boron-silicon metal matrix composite (MMC) to greatly increase its hardness and wear-resistance when compared to the AISI 304 substrate. The highest recorded hardness was 590 HV, which is 2.5 times higher than the substrate's. A composite coating consisting of titanium carbide with Inconel 825 matrix was applied on AISI 304 using GTA cladding by Saroj et al. [30]. They investigated how the coating's microstructure and mechanical performance were affected by the TiC content, coating thickness, and current. The nickel-based matrix exhibited excellent wettability with TiC, leading to strong metallurgical bonding. The coated layers reached a hardness of 1100 HV and showed a wear rate nearly seven times lower than the uncoated austenitic stainless steel. Sahoo and Masanta [96] produced a composite coating using nickel and titanium carbide powders on AISI 304 through GTA cladding. X-ray diffraction established the presence of titanium carbide and nickel-titanium intermetallic compounds. The coated surface demonstrated superior hardness and resistance to wear compared to the substrate, with nickel contributing to improved thermal and electrical conductivity. This resulted in a stable arc during the cladding process, reduced energy demand for melting the powders, and enhanced bonding strength with the substrate. The coating hardness was recorded at 1300 HV, while its resistance to wear was 70 times greater than that of AISI 304. Key parameters like current and scanning speed significantly influenced the tribo-mechanical qualities of the coating. Heidarshenas et al. [97] developed a $TiC/Cr_{23}C_6$ cladding on AISI 304 using TIGC with Ti-cored wire and graphite powder. They found that higher currents increased the hardness and resistance to wear, while higher scanning speeds decreased them. The coating achieved a micro-hardness 4.5 times higher than AISI 304. The resistance to wear also improved by a factor of 4.5 compared to the substrate. This enhancement was linked to the formation of TiC and $Cr_{23}C_6$ phases. The coated layer exhibited a coefficient of friction of 0.35, which is nearly half that of the substrate material.

2.2. Applying nano-composite and high-entropy alloys for superior performance

Nano-composite refers to a composite material that includes at least one phase at the nanoscale, ranging from 1 to 100 nanometers. Typically, the reinforcing phases utilized for coatings are ceramic materials, such as oxides, carbides, borides, and nitrides. These reinforcement materials are incorporated as nanoparticles within the coating formulation to create nanocomposite coatings on metallic substrates. The inclusion of nanomaterials disrupts the movement of dislocations within the coating, leading to a reduction in grain size and an enhancement in the coating's properties and strength. Nanocomposite coatings offer superior characteristics compared to coatings made from Ni, Co, and Fe alloys. They exhibit high hardness, impressive fracture toughness, and strong resistance to corrosion, oxidation and wear, particularly under elevated temperatures. According to Singh et al. [52, 94], a nanocomposite coating comprising nano-WC and mixed powders of Co and Cr was applied to AISI 304 using the GTA coating technique. The results indicated that this coating achieved the highest micro-hardness and resistance to wear, attributed to the presence of WC nanoparticles within the Co-Cr matrix. The stand-off distance, scanning speed, and applied current were the main determinants of the tribo-mechanical properties, whereas the argon flow rate had minimal impact on the microstructure and mechanical features. The applied current plays an important part in improving the microhardness and resistance to wear of the nanocomposite coating.

High entropy alloys are multi-element systems that consist of five or more different chemical elements, each contributing between 5% and 35% to the overall composition. This innovative approach to alloy design offers unique benefits. Due to features such as lattice distortion, high entropy effect, etc., these alloys exhibit excellent mechanical properties, as well as increased resistance to wear, corrosion, and oxidation at elevated temperatures. The high mixing entropy in high entropy alloys decreases the Gibbs free energy of chemical reactions. A reduction in Gibbs free energy leads to enhanced chemical reactivity of the materials, particularly as temperature rises. Huo et al. [98] applied a high entropy alloy coating to AISI 304 using a TIG torch coating technique with a mixture of Co-Fe-Ni-Cr-Mn-Nb powders. Their research identified a microstructure featuring a face-centered cubic (FCC) solid solution alongside a Nb-enriched Laves phase. During dry sliding testing, resistance to wear of the coating was noticeably higher than the base materials, mostly because of the hard Laves phases and the FCC solid solution. Furthermore, the FCC solid solution's grain development was inhibited by the coating's Nb addition. While the FCC phase increases toughness and lowers the risk of brittle failure, the Laves phase improves resistance to wear and plastic deformation. Consequently, under dry sliding circumstances, the high-entropy alloy coating exhibits remarkable resistance to wear due to the combined action of the Laves phase and FCC structure.

2.3. Applying solid lubricant coatings for enhanced durability

Solid lubricants play a crucial role in minimizing the friction coefficient and improving the resistance to wear of coatings. Their effectiveness as antifriction and anti-wear agents is attributed to their layered, hexagonal structure. These lubricants possess characteristics such as low density and low shear strength, which contribute to a decreased friction coefficient. Commonly used solid lubricants as additives in coatings include MoS_2, WS_2, BaF_2, h-BN, graphite, and CaF_2. Sahoo and Masanta [29] utilized a GTA torch to deposit a layer of TiC-Ni metal matrix composite (MMC) with CaF_2 onto austenitic stainless steel. When tested against a hardened steel equivalent, they discovered that the coating had a lower friction coefficient and better resistance to wear than the underlying material. The self-fluxing properties of CaF_2 contribute to better heat retention in the coating area, serving as a solid lubricant and enhancing the tribological characteristics of the coating. The coating's hardness was recorded at 800 HV, but it decreased as the proportion of CaF_2 increased. Additionally, a higher dilution rate caused a decrease in coating hardness when the applied current was increased, while the CaF_2 content remained constant. At a CaF2 content of 5 wt%, the coefficient of friction was recorded at 0.7, which decreased to 0.4 as the CaF2 content increased.

3. MICROSTRUCTURAL BEHAVIOR OF THE COATINGS

The chemical composition of both the cladding material and the substrate has a significant impact on the coating's microstructural properties. Furthermore, the conditions established during the laser cladding process influence these microstructural characteristics. Analyzing the microstructure entails determining grain size and shape, the chemical composition of the cladding material, and the direction of grain structures within the heat-affected zone. These factors are vital for evaluating their effects on tribological and mechanical properties. Traditionally, metallographic techniques have been used to analyze the microstructure of these coatings. Several modern technologies are now available for investigating the microstructure and composition of distinct phases inside the coating. These methods include EPMA (electron probe microanalyzer), FESEM with EDS, and TEM, among others. Samples were polished using abrasive sheets to achieve a near-mirror finish, followed by diamond polishing. The microstructure was revealed through etching with either vilella or nital solution and subsequently examined under an optical microscope (OM). A significant portion of research focuses on microstructural characteristics, with some recent studies specifically investigating carbon nanotube coatings.

4. ANALYSIS OF TRIBO-MECHANICAL CHARACTERISTICS OF THE COATINGS

The tribo-mechanical examination of the modified surface involved measuring microhardness and evaluating tribological performance.

4.1 Microhardness analysis

"Hardness" refers to a material's resistance to plastic deformation produced by processes such as indentation, scratching, and friction. To determine microhardness, a Vickers indenter was utilized in combination with a microhardness testing instrument. It is vital to note that around 70% of the study on laser cladding methods focuses on understanding the hardness characteristics of the coatings. Majumdar et al. [11] studied surface alloying as an approach for improving surface features while preserving the material's bulk properties. They utilized a laser to precisely heat titanium boride (TiB_2), which was alloyed with SS304 to increase its hardness and resistance to wear. Compared to the substrate AISI 304, which had a hardness of roughly 220 HV, the resulting clad layer exhibited a significant increase in hardness, reaching approximately 350 HV, while the gain in wear resistance was small. Sun et al. [99] used Cr-CrB2 coating powder to coat SS304 substrate using laser surface alloying technique. The results showed significant increases in microhardness, resistance to wear, and corrosion resistance. On a steel substrate, Sahoo et al. [27] applied a TiC-reinforced composite layer using a Nd laser. SEM analysis showed the presence and deposition of TiC particles, and at peak power levels between 1 and 1.5, the coating dimensions were relatively small. The TiC-reinforced layer achieved an average hardness of 1200HV (6-times superior than the substrate). Zhao et al. [100] used a non-transferred arc plasma cladding technique to create a layer of Stellite Ni60 alloy coated on steel. According to the Vickers microhardness tests, the clad layer's maximum hardness was around 800 HV. A TiC-steel composite coating was deposited using argon arc cladding by Sahoo et al. [92] also examined the impact of input current and scan speed on the microstructure and morphology of the coating. At a modest argon arc cladding input current of 60A, the maximum hardness of 1600HV was achieved. Detailed information regarding these hardness-focused studies can be found in Table 1.

4.2 Tribological properties analysis

When two solid surfaces engage in sliding or rolling contact, they experience a process called material degradation, commonly known as surface wear. This is a widespread challenge in various industrial fields. Wear involves multiple factors, including oxidation, abrasion, erosion, impact, and corrosion, either individually or in combination. The pin-on-disk tribometer is recognized as the leading and highly effective device for evaluating the tribological characteristics of materials. Wang et al. [101] examined how rare earth oxides affect the wear performance of Fe-based ceramics produced in situ, discovering an optimal Y2O3 concentration that improved the wear characteristics of the cladding. Tian et al. [102] created a Fe-Si-Mn-Ni-Cr alloy coating on steel using a 6-kW fiber laser through in situ deposition. Their findings indicated that the alloy coating comprised planar, dendritic, and equiaxed crystals, with the coefficient of friction (COF) and wear-rate (WR) being lower than that of SS304. They attributed the increased wear resistance of the coating to its self-accommodating stress feature. Yuan et al. [103] developed a dense WC/Ni-Al coating on the carbon steel using the plasma transferred arc (PTA) process. Their results showed that incorporating Fe into the Ni-Al/WC coating reduced the occurrence of fractures and facilitated the melting of WC particles into uniformly distributed small sizes within the Fe-rich dendritic structure. This even distribution of WC allowed the newly developed NiAl/WC-Fe5 clad layer to achieve superior COF and wear resistance compared to all other coatings tested. Saroj et al. [30] developed a composite coating made of Titanium carbide (TiC) and Inconel825 on steel using argon arc cladding technique. Their results showed that the coated layer's hardness had significantly increased, resulting in a sevenfold decrease in sliding abrasive wear compared to the uncoated steel. This advancement is critical for applications such as canister materials for high-level liquid waste storage and structural components in nuclear settings, where wear is a significant source of material deterioration [66]. The studies are summarized in Table 1.

5. CONCLUSIONS AND FUTURE PROSPECTS

The introduction of innovative cladding designs for AISI 304 steel has successfully tackled the issue of achieving an optimal balance between wear resistance and toughness, a challenge often faced with traditional uniform cladding approaches. These advancements draw inspiration from highly efficient materials. Nevertheless, these new designs are currently limited by their relatively simplistic microstructural configurations and dependence on a single strengthening and toughening mechanism. This may impede possible improvements in resistance to wear, toughness, and hardness. Future research in this subject should focus on overcoming these constraints and discovering creative techniques to increase the resistance to wear of AISI 304 steel.

5.1 Implementation of Advanced Manufacturing Techniques in Cladding

Traditional surface modification procedures are used to increase the resistance to wear of AISI 304 steel by developing coatings with higher toughness and hardness. However, creating coatings with specified spatial patterns is a difficult operation, limiting their industrial applicability. Therefore, there is a need for advanced manufacturing technologies that can create wear-resistant coatings with appropriate shapes and designs. Future study can focus on adapting the hybrid cladding techniques to SS304, as no substantial studies have previously investigated. Investigating laser-induction or similar hybrid methods on SS304 may yield improvements in coating quality, metallurgical bonding, and wear and corrosion resistance [104]. Recently, 3D printing has gained popularity as a feasible method for producing coatings with increased toughness and hardness. This approach allows for exact control over microstructure design, resulting in higher efficiency compared to conventional methods. Furthermore, 3D printing allows for the manufacturing of near-net-shape items, reducing the need for additional material processing and increasing production efficiency.

5.2 Optimization of the process parameters

To develop wear-resistant cladding with improved toughness and hardness, a bionic structural design approach can be employed, focusing on multiscale strengthening and toughening. To optimise coating performance, it is necessary to improve the interface structure, distinct morphologies, diverse elements, and different levels inside the cladding. Additionally, new structural coatings should be designed concurrently with specific application needs and performance standards in mind, aiming to expand the application range of AISI 304 steel coatings.

5.3 Use of numerical simulation technology

Traditionally, material research and development used the "hypothesis formulation followed by experimental validation" technique. However, this method is increasingly time-consuming and labor-intensive in light of the growing industrial demand for innovative materials. With advancements in computer technology, numerical simulation and computation have become crucial for materials research. These techniques can be utilized to analyze the design and mechanical characteristics of coatings, thus overcoming the limitations of experimental setups.

Based on this, the authors outline a technical roadmap for creating wear-resistant coatings with enhanced toughness and hardness on AISI 304 steel surfaces.

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