MATERIALS PHYSICS AND MECHANICS REVIEW

Submitted: September 18, 2023 **Revised:** March 7, 2024 **Accepted:** July 25, 2024

Surface modification by laser cladding: state-of-the-art and future prospects

R. Ranjan [1,2] ✉, **A.K. Das** [2]

[1] Dr. B.C. Roy Engineering College, Durgapur, India

[2] National Institute of Technology, Patna, India

✉ rajeevranjan.br@gmail.com

ABSTRACT

Laser surface modification is an advanced technique utilized for the creation of robust coatings on substrates by melting and fusing pre-placed or blown powder materials. In some instances, multiple coatings are applied to achieve intricate geometries. This method serves the purpose of enhancing substrate surface properties and rectifying surface imperfections. Over the past three decades, laser surface modification has garnered significant attention due to its capacity to process a wide range of materials, because of its high energy density and rapid cooling capabilities. Researchers have extensively explored scientific aspects, including the clad-substrate inter-face, microstructure, chemical composition, mechanical properties, and tribological characteristics of deposited materials, as well as their practical applications. This article primarily focuses on the application of laser surface modification to various substrates using suitable cladding materials. Furthermore, it delves into the survey of modification parameters, such as microstructural refinement, mechanical attributes, and tribological performance, as investigated by previous scholars. Additionally, this article presents the findings of past research endeavors and offers insights into potential avenues for future investigations within the realm of laser surface modification.

KEYWORDS

surface modification • laser cladding • microstructure • microhardness • tribological properties

Citation: Ranjan R, Das AK. Surface modification by laser cladding: state-of-the-art and future prospects. *Materials Physics and Mechanics*. 2024;52(4): 41–51.
http://dx.doi.org/10.18149/MPM.5242024_5

Introduction

Many components of machines used in mining, mineral processing, manufacturing, agriculture, and many other industries need to improve their surface performance under corrosion, wear, fracture, and oxidation environments, which is unable to be satisfied through traditional methods of surfacing and coatings [1]. Due to the effects of corrosion, mechanical components often experience premature degradation and fracture before reaching their intended operational lifespan [2,3]. The wear process contributes significantly to the surface deterioration of these components, leading to increased downtime and elevated production expenses. Various types of wear, such as abrasion, impact, and corrosion, are responsible for this phenomenon. This problem is commonly encountered in the context of agricultural implements, mining machinery, and earthmoving equipment when operating on abrasive surfaces [4]. Tool steels, for example, are widely used in practically all industries to manufacture molds, dies, and other components that are subjected to exceptionally high loads [5]. These tool steels must have good wear resistance, whether they are used for cold or hot operations.

Publisher: Peter the Great St. Petersburg Polytechnic University

Likewise, machinery within the chemical and petroleum sectors grapples with corrosion issues. Consequently, laser cladding emerges as a prime method for improving surface attributes. Laser cladding, an adept surface modification technique, proves invaluable in extending the operational lifespan of both weathered machine components and fresh ones, all while maintaining economical feasibility. To cultivate favorable tribological characteristics, these cladding methods are employed to amalgamate bulk materials with the substrate. In the course of this surface modification procedure, a more durable, wear-resistant material is incorporated, thereby bolstering the longevity of the component or rectifying deteriorated surfaces [6,7].

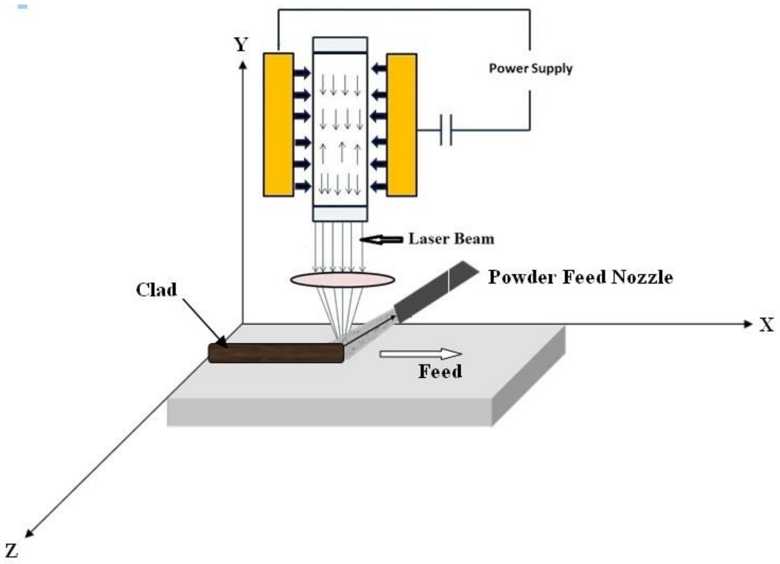

Fig. 1. Laser cladding process by powder injection

Laser cladding is a technique characterized by the fusion of a dissimilar material onto a substrate using a focused laser beam. This process involves selectively melting only a minimal layer of the substrate to establish metallurgical bonding, thereby preserving the inherent properties of the coating material [8,9]. Figure 1 illustrates the process, where a high-intensity laser beam interacts with a metallic specimen while powdered material is introduced over the molten pool. Upon solidification, this procedure results in the formation of a distinct layer referred to as the "clad". This technique uses a concentrated high-powered laser to melt the substrate's thin surface as well as the clad materials while simultaneously producing a new layer of material with specified qualities following solidification. It can produce a 0.3–5.0 mm thick coating onto a substrate, which is joined by a strong fusion bond [10,11]. Some time multi layers of coating are deposited to get complex shape geometry. The clad materials are added onto the substrate employing laser fusion of pre-placed powder or blown powders. To achieve varied qualities, a wide range of powder materials or powder combinations can be efficiently deposited onto the substrates. The deposited layer's microstructure is often exceedingly fine, resulting in excellent metallurgical characteristics. It is possible to attain excellent results, such as enhanced microstructure, mechanical and tribological properties, by selecting suitable clad materials and optimized process parameters [12]. Laser cladding has gained a lot of attention in extensive research over the past three decades because the fast cooling rates and high-density energy make this technique suited for processing a variety of materials [13].

In this paper, we present the numerous research investigations conducted on the subject of laser cladding. The paper provides an overview of cladding processes involving diverse substrates and clad materials, highlighting distinct output parameters. Additionally, it synthesizes research outcomes from previous studies, particularly in the realms of microstructural analysis, hardness assessment, and wear resistance. The comprehensive compilation of earlier research findings is presented in Table 1 for reference. Subsequently, the essential facets of each delineated domain are expounded upon in subsequent subsections. The paper culminates with a discussion of conclusions drawn from the gathered insights and offers perspectives on future directions in the field of laser cladding.

Table 1. A Summary of studies on laser cladding (LC) technology

Authors (year) [Ref.]	Substrate material	Clad materials	Investigations	Variable processing parameters	Research findings
Qian etal. (1997) [14]	AISI 1020	Colmonoy 88 nickel	Microstructure, dilution, hardness, microstructures	Powder feed rate, translation speed	Optimal cladding parameters are revealed to increase hardness and improve the microstructure of the coating.
Haemers etal. (2000) [15]	AISI 316L	Colmonoy 5	Microstructure, dilution		Microstructural analysis of the coating showed the formation of the dendritic and eutectic interdendritic phases.
Sha etal. (2001) [16]	K02600 steel	S42000 stainless steel	Microstructure, wear, microhardness		In comparison to SAW cladding, Laser cladding increased the hardness of coating about twice.
Yao etal. (2006) [17]	Medium carbon steel	CNTs	Microstructure, microhardness, wear	Beam travel speeds, laser power	Resistance to wear of the cladding is increased by three times that of the untreated substrate.
Baldridge et al. (2013) [18]	Inconel 600	Inconel 690	Microstructure, microhardness	Laser power, scanning speed, beam overlap, powder feed rate	Results revealed an admirable metallurgical bond between the substrate and the clad layer with min porosity & minute surface contamination. Higher laser power may produce the best cladding quality with the least amount of porosity and surface imperfections. Suggested optimizing Inconel 690 powder chemistry for future research.
Tanigawa et al. (2015) [19]	304 stainless steel	Ni–Cr–Si–B	Surface roughness, hardness	Overlap ratio	The hardness and roughness of the coating layer inversely depended on the overlap ratio.
Das et al. (2016) [20]	Ti–6Al–4V	Rare earth oxide (Y_2O_3)	Microstructure, microhardness, wear	Laser power, scanning speed	The addition of Y_2O_3 improved the coating's micro-hardness and wear resistance.
Murzakov etal. (2016) [21]	C5140 steel	TaC and WC	Microstructure, wear		The cladding's microstructure and mechanical properties improved as a result of the research. When compared to the substrate, wear resistance is increased by 2–6 times.
Stanciu etal. (2016) [22]	AISI 5140	NiCrBSi, Inconel 718	Hardness, wear		Concerning the substrate, the cladding layers' wear coefficient and hardness increased.
Alam etal. (2017) [23]	AISI 1018	420 martensitic stainless steel	Microstructure, residual stresses, microhardness	Laser speed, power, powder feed rate	The rise in laser power and speed led to an augmentation in both hardness and residual stress levels.
Liu etal. (2017) [24]	Forged 300 M steel	AerMet100 steel	Microstructure, hardness, tensile properties		Results revealed a superb clad-to-substrate metallurgical bond with enhanced mechanical properties.

Riquelme et al. (2017) [25]	AA6082 aluminum	Al/SiCp	Microstructure, mechanical properties		The cladding had better mechanical qualities than the substrate, according to the findings.
Lei et al. (2018) [26]	1Cr13 stainless steel	Carbon fibers reinforced nickel	Microstructure, microhardness, wear, corrosion	Laser scanning speed	Higher laser scanning speeds increase the coatings' wear and corrosion resistance.
Chen et al. (2019) [27]	IN718	Multi-walled carbon nanotubes (MWCNT)	Microstructure		The enhancement of graphene structure within GNSs and CNRs led to an intensified adverse effect on element segregation and the formation of Laves phase in the IN718 superalloy.
He et al. (2019) [28]	Ti-6Al-4V	TiC, CNT	Microstructure, microhardness, wear		According to the findings, the coating had a higher microhardness, a lower friction coefficient, and a much higher wear resistance than the substrate.
Sibisi et al. (2019) [29]	Ti-6Al-4V	CpTi/SiAlON	Microstructure, microhardness		Enhancement in microstructural and hardness properties as compared to the substrate.
Zhao et al. (2019) [30]	H13 mild steel	Cobalt-based alloy	Microstructure, microhardness, wear resistance		Compared Laser cladding with plasma cladding and revealed superior wear resistance and microhardness of the laser cladding.
Hulka et al. (2020) [31]	S235JR steel	WC-Co/NiCrBSi(Ti)	Microstructure, corrosion resistance	Laser power, Ti-contents	The results demonstrated an excellent clad-to-substrate metallurgical bonding with fine microstructure, enhanced microhardness, and reduced Fe penetration from the substrate to the clad.
Spranger et al. (2020) [32]	Tool steel X38CrMoV5	TiB$_2$	Microstructure, hardness		A significant increase in hardness with the implantation of TiB$_2$ particles was found.
Wang et al. (2020) [33]	5CrNiMo steel	TiMoB$_2$, Ti,MoC, Fe$_7$Cr$_7$C$_3$ with Y$_2$O$_3$	Microstructure, wear	Y$_2$O$_3$ contents	The mechanical properties of the cladding were enhanced by adding Y$_2$O$_3$ and got optimum values with Y$_2$O$_3$ content of 2 wt. %.
Zhu et al. (2020) [34]	Inconel 625	NiCrAlY/Ag$_2$O/Ta$_2$O$_5$	Microstructure, microhardness, Friction, wear performance		Revealed 1.5 times lower coefficient of friction and 2 times lower wear rate of coating as compared to the substrate.
Chen et al. (2020) [35]	IN718	Ni-CNTs	Microstructure, tensile, wear properties		The findings revealed effective improvement in the tensile and wear quality of the clad.
Li et al. (2020) [36]	A36 mild steel	MSS with FeeNb powder	Microhardness, Tensile propt., Corrosion res.		Found remarkable enhancement in mechanical properties of the coating.
Li et al. (2020) [37]	TA1 titanium	Deloro22-Si$_3$N$_4$-B$_4$C	Microstructure, toughness		The result exhibited dense microstructure and enhanced the toughness as compared to the substrate.
Luo et al. (2020) [38]	1045 steel	Fe-Al	Microstructure, compositions, tribological properties		The coating achieved a low frictional coefficient and low rate of wear.
Ma et al. (2020) [39]	316 stainless steel	C$_4$ coating	Microstructure, corrosion		Because of oxide film formation on the surface due to the C$_4$ coating, there was an increase in corrosion resistance in sulfuric acid solution.
Mohammed et al. (2020) [40]	Mild steel (ASTM A36)	WT-6	Dilution ratio, hardness	Laser power, scanning speed, wire feed rate	Experimentally found optimal process parameters as laser power = 3.7 – 3.9 kW, feed rate = 75 mm/s, and scanning speed = 6 mm/s.
Savrai et al. (2020) [41]	Low carbon steel	CoNiCrW	Microstructure, phase composition, microhardness, micromechanical properties		Findings revealed remarkable enhancement in the mechanical properties of the coating.

Xiang et al. (2020) [42]	Ti	CoNiTi medium entropy alloy	Microstructure, hardness		Results revealed a superb metallurgical bond between CoNiTi MEA and Ti-substrate. Hardness measurements of the clad were found ~5 times advanced than the substrate.
Xiao et al. (2020) [43]	Q235 steel	Nb10 alloy	Microstructure, microhardness, wear resistance		An outstanding metallurgical coating, characterized by its uniformity and absence of cracks, was achieved, resulting in enhanced mechanical characteristics.
Zhang et al. (2020) [44]	A3 steel	Ni-Cu/WC-12Co	Microstructure, microhardness, wear, corrosion resistance	WC-12Co contents	Microhardness directly depended on WC-12Co content. Optimal wear resistance was found at WC-12Co content of 20 wt.%.
Zhang et al. (2020) [45]	Ti6Al4V	Graphene reinforced Ti6Al4V	Microstructure		When Ti_6Al_4V was cladding by Graphene/Ti_6Al_4V, feathery TiC was produced.
Zhao et al. (2020) [46]	No. 45 steel	TiC/B_4C/Ni204-based	Microstructure, microhardness		Results revealed microhardness and coefficient of friction were 3.23 and 0.281 times respectively of the initial Ni_20_4 cladding when coated by 30 % TiC. On the other hand, microhardness and coefficient of friction were 4.38 and 0.752 times respectively of the previous layer when coated by 30 % B_4C and 5 % TiC.
Zhou et al. (2020) [47]	S355 steel	Cr- & Mo-Reinforced FeSiB	Microstructure, CoF, corrosive-wear		The result showed excellent resistance to corrosive wear of FeSiBCr coating among the three coatings namely, coating of FeSiB, coating of FeSiBCr, and coating of FeSiBCrMo. This revealed that wear resistance is mainly affected by the phase distribution.
Hu et al. (2021) [48]	$5Cr_5MoSiV1$ steel	Ni3Ta-TaC reinforced Ni-based	Microstructure, wear		The wear characteristics of Ni-Ta cladding and Ni-TaC cladding were found to be 2 and 4-times greater than the substrate, respectively.
Li et al. (2021) [49]	Nickel-aluminum bronze	TaC/Co-based	Microstructure, microhardness, wear, electrochemical corrosion		When compared to the substrate, the coating demonstrated a 6.2-fold increase in microhardness, a 0.303-fold drop in frictional coefficient, and a 0.4-fold drop in wear rate.
Liu et al. (2021) [50]	AISI 304	$AlCoCrFeNiSi_x$	Microstructure, microhardness, wear	Si - contents	The microhardness of the coating was significantly enhanced. Increased Si concentration also lowered the coating's frictional coefficient and wear rate.
Tian et al. (2021) [51]	2Cr13 steel	Inconel 625/WC	Microstructure, microhardness, corrosion resistance	WC-contents	Optimal corrosion resistance was found at 10 wt. % WC.
Yuan et al. (2021) [52]	AISI 1045	Ni45	Microstructure, microhardness, wear, corrosion resistance		Results revealed better mechanical properties at higher-speed lasers.
Li et al. (2021) [53]	5083 aluminum	$Al_xCrFeCoNiCu$	Hardness, wear	Al-contents	The hardness and the wear resistance directly depended on Al-contents.
Bartkowski et al. (2021) [54]	Low carbon steel	Fe/WC	Macroscopic observation, microstructure, microhardness	Laser power, powder feed rate	The optimal coating was produced based on microhardness and corrosion resistance at 12.50 g/min powder feeding rate.
Liu et al. (2021) [55]	15CrMn steel	CoCrFeMnTi 0.2	Microstructure, microhardness, wear		The coating was enhanced in terms of wear resistance and microhardness. When compared to the substrate, the microhardness was raised by around 3.5 times.
Riquelme et al. (2021) [56]	ZE41 Magnesium Alloy	Al/SiC	Wear behavior, corrosion resistance		Result revealed enhancement in wear properties of the coating concerning the substrate. Also, it was concluded that wear resistance and corrosion property are improved by adding Si or Ti.
Li et al. (2022) [57]	40CrNiMo Steel	AlCoCrFeNi-xTiC	Microstructure, wear resistance	TiC- contents	The in-situ generation of TiC particles significantly enhances hardness and wear resistance.

Ding et al. (2023) [58]	U71Mn rail	316L stainlesssteel	Grain size, Microhardness	Scanspeeds, laserpower	Grain size increases with laser power but decreases with scan speed, while hardness increases with both power and speed.
Zhang et al. (2024) [59]	SS304	NbC	Microhardness, frictioncoefficient, corrosionresistance	Composition of coating (A-NbC and I-NbC)	The experimental results could serve as a technical guide for enhancing the performance of laser-cladded iron-based composite coatings.
Zhang et al. (2024) [60]	Ti6Al4V	$FeCrAlMoSi_x$	Micro-hardness, microstructure, wear resistance	Si- contents	Laser cladding enhances microhardness, decreases wear loss, and reduces the coefficient of friction (COF).

Substrates and clad alloys materials

Substrates

Steel serves as the predominant choice for substrate materials in the fabrication of clad components. The selection of substrates hinges on specific application demands, encompassing factors like elevated temperature resilience and resistance to corrosive and abrasive wear. Among the varied options are: (i) stainless steels, (ii) diverse grades of carbon steels, spanning high, medium, and low carbon content, (iii) high-speed steels, (iv) Inconel, (v) titanium alloys, (vi) manganese alloys, (vii) low nickel-chrome steels, (viii) cast iron, including both grey and white cast iron varieties.

Clad Alloys

Surface enhancement through cladding improves the characteristics of a component's exterior while leaving its internal properties unchanged. This technique is employed on surfaces vulnerable to deterioration, oxidation, and corrosion. Among the frequently utilized clad alloys, iron-based, titanium-based, cobalt-based, and nickel-based alloys stand out. The applications span a wide spectrum, encompassing tasks such as crushing rocks and manufacturing control valves to minimize metal-to-metal wear. In situations marked by elevated temperatures and corrosive environments, cobalt and nickel-based clad alloys find common usage.

Microstructural characterization

The composition of both the cladding material and the substrate plays a significant role in shaping the microstructural characteristics of the coating. Additionally, laser cladding parameters exert influence over these microstructural attributes. Microstructural analysis involves the examination of grain size and shape, the composition of the cladding material, and the orientation of grain structures in the heat-affected zone (HAZ), all of which are crucial for assessing their impact on tribological and mechanical properties. Traditional metallographic methods have traditionally been employed to characterize the microstructure of these coatings. However, there are various advanced tools available for evaluating the microstructure and composition of different phases within the resulting coating. These tools encompass techniques such as EPMA (electron probe microanalyzer), FESEM (field emission scanning electron microscope) equipped with EDS (energy-dispersive X-ray spectroscopy), TEM (transmission electron microscope), among others. Abrasive sheets were used to polish the samples to a near-mirror finish, followed by diamond polishing. The microstructure was then found out by etching them with either vilella or nital solution under the optical microscope (OM). Much of the research is centered on inquiries into microstructural aspects. Some recent research concentrated on carbon nano-tubes coatings. Chen et al. [35] studied the link between IN718 substrate and Nickel-coated carbon nanotubes (Ni-CNTs) coating and found they were bonded effectively. The findings revealed that IN718/NiO- 5CNTs composite alloys' tensile and wear characteristics can be significantly enhanced. Hu et al. [48] studied Ni_3Ta-TaC reinforced Ni-based cladding on the substrate $5Cr_5MoSiV1$ steel. They found Ni-Ta and Ni-TaC claddings have two and four-times the wear resistance of $5Cr_5MoSiV1$ steel, respectively. Li et al. [36] examined TA1 titanium cladding by Deloro22-Si_3N_4-B_4C and the result exhibited dense microstructure and enhanced the toughness as compared to the substrate. Liu et al. [37] studied the effect of Si content on the tribological behavior of the cladding and found frictional coefficient and wear rate of the coating were reduced with an increase in Si content. Bartkowski et al. [54] produced Fe/WC cladding on low carbon steel. They got an optimal coating based on microhardness and corrosion resistance at 12.50 g/min powder feeding rate. The study-specific investigations column in Table 1 provides a breakdown of research findings derived from microstructural analyses.

Mechanical characterization

The analysis of altered surface mechanical properties was conducted by evaluating micro-hardness measurements and assessing tribological behavior.

Microhardness analysis

The term "hardness" denotes the material's resistance to undergoing plastic deformation due to processes like indentation, scratching, or friction. To quantify microhardness, a Vickers indenter was employed, utilizing a microhardness tester. It is noteworthy that approximately 70 % of the collective body of research pertaining to laser cladding techniques centers on investigating the hardness characteristics of the coating. Among the 43 referenced works, 30 of them specifically delve into the examination of cladding hardness behavior. The particulars of these studies predicated on hardness can be found in Table 1, within the designated "investigations" section for their respective research endeavors. Li et al. [37] studied cladding on the titanium alloy and concluded that because of the dense grain strengthening effects of CeO_2 coating, wear-resistance and microhardness were greatly enhanced. Mohammed et al. [40] investigated the three parameters, scanning speed, laser power, and wire feed rate, which have an influence on the mechanical properties of mild steel (ASTM A36) cladding. Xiang et al. [42] examined cladding of titanium using CoNiTi medium entropy alloy. Results revealed a superb metallurgical bond between CoNiTi MEA and Ti-substrate. Hardness measurements of the coating were discovered to have hardness 5 times that of the substrate. Li et al. [49] researched 5083 aluminum substrate and AlxCrFeCoNiCu clad. The results showed the hardness increases with an increase of Al-contents.

Tribological properties analysis

When two solid surfaces interact through sliding or rolling in solid-state contact, they undergo a process known as material degradation, which is often referred to as surface wear. This phenomenon is a prevalent issue across numerous industrial sectors. Wear encompasses various factors, such as oxidation, abrasion, erosion, impact, corrosion, or a combination thereof. The pin-on-disk tribometer stands out as the primary and highly efficient instrument for conducting tests related to the tribological properties of materials. Wang et al. [33] studied the influence of rare earth oxide on the wear quality of Fe-based ceramics produced in situ and found an optimum value of Y_2O_3 content to enhance the wear properties of the cladding. Zhu et al. [34] successfully formed coating over Inconel 625 substrate and demonstrated that 1.5 times lower coefficient of friction and 2 times lower wear rate of coating as compared to the substrate. Hu et al. [48] showed the wear characteristics of Ni-Ta cladding and Ni-TaC cladding on IN718 substrate and found enhancement in the wear resistance by 2-times and 4-times respectively. Riquelme et al. [25] studied experimentally and revealed an admirable metallurgical bond between Al/SiC metal matrix composite and ZE41 magnesium alloy substrate with improvement in wear properties. Also, it was concluded that wear resistance and corrosion properties are improved by adding Si or Ti. The details of the studies are presented in Table 1.

Conclusions and future perspectives

From a comprehensive review of various research papers on laser cladding techniques, several significant observations and recommendations for future research emerge:

1. Laser cladding is the most suitable technique to produce an excellent metallurgical bond between the substrate and clad of thickness 50 µm to 2 mm with low dilution and defect-free coatings.
2. It can be applied to an extensive range of substrates to develop a high-quality coating.
3. It has been found that Co-based, Ni-based, WC-based, Fe-based alloys, high entropy alloy, and many other alloys can be excellently metallurgical bounded with different substrates by laser cladding technique.
4. Laser cladding's effectiveness mostly depends on the laser parameters (wavelength, power), process parameters (scan speed, feed rate, assist inert gas type and pressure), clad materials and their powder size, and substrate materials.
5. Researchers have mostly focused on studying characteristics like microhardness, wear resistance, and microstructure; relatively few research have examined how well coatings function in connection to oxidation and erosion-corrosion behavior.
6. In-depth research efforts are essential to gain the complex physical and chemical interactions that take place between the substrate and the materials utilized in laser cladding processes.
7. Not enough focus has been placed on optimizing the laser cladding technique's parameters. Because of this, researchers should work more diligently to optimize these parameters through the use of AI-driven modeling and optimization techniques.

References

1. Gu Y, Xia K, Wu D, Mou J, Zheng S. Technical characteristics and wear-resistant mechanism of nano coatings: a review. *Coatings*. 2020;10(3): 233.
2. Uhlig HH, Revie RW. *Corrosion and corrosion control*. 1985.
3. Ranjan R, Das AK. A review on surface protective coating using cold spray cladding technique. *Materials Today: Proceedings.* 2022;56: 768–773.
4. Ranjan R, Das AK. Recent Advancements in Surface Modification by Gas Tungsten Arc Cladding Technique: A Review. *Advanced Materials Research.* 2022;1173: 113–122.
5. Bajaj P, Hariharan A, Kini A, Kürnsteiner P, Raabe D, Jägle EA. Steels in additive manufacturing: A review of their microstructure and properties. *Materials Science and Engineering: A.*2020;772: 138633.
6. Ranjan R, Das AK. Protection from corrosion and wear by different weld cladding techniques: A review. *Materials Today: Proceedings.* 2022;57: 1687–1693.
7. Ranjan R. An Overview on Enhancing Materials' Tribological and Mechanical Characteristics by Using Gas Metal Arc Weld Hardfacing. *Journal of Engineering Science & Technology Review*. 2024;17(1): 54–62.
8. Komvopoulos K, Nagarathnam K. *Processing and characterization of laser-cladded coating materials*. 1990.
9. Ranjan R, Das AK. Improving the Resistance to Wear and Mechanical Characteristics of Cladding Layers on Titanium and its Alloys: A Review. *Tribology in Industry*. 2023;44(1): 136.
10. Barekat M, Razavi RS, Ghasemi A. Nd: YAG laser cladding of Co–Cr–Mo alloy on γ-TiAl substrate. *Optics & Laser Technology*. 2016;80: 145–152.
11. Parekh R, Buddu RK, Patel RI. Multiphysics simulation of laser cladding process to study the effect of process parameters on clad geometry. *Procedia Technology.* 2016;23: 529–536.
12. Guo W, Li X, Ding N, Liu G, He J, Tian L, Chen L, Zaïri F. Microstructure characteristics and mechanical properties of a laser cladded Fe-based martensitic stainless steel coating. *Surface and Coatings Technology.*2021;408:126795.
13. Mazumder J. Laser-aided direct metal deposition of metals and alloys. In:*Laser additive manufacturing.*Woodhead Publishing; 2017. p.21–53.
14. Qian M, Lim LC, Chen ZD, Chen WI. Parametric studies of laser cladding processes. *Journal of Materials Processing Technology.* 1997;63(1–3): 590–593.
15. Haemers TA, Rickerby DG, Lanza F, Geiger F, Mittemeijer EJ. Hardfacing of stainless steel with laser melted colmonoy. *Journal of Materials Science.* 2000;35: 5691–5698.
16. Sha CK, Tsai HL. Hardfacing characteristics of S42000 stainless steel by using CO2 laser. *Journal of Materials Engineering and Performance.* 2001;10: 37–41.
17. Yao J, Ma C, Gao M, Kong F, Zhang Q. Microstructure and hardness analysis of carbon nanotube cladding layers treated by laser beam. *Surface and Coatings Technology*. 2006;201(6): 2854–2858.
18. Baldridge T, Poling G, Foroozmehr E, Kovacevic R, Metz T, Kadekar V, Gupta MC. Laser cladding of Inconel 690 on Inconel 600 superalloy for corrosion protection in nuclear applications. *Optics and Lasers in Engineering.* 2013;51(2): 180–184.
19. Tanigawa D, Abe N, Tsukamoto M, Hayashi Y, Yamazaki H, Tatsumi Y, Yoneyama M. Effect of laser path overlap on surface roughness and hardness of layer in laser cladding. *Science and Technology of Welding and Joining.* 2015;20(7): 601–606.
20. Das AK, Shariff SM, Choudhury AR. Effect of rare earth oxide (Y2O3) addition on alloyed layer synthesized on Ti–6Al–4V substrate with Ti+ SiC+ h-BN mixed precursor by laser surface engineering. *Tribology International.* 2016;95: 35–43.
21. Murzakov MA, Chirikov SN, Markushov YV. Research on microstructure and wear resistance of coatings obtained by adding nanoparticles of refractory compounds in laser cladding. *Journal of Physics: Conference Series.* 2016;747(1): 012062.
22. Stanciu EM, Pascu A, Ţierean MH, Voiculescu I, Roată IC, Croitoru C, Hulka I. Dual coating laser cladding of NiCrBSi and Inconel 718. *Materials and Manufacturing Processes.* 2016;31(12):1556–1564.
23. Alam MK, Edrisy A, Urbanic J, Pineault J. Microhardness and stress analysis of laser-cladded AISI 420 martensitic stainless steel. *Journal of Materials Engineering and Performance.* 2017;26:1076–1084.
24. Liu J, Li J, Cheng X, Wang H. Microstructures and tensile properties of laser cladded AerMet100 steel coating on 300 M steel. *Journal of Materials Science &Technology.* 2018;34(4):643–652.
25. Riquelme A, Escalera-Rodríguez MD, Rodrigo P, Otero E, Rams J. Effect of alloy elements added on microstructure and hardening of Al/SiC laser clad coatings. *Journal of Alloys and Compounds.* 2017;727:671–682.

26. Lei J, Shi C, Zhou S, Gu Z, Zhang LC. Enhanced corrosion and wear resistance properties of carbon fiber reinforced Ni-based composite coating by laser cladding. *Surface and Coatings Technology.* 2018;334:274–285.
27. Chen Y, Zhang Q, Chen Z, Wang L, Yao J, Kovalenko V. Study on the element segregation and Laves phase formation in the carbon nanotubes reinforced IN718 superalloy by laser cladding. *Powder Technology.* 2019;355:163–171.
28. He B, Ma D, Ma F, Xu K. Microstructures and wear properties of TiC coating produced by laser cladding on Ti-6Al-4V with TiC and carbon nanotube mixed powders. *Ferroelectrics.* 2019;547(1):217–225.
29. Sibisi PN, Popoola AP, Kanyane LR, Fatoba OS, Adesina OS, Arthur NK, Pityana SL. Microstructure and microhardness characterization of Cp-Ti/SiAlON composite coatings on Ti-6Al-4V by laser cladding. *Procedia Manufacturing.* 2019;35:272–277.
30. Zhao J, Gao Q, Wang H, Shu F, Zhao H, He W, Yu Z. Microstructure and mechanical properties of Co-based alloy coatings fabricated by laser cladding and plasma arc spray welding. *Journal of Alloys and Compounds.* 2019;785:846–854.
31. Hulka I, Utu D, Serban VA, Negrea P, Lukáč F, Chráska T. Effect of Ti addition on microstructure and corrosion properties of laser cladded WC-Co/NiCrBSi (Ti) coatings. *Applied Surface Science.* 2020;504:144349.
32. Spranger F, de Oliveira Lopes M, Schirdewahn S, Degner J, Merklein M, Hilgenberg K. Microstructural evolution and geometrical properties of TiB 2 metal matrix composite protrusions on hot work tool steel surfaces manufactured by laser implantation. *The International Journal of Advanced Manufacturing Technology.* 2020;106:481–501.
33. Wang XH, Liu SS, Zhang M, Qu KL. Effect of rare earth oxide on the microstructure and wear properties of in situ–synthesized ceramics-reinforced Fe-based laser cladding coatings. *Tribology Transactions.* 2020;63(2):345–355.
34. Zhu R, Zhang P, Yu Z, Yan H, Li S, Wu D, Shi H, Tian Y. Microstructure and wide temperature range self-lubricating properties of laser cladding NiCrAlY/Ag2O/Ta2O5 composite coating. *Surface and Coatings Technology.* 2020;383:125248.
35. Chen Z, Chen Y, Zhang Q, Yao Z, Zhang Q, Wang L, Yao J, Wang X. Study on the tensile and wear properties of laser-cladded IN718 superalloy reinforced by carbon nanoproducts transformed from carbon nanotubes. *Journal of Materials Research.* 2020;35(20):2643–2651.
36. Li BC, Zhu HM, Qiu CJ, Zhang DK. Development of high strength and ductile martensitic stainless steel coatings with Nb addition fabricated by laser cladding. *Journal of Alloys and Compounds.* 2020;832:154985.
37. Li J, Tian Y, Zhang L, Wang X, Wang X. Laser/argon-arc strengthening of titanium alloy surface with Deloro matrix composites. *Optics & Laser Technology.* 2020;123:105911.
38. Luo X, Cao J, Meng G, Chuan Y, Yao Z, Xie H. Systematical investigation on the microstructures and tribological properties of Fe-Al laser cladding coatings. *Applied Surface Science.* 2020;516:146121.
39. Ma J, Liu Z. Corrosion Behavior of C4 Coating Produced by Cladding Laser in Sulfuric Acid. *Journal of Physics: Conference Series.* 2020;1635(1): 012074.
40. Mohammed S, Zhang Z, Kovacevic R. Optimization of processing parameters in fiber laser cladding. *The International Journal of Advanced Manufacturing Technology.* 2020;111:2553–2568.
41. Savrai RA, Soboleva NN, Malygina IY, Osintseva AL. The structural characteristics and contact loading behavior of gas powder laser clad CoNiCrW coating. *Optics & Laser Technology.* 2020;126:106079.
42. Xiang K, Chai L, Wang Y, Wang H, Guo N, Ma Y, Murty KL. Microstructural characteristics and hardness of CoNiTi medium-entropy alloy coating on pure Ti substrate prepared by pulsed laser cladding. *Journal of Alloys and Compounds.*2020;849:156704.
43. Xiao Y, Liu Z. Characteristics study on in-situ NbC particles reinforced Ni-based alloy composite coating by laser cladding. *Journal of Physics: Conference Series.* 2020;1635(1): 012076.
44. Zhang J, Lei J, Gu Z, Tantai F, Tian H, Han J, Fang Y. Effect of WC-12Co content on wear and electrochemical corrosion properties of Ni-Cu/WC-12Co composite coatings deposited by laser cladding. *Surface and Coatings Technology.* 2020;393:125807.
45. Zhang L, Zhao Z, Bai P, Du W, Li Y, Yang X, Wang Q. In-situ synthesis of TiC/graphene/Ti6Al4V composite coating by laser cladding. *Materials Letters.* 2020;270:127711.
46. Zhao Y, Yu T, Sun J, Jiang S. Microstructure and properties of laser cladded B4C/TiC/Ni-based composite coating. *International Journal of Refractory Metals and Hard Materials.*2020;86:105112.
47. Zhou J, Kong D. Microstructure, Tribological performance, and wear mechanism of Cr-and Mo-reinforced FeSiB coatings by laser cladding. *Journal of Materials Engineering and Performance*. 2020;29:7428–7444.

48. Hu D, Liu Y, Chen H, Wang M, Liu J. Microstructure and properties of in-situ synthesized Ni3Ta-TaC reinforced Ni-based coatings by laser cladding. *Surface and Coatings Technology.* 2021;405:126599.
49. Li Z, Yan H, Zhang P, Guo J, Yu Z, Ringsberg JW. Improving surface resistance to wear and corrosion of nickel-aluminum bronze by laser-clad TaC/Co-based alloy composite coatings. *Surface and Coatings Technology.* 2021;405:126592.
50. Liu H, Sun S, Zhang T, Zhang G, Yang H, Hao J. Effect of Si addition on microstructure and wear behavior of AlCoCrFeNi high-entropy alloy coatings prepared by laser cladding. *Surface and Coatings Technology.* 2021;405:126522.
51. Tian ZH, Zhao YT, Jiang YJ, Ren HP. Microstructure and properties of Inconel 625+ WC composite coatings prepared by laser cladding. *Rare Metals.* 2021;40:2281−2291.
52. Yuan W, Li R, Chen Z, Gu J, Tian Y. A comparative study on microstructure and properties of traditional laser cladding and high-speed laser cladding of Ni45 alloy coatings. *Surface and Coatings Technology.* 2021;405:126582.
53. Li Y, Shi Y. Microhardness, wear resistance, and corrosion resistance of AlxCrFeCoNiCu high-entropy alloy coatings on aluminum by laser cladding. *Optics & Laser Technology.* 2021;134:106632.
54. Bartkowski D, Bartkowska A, Jurči P. Laser cladding process of Fe/WC metal matrix composite coatings on low carbon steel using Yb: YAG disk laser. *Optics & Laser Technology.* 2021;136:106784.
55. Liu H, Li X, Liu J, Gao W, Du X, Hao J. Microstructural evolution and properties of dual-layer CoCrFeMnTi0. 2 high-entropy alloy coating fabricated by laser cladding. *Optics & Laser Technology.* 2021;134:106646.
56. Riquelme A, Rodrigo P, Escalera-Rodriguez MD, Rams J. Evaluation of the wear resistance and corrosion behavior of laser cladding al/sic metal matrix composite coatings on ze41 magnesium alloy. *Coatings.* 2021;11(6): 639.
57. Li Y, Wang K, Fu H, Guo X, Lin J. Microstructure and wear resistance of in-situ TiC reinforced AlCoCrFeNi-based coatings by laser cladding. *Applied Surface Science.* 2022;585:152703.
58. Ding H, Yang T, Wang W, Zhu Y, Lin Q, Guo J, Xiao Q, Gan L, Liu Q. Optimization and wear behaviors of 316L stainless steel laser cladding on rail material. *Wear.* 2023;523:204830.
59. Zhang HF, Zhang S, Wu H, Wang R, Zhang CH, Wu CL, Chen J, Chen HT. Mechanical properties and corrosion resistance of laser cladding iron-based coatings with two types of NbC reinforcement. *Surface and Coatings Technology.*2024;479:130558.
60. Zhang Z, Hua K, Cao Y, Song Y, Li X, Zhou Q, Wang H. Microstructures and properties of FeCrAlMoSix high entropy alloy coatings prepared by laser cladding on a titanium alloy substrate. *Surface and Coatings Technology.* 2024;478:130437.

About Authors

Ranjan Rajeev Sc

Asst. Professor (Dr. B.C. Roy Engineering College, Durgapur, India), Research Scholar (National Institute of Technology, Patna, India)

Das Anil Kumar Sc

PhD, Associate Professor (National Institute of Technology, Patna, India)