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REVIEW

Improving the Resistance to Wear and Mechanical Characteristics of Cladding Layers on Titanium and its Alloys: A Review

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A B S T R A C T

Because of inadequate hardness, low resistance to wear, and excess friction coefficient of titanium, and its alloys are limited in their applicability. Cladding, a type of surface modification process, is used to create layers on titanium and its alloys that have superior mechanical qualities, wear characteristics, oxidation resistance at high temperatures, and good biocompatibility. Material selection is critical for achieving the increased qualities mentioned above, in addition to various cladding techniques and associated process parameters. A review of the outcomes of various common wear-resistant cladding techniques applied to the titanium alloy surface is the subject of this study. The most important functional claddings in this domain are also presented and investigated in depth. The present issues and future initiatives are also discussed, with an emphasis on identifying knowledge and technological gaps as well as attempting to establish future research possibilities. On this foundation, it is suggested that in the coming years, resistant-to-wear cladding with significant improvements in toughness and hardness should progress on the path of smart manufacturing techniques, optimising and precisely customising microstructural configurations, and developing numerical simulation techniques of cladding.

1. INTRODUCTION

Many researchers have been studying the surface modification of titanium alloy in recent years. On account of their high strength-to-weight ratio and strong corrosive property, titanium and its alloys are extensively utilised in the components of aerospace, marine, biomedical devices, chemical industry, aviation, and other industries [1–3]. However, the bearing components fail in their early stages and the service life is considerably decreased due to the low hardness, low resistance to wear and high friction coefficient of titanium alloy during operations, which severely limits the useful applications of titanium alloys [4,5]. Due to work hardening and low shear resistance, titanium alloys have poor wear resistance [4]. Preparing a clad surface layer on titanium alloy is currently one of the most successful approaches to overcome the above problems of titanium alloys. The most common procedures for applying a hard and resistant surface layer are weld cladding and thermal spraying. These techniques are most commonly utilised with powder cladding materials, although they may be applied on any base material that can be melted without vaporization and decomposition. The feature and quantity of the project to be cladded, the purpose where it will be employed, the substrate composition, and the availability of weld equipment can affect cladding procedures used. The cladding can be done in a variety of ways, from traditional oxyacetylene gas welding to laser welding and plasma transferred arc [6].

For the fabrication of claddings on the surfaces of Ti and Ti6Al4V, a variety of surface modification procedures have been applied as shown in Fig. 1, including tungsten inert gas cladding (TIGC), laser cladding (LC), plasma arc cladding, and microwave cladding. In the form of a flow chart, the entire cladding process is depicted. The process for creating the cladding layer on top of the substrate is shown step-by-step in the flow diagram in Fig. 2. Sandpaper was used to grind the surfaces, and any organic matter was subsequently removed with alcohol. Subsequently, a paste made from the cladding powders and polyvinyl alcohol was applied to the substrate's surface while maintaining the proper thickness to create a green coating layer. Then, heat is applied by different techniques (as shown in Fig.1) on the green coated layer to melt the coating powder to fabricate cladding with enhanced mechanical and tribological properties.

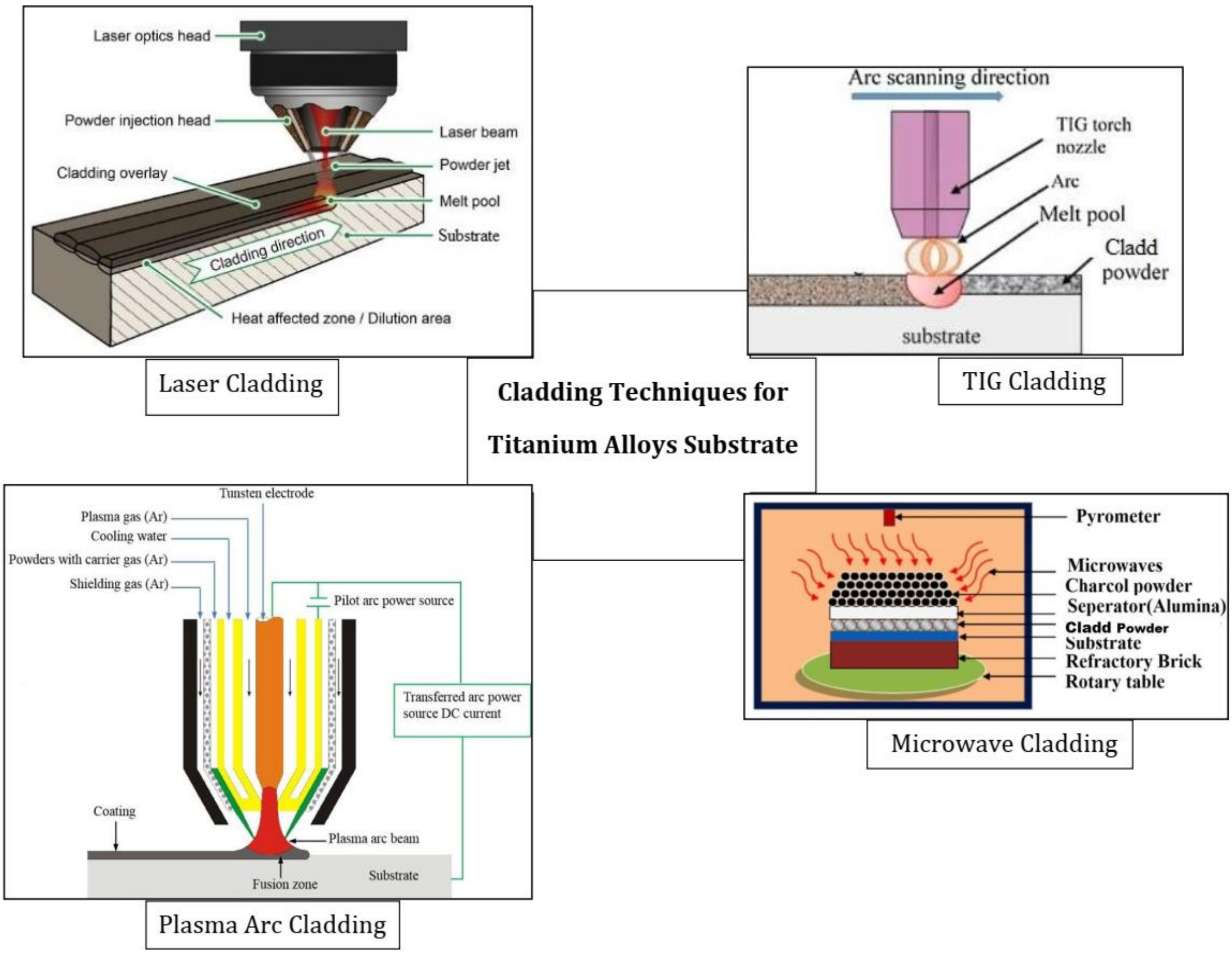

Fig. 1. Cladding methods for Titanium-alloys substrate.

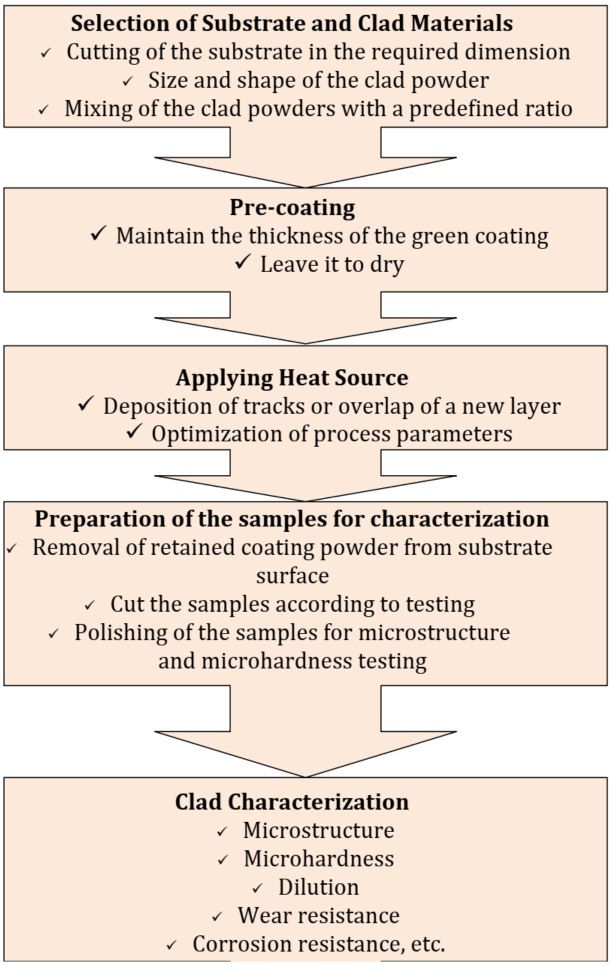

Fig. 2. Flow diagram of procedures for producing the cladding layer over a substrate.

Laser cladding is one of them widely applied due to its excellent metallurgical bonding in the coating, fast cooling rate, least HAZ (heat affected zone), and higher energy density [7]. The ceramics composite cladding was made by combinations of metal-ceramic powders using laser cladding. This retains not only the ceramic phases, excellent microhardness, and temperature stability, but also the metal matrix's good plastic toughness properties. As a result, composite claddings combine the benefits of the matrix and reinforcement, improving the oxidation resistance at higher temperatures and resistance to wear of titanium alloys [8,9]. TiC, TiB, and TiB2 are commonly employed as excellent reinforcements for composite claddings to increase the high-temperature performance and wear characteristics of Ti6Al4V alloy [10]. According to earlier research, adding rare earth oxides improve cladding microstructure, increases antispalling at high temperatures and minimises thermal stresses [11–13]. The inclusion of rare earth oxides also boosted the oxide layers' self-healing abilities. Furthermore, the concentration of rare earth oxides at grain boundaries retarded the oxidation process by preventing oxygen atoms from diffusing into the coatings. At 650°C –750°C, Zhang et al. investigated the cyclic oxidation behaviour of Ti-alloy with varying Y (yttrium) cladding. The addition of increasing percentage in Y reduced the grain size of the oxide layer, which decreased oxygen diffusion and increased the alloys' oxidation resistance. The addition of yttrium improves the adhesive strength between the oxide coating and the base material [14]. However, the inclusion of rare-earth oxides increased the oxygen concentration of the coatings. Instead of directly adding rare-earth elements, rare earth oxides or rare-earth borides or rare-earth carbides can be added to the powder mixture for the coatings, which is favourable to improve oxidation resistance.

The reinforcing phase in traditional hard cladding is usually a single kind of ceramic particle, and the volume fraction of the reinforcing phase improves the coating's wear property and hardness. However, a gain in wear property and hardness is frequently followed by a large drop in toughness, indicating that toughness and hardness have a clear "inverse connection" [15,16]. Inspire by the "inverse relationship" between the toughness and resistance to wear (hardness) of the cladding on the surface of titanium alloy, researchers have produced some innovative structural resistant-to-wear cladding with higher toughness and higher hardness, like gradient design cladding [17–19], multiscale design cladding [20–22], and layered design resistant-to-wear cladding [23–25]. Gradient-designed claddings can reduce thermal stress brought on by fluctuations in the thermal properties of various phases within the coating as well as stress between the base and cladding resulting from abrupt changes in physical properties. The load transfer effect, toughness, and hardness are improved by altering the microstructure gradient in the direction of coating thickness [19]. Multi-functional response and coupling mechanisms between reinforcements of various sizes (micron, submicron, and nano), morphologies (whiskers, particles), and phases are largely employed to increase the coating's toughness, resistance to wear, and hardness [22,26]. The layered design cladding controls the formation and propagation of fractures that arises in the coating by coordinating and balancing the "inverse relationship" between hardness (wear-property) and toughness [23–25,27].

The different cladding techniques applied for titanium alloy followed by previous researchers are represented in Table 1. The application of various substrate materials with their respective coating techniques and the major findings of the articles are also shown in the table. For producing dense microstructures and solid metallurgical bonds with substrates, laser cladding is one of these techniques that are comparatively beneficial. In an effort to increase wear resistance, high-temperature oxidation resistance, and biocompatibility, researchers have focused a lot of their emphasis on understanding the effects of laser cladding on titanium and its alloys. Recent advancements in the laser cladding of titanium alloys have emphasised the optimization of process variables, design of cladding materials, and attainment of desired qualities. Nonetheless, there are still issues that need to be resolved in the realm of titanium alloy cladding. Recent advances in diverse cladding methods onto the titanium alloy surface with higher hardness, enhanced wear characteristics, better corrosion & oxidation resistance, and superior medical biocompatibility are discussed in this study. Finally, a future trend in this research field is also predicted.

Table 1. Summary of the cladding techniques applied for titanium and its alloys.

Process of coating	Substrate	Coating / Clad powders	Findings / Results	Authors (Ref.)
Laser	Ti-6Al-4V	Different carbide powders	Enhancement of microstructure	Folkes et al. 1994 [28]
Laser	Ti-6Al-4V	TiC + NiCrBSi	Strengthening of fine TiC dendrites	Sun et a. 2001 [29]
Plasma nitriding	Ti-6Al-4V	Carbon nitride (CNX)	Improvement in resistance to wear and the friction property.	Fu et al. 2001 [30]
Laser	TiAl alloy	Ni-Cr and Cr3C2	Non-equilibrium solidified reinforced Cr7C3 and TiC carbides are formed.	Liu et al. 2007 [31]
Plasma spray	Ti-6Al-4V	Ca-Si-Ti	The coating's bonding strength, chemical stability, and cellular bioactivity were all outstanding.	Wu et al. 2009 [32]
Laser	Ti alloy	Ni, Cr, B, Si	Improved strengthening	Guo et al. 2011 [33]
Laser	Ti-6Al-4V	Ti6Al4V	Microstructure refinement with a slower laser traversal speed.	Cottam et al. 2011 [34]
Laser	Ti-6Al-4V	TiBx and TiC	Enrichment of microstructure and microhardness.	Liang et al. 2011 [35]
Tungsten inert gas	Ti-6Al-4V	SiC	Enhancement of microstructure, resistance to wear, and microhardness.	Lin et al. 2011 [36]
Tungsten inert gas cladding	Ti-6Al-4V	Tungsten boride (WB)	Enhancement of resistance to wear and microhardness.	Lin et al. 2011 [37]
Tungsten inert gas cladding	Ti-6Al-4V	SiC	Enhancement of microstructure and microhardness.	Bochnowski et al. 2012 [38]
Tungsten inert gas cladding	Ti-6Al-4V	Titanium nitrides (TiNs)	Enhancement of resistance to wear and microhardness.	Lin et al. 2012 [39]
Laser cladding	Ti	CNT with Ti	TiC phase formed.	Li et al. 2014 [40]
Tungsten inert gas cladding	Commercia l purity titanium	Fe, C, and Si	Compared to the substrate, the microhardness of the cladded surface was raised by 3-4 times.	Adeleke et al. 2014 [41]
Laser	Ti–6Al–4V	Ni5Al + hBN + B4C + SiC	Enhancement of resistance to wear and microhardness.	Dhanda et al. 2014 [42]
Laser	Ti-6Al-4V	Vanadium carbide	Enhancement of resistance to wear and microhardness (almost twice). The cladding layer also showed improved corrosion resistance.	Labban et al. 2014 [43]

Process of coating	Substrate	Coating / Clad powders	Findings / Results	Authors (Ref.)
Tungsten inert gas cladding	Ti-6Al-4V	TiN or TiN + TiNx	Enhancement of resistance to wear.	Lin et al. 2014 [44]
Tungsten inert gas cladding	Pure titanium	Fe, C, and Si	Enhancement of microhardness.	Sakiru et al. 2014 [45]
Laser	Ti-alloy	Ti / TiB2 / TiC	Enhancement of resistance to wear and microhardness.	Diao et al. 2015 [46]
Laser	Ti-6Al-4V	Mo + Zr + Stellite6	Enhancement of resistance to wear.	Adebiyi et al. 2015 [47]
Laser	Ti-6Al-4V	Mo + Zr + Stellite6	Enhancement of resistance to wear and microhardness from 357.6 HV0.1 in the native alloy to 1145.2 HV0.1 in the composite coating	Adebiyi et al. 2015 [48]
Laser	Ti-6Al-4V	Co42, B4C, SiC & Y2O3	When compared to the substrate, the resistance to wear was increased by almost tenfold. However, with a greater SiC content (14 wt.%), a better micro-hardness was achieved at the expense of poor resistance to wear.	Weng et al. 2015 [49]
Laser	Ti-6Al-4V	Co42, TiN & Y2O3	Enhancement of resistance to wear and microhardness by 3 to 4 times and 9.5 to 11.9 times, respectively.	Weng et al. 2015 [50]
Plasma-spray	Ti-6Al-4V	Merwinite (Ca3MgSi2O8)	The results showed that merwinite coat with a dense and homogeneous microstructure was produced on the Ti-6A l-4V surface.	Hadipour et al. 2015 [51]
Laser	Ti-6Al-4V	FA / ZrO2	Enrichment of microstructure and microhardness.	Chien et al. 2016 [52]
Laser	Ti alloy	Ni60, Ag, Si3N4, and Y2O3	Enrichment of microstructure and microhardness.	Ma et al. 2016 [53]
Laser	Ti–6Al–4V	TiþSiCþh-BN + Y2O3	The addition of Y2O3 improved the coating's microhardness and resistance to wear.	Das et al. 2016 [54]
Laser	Ti-6Al-4V	TiC, W2C reinforced Ti-W MMC	Enrichment of microstructure and microhardness.	Gattani et al. 2016 [55]
Laser	Ti-6Al-4V	Co42 - TiN	Enrichment of microstructure and microhardness.	Weng et al. 2016 [56]
Plasma nitriding	Ti-6Al-4V	Zr-N composite	Enhancement of antifriction with resistance to wear and microhardness.	Chen et al. 2016 [57]
Laser	Ti-6Al-4 V	NiCrCoTiVAl	Enhancement of microstructure and microhardness.	Cai et al. 2017 [58]
Laser	Ti-6Al-4V	ZrB2-reinforced Ti-SiC	Enhancement of microhardness.	Farotade et al. 2017 [59]
Laser	Ti-6Al-4V	TiC	Enhancement of microhardness.	Liu et al. 2017 [60]
Laser	Ti-6Al-4V	Ti-6Al-4V	Empirical-statistical relationships were found to be in better agreement with the values observed.	Nabhani et al. 2017 [61]
Laser	Ti-6Al-4V	Ti	Enhancement of microhardness.	Sobiyi et al. 2017 [62]
Electro-discharge coating	Ti-6Al-4V	TiC-TiB2	Microhardness and resistance to wear are improved.	Tijo et al. 2017 [63]
Laser	Ti-6Al-4V	Ti5Si3 / TiC	Microhardness and resistance to wear are improved by 3 times and (18.4–57.4 times) respectively.	Weng et al. 2017 [64]
Tungsten inert gas cladding	Ti-6Al-4V	TiN, Ti2N	Enhancement of resistance to wear.	Samanta et al. 2018 [65]

Process of coating	Substrate	Coating / Clad powders	Findings / Results	Authors (Ref.)
Laser	Ti-6Al-4 V	NiCrCoTiV	Enhancement of abrasion resistance	Cai et al. 2018 [66]
Laser	Titanium	TiZrNbHfTa	Enhancement of microstructure	Dobbelstein et al. 2018 [67]
Laser	Ti-6Al-4V	B4C, hBN, and Ti	Enhancement of microhardness and resistance to wear.	Haldar et al. 2018 [68]
Tungsten inert gas cladding	Ti-6Al-4V	SiC + Y2O3	Microhardness and resistance to wear are improved.	Lin et al. 2018 [69]
Tungsten inert gas cladding	Ti-6Al-4V	TiC- TiB2	Enhancement of microstructure and affected by current and scan speed.	Tijo et al. 2018 [70]
Tungsten inert gas cladding	Ti-6Al-4V	TiC- TiB2	Enhancements of hardness up to four times and resistance to wear by three times as compared to Ti-6Al-4V alloy substrate.	Tijo et al. 2018 [71]
Tungsten inert gas cladding	Ti-6Al-4V	NiTi	Microhardness and resistance to wear are improved.	Waghmare et al. 2018 [72]
Laser	Ti6Al4V	Ti (N, C)	After three passes, the resistance to wear had increased by around 37 times.	Zeng et al. 2018 [73]
Laser	Ti-6Al-4V	Ti-Si-Al	Microhardness and resistance to wear are improved.	Zhang et al. 2018 [74]
Laser	Ti–6Al–4V	Ni, B4C, graphite, and Si3N4	Microhardness and resistance to wear are improved with excellent toughness and lubrication.	Zhou et al. 2019 [75]
Laser	Ti-6Al-4V	TiN / TiW + TiS / WS2	Microhardness and resistance to wear are improved.	Gao et al. 2019 [76]
Laser	Ti-6Al-4V	NiCrBSi / TiN / h-BN	Enhancement of resistance to wear and friction coefficient.	Guo et al. 2019 [77]
Laser	TC11 titanium alloy	ZrN	Microhardness and resistance to wear are improved.	Li et al. 2019 [78]
Laser	Ti-6Al-4V	WC	Enhancement of microstructure and microhardness.	Qi et al. 2019 [79]
Microwave cladding	Pure titanium grade-2	Co-Mo-Cr-Si	Enhancement of microhardness and friction coefficient.	Prasad et al.2019 [80]
Laser	Ti-6Al-4V	TiC, CNT	The cladding exhibited better microhardness, lower friction coefficient, and substantially stronger resistance to wear than the substrate.	He et al. (2019) [81]
Ultrasonic vibration-assisted forging	Ti-6Al-4V	Ti-6Al-4V	Microhardness and resistance to wear are improved.	Gao et al. 2020 [82]
Laser	Ti6Al4V	LaB6 + TiC + TiBx	Microhardness and resistance to wear are improved.	Liang et al. 2020 [83]
Laser	Ti6Al4V	TiC	Enhancement of microhardness and resistance to wear.	Ma et al. 2020 [84]
Laser	Ti6Al4V	Y2O3	Enhancement of microhardness and resistance to wear.	Zhang et al. 2020 [85]
Laser	Ti6Al4V	TiC / TiB	Enhancement of toughness and resistance to wear.	Chen et al. 2021 [86]
Electron beam cladding	Ti-6Al-4V	WC-10Co	Enhancement of microhardness, resistance to wear, and friction coefficient.	Chen et al. 2021 [87]
Laser	Ti-6Al-4V–B4C	TiB, TiB2 & TiC	Enhancement of resistance to wear.	Golyshev et al. 2021 [88]

Process of coating	Substrate	Coating / Clad powders	Findings / Results	Authors (Ref.)
Tungsten inert gas cladding	Ti-6Al-4V	Ti6Al4V	Enhancement of corrosion resistance.	Huang et al. 2021 [89]
Tungsten inert gas cladding	TiBw/Ti6Al 4V	TIG remelting	Enhancement of tensile strength and hardness.	Ji et al. 2021 [90]
Laser	Ti-6Al-4V	SiC nanoparticles	Enhancement of microhardness, resistance to wear, and friction coefficient.	Jiang et al. 2021 [91]
Laser	Ti-6Al-4V	Ti10-Fe5-Si5-Cr3-Nb	Enhancement of microhardness.	Malatji et al. 2021 [92]
Laser	Ti-6Al-4V	Pure Co, Co-Ti3-Si-C2, and Co-Cu / Ti-3Si-C2	Enhancement of resistance to wear and friction coefficient.	Zhu et al. 2021 [93]
Laser	Ti-6Al-4V	TiC + TiB2 + Ti2Ni + CeO2	Enhancement of microhardness, resistance to wear, and friction coefficient.	Zhuang et al. 2021 [94]
Tungsten inert gas cladding	Ti-6Al-4V	Ti-6Al-4V	Enhancement of microhardness	Huang et al. 2022 [95]
PTA technique	Ti-6Al-4V	Fe, Co, Cr, Ni, and Al	Enhancement of microhardness and resistance to wear.	Jeyaprakash et al. 2022 [96]

2. GRADIENT DESIGN CLADDING

Functionally graded materials (FGMs) were introduced in 1987 to address thermal stress in high-speed aerospace vehicles [97]. While FGMs cannot be artificially developed, many natural materials, such as teeth, bamboo, and bones, have gradient designs and functions. Bamboo, for example, exhibits a gradient distribution pattern, where the distribution of fiber tube bundles steadily decreases from the outside to the inside of the cross-section, resulting in significant toughness and hardness [98]. Researchers have used this unique design concept of FGMs for surface modification of components, resulting in controlled production of gradient design claddings, which are non-homogeneous structure coatings with a progressive change in chemical composition or microstructure, leading to a gradient shift in mechanical properties [17–19,99-100]. The interface in the substrate-coating system is critical to material performance and operational life. The interface gradient design can efficiently restrict the progression of damage at or near interfaces, which can help to reinforce and toughen the material. For example, human teeth have an interfacial strengthening and toughening mechanism that skillfully integrates the different elements of dentin and enamel at the gradient contact, providing significant resistance to catastrophic destruction during chewing [101]. Gradient design cladding has greater designability than a homogeneous structural coating, and depending on the operating circumstances of the components, the expected composition and structure can be modified, reducing performance mutation and discrepancies between phases and extending the workpiece service life [102]. In addition, the phase composition of the coating exhibits a gradient shift from the coating surface to the substrate, and the volume percentage of the reinforcement progressively declines (or increases) from the coating surface to the substrate. For example, Bai et al. [19] created cladding of pure titanium with a TiC-Fe gradient design using a two-step in-situ reaction approach. The volume percentage and grain size of TiC particles raise as they move from the coated surface to the substrate, and their shape shifts from columnar to equiaxed crystals. Li et al. (103) were able to use the laser cladding method to create a Ti2-Al-Nb/Ti-C + Ti3-Si-C2 gradient design cladding on a titanium alloy. They achieved this by layering a Ti interaction layer, a Ti + SiC mixed transition layer, and a ceramic composite layer on the surface of the titanium alloy. The coating appears to have a gradient design with varying properties at different depths, resulting in a gradual reduction in hardness from the surface to the substrate. This could be advantageous for applications where a coating with different properties is needed, such as wear-resistant coatings or biomedical implants. However, further information on the coating's specific properties and potential applications is required, including its wear and corrosion resistance, biocompatibility, and other characteristics. As a result, the gradient design of the coating increases the coating's toughness and bonding ability to the substrate.

Carburizing, boronizing, nitriding, or laser claddings are commonly used for the formation of gradient design cladding on the surface of titanium alloy. Nitrogen, boron, and carbon atoms are generally employed to pervade the surface of titanium alloys via concentrated gradient diffusion at higher temperatures to produce Ti-C, Ti-B, Ti-B2, or Ti-N gradient design claddings [104]. These techniques significantly enhance the resistance to wear or hardness of the surface of the coating without affecting the substrate performance or macroscopic size.

The utilization of in-situ extension during the production of gradient design cladding can significantly enhance the bonding between the substrate and coating while simultaneously addressing issues such as thermal expansion coefficient discrepancies and weaving. However, due to limitations in the thickness of the coating that can be achieved using this approach, it may not be appropriate for high-load or high-wear service conditions. For example, researchers used the concentrated gradient diffusion features of carbon atoms in cast iron to produce a Ti-C/Ti gradient design coating on pure titanium using solid carburization. This resulted in a coating with improved bonding strength in comparison to a homogeneous TiC coating. Although this method has potential for improving coating performance in high-stress environments, further studies are required to evaluate its effectiveness in diverse applications [102]. The hardness rose steadily from the coated surface to the substrate, from 25 GPa to 32 GPa. The Ti-C / Ti gradient design cladding considerably enhances the bonding strength (50 N) between the substrate and coating when compared to a homogenous TiC coating (38 N).

3. MULTISCALE DESIGN CLADDING

The concept of "multiscale hybrid reinforcement" was developed in the 1970s to describe the use of mixed reinforcement in resin-based composites that utilize different scales, morphologies, and phases to maximize their benefits and overall performance [104]. The main objective of this approach is to reduce costs and increase the material's versatility. By incorporating different types of reinforcement, these composites can take advantage of their unique properties and improve their overall characteristics. In summary, "multiscale hybrid reinforcement" involves combining multiple types of strengthening phases with varying feature parameters to create composites that exhibit superior performance [105]. Materials research has recently included the structure concept of "multiscale hybrid reinforcement" into the coating design, which was inspired by this study. In traditional single homogeneous coatings, the "inverse relationship" between resistance to wear (hardness) and toughness is assumed to be allayed and balanced through multiscale microstructure configuration to generate a multiscale design coating with toughness, high hardness, and high wear resistance [20–22]. Particle (WC, TiC, etc.), whisker, and other forms (1-D carbon nanotube, 2-D graphene nanoplate, graphene oxide, epoxy, and so on) are the several types of strengthening phases that may be employed for multiscale design coatings. Particle + particle [105] whisker + whisker [106,107], particle + whisker [108–110], and particle + others are the four most prevalent hybrid kinds in multiscale design coatings. The multiscale design coating (TiBw + TiB2p + TiCp) / Ti exhibits excellent toughness (5.65–6.97MPa/m^2), along with higher hardness (1200HV0.5) and higher wear resistance. Furthermore, Taheridoustabad et al. [111] created a (TiB2p-nm + TiCp-nm + RGO + GO) / Ti multiscale design coating on Ti-6Al-4V via electro - discharge cladding. When compared to an untreated base material, the composite cladding considerably improves the coating resistance to wear (8.5 times) and the substrate hardness from 339 HV to 1313 HV. Research has indicated that the creation and preparation of multiscale design layers on the surface of titanium alloys is a promising approach for extending the serviceability of these materials. The effectiveness of this approach hinges on incorporating suitable hybrid strengthening phases in the coating design, in the right amounts and proportions, to leverage their individual benefits and achieve synergistic effects. This can lead to the development of coatings with superior properties, such as high toughness, wear resistance, and hardness. Nonetheless, the use of multiscale design coating strengthening elements is still in its nascent stages and requires further refinement through quantitative techniques.

4. LAYERED DESIGN CLADDING

In recent years, a surface deposition technique has been used to create a micro/nano-scale layered design coating on titanium alloys by depositing two or more materials with different properties alternately. This is considered one of the most efficient methods to enhance the mechanical characteristics of the cladding, such as wear resistance, toughness, and load-bearing capacity, without compromising on hardness [113]. The improved overall mechanical characteristics of the cladding are due to two factors. Firstly, the large volume fraction interface structure present in the layered design coating increases both toughness and hardness simultaneously [114,115]. The structure of the interface has the ability to absorb and dissipate fracture energy, modify the crack growth direction, cause crack bifurcation and deflection, and thus reduce the generation force and crack growth [116]. Additionally, it can inhibit dislocation movement, leading to an increase in hardness [114-116]. Secondly, a layered design coating can create a multifunctional combination of various component layers, such as ceramic-ceramic and metal-ceramic. The material of the component layers is not a determining factor, as they can all be classified into soft phase and hard phase layers. Under external stresses, cracks tend to form and propagate within the hard phase layer of the coating. The presence of a soft phase layer with high damage tolerance can prevent fractures from propagating further by bridging, deflecting, or passivating them. A large and continuous soft phase layer can effectively mask the crack tip as it extends toward the interface between the layers [116]. Therefore, the multifunctional combination of hard and soft layers results in a high hardness and a high damage tolerance for the layered design coating [115,116]. For example, Ye et al. [113] used the indentation approach to analyze the toughness of homogeneous and layered design coatings and employed FIB technology to examine the indentation morphology. Ma et al. [117] also employed a multi-arc ion plating process to develop a Ti-Al-Si-N coating with a homogeneous structure and a Ti-N / Ti-Al-Si-N layered design on titanium alloy. When compared to the Ti-Al-Si-N homogeneous structure cladding, the Ti-N / Ti-Al-Si-N layered design coating greatly improves resistance to wear, bonding strength, and hardness of the coating.

The toughening mechanisms in a material aim to promote deformation and plasticity, which can help to prevent or slow the propagation of cracks through the material, while the strengthening mechanisms aim to increase the strength and hardness of the material by limiting the movement of dislocations and other defects within the material. As a result, the aforementioned two requirements must be satisfied to attain higher toughness simultaneously. The mobility of dislocations and the initiation and propagation of cracks in layered design coatings, which ultimately determine the toughness and strength of the coating, are directly influenced by the modulated period, modulation ratio, and type of interface between the component layers [112,115,118,119]. As a result, the focus of this section will be on the effect of the modulated period, modulation ratio, and component layer interface type on the layered design coating performance.

The toughness, hardness, and resistance to wear of the coating are affected by the thickness of the layered system. Cracks start in the hard phase layer and propagate faster, whereas the soft phase layer with high damage tolerance is responsible for fracture bridging, deflection, energy absorption, and toughness enhancement [116]. The coating's mechanical properties are at their optimum when the modulation ratio comes to the threshold value [113,118–120]. When the modulation ratio is altered, Dang et al. [119] found that a critical value must be attained for the coating's toughness, resistance to wear, and hardness to be maximised. Jeyaprakash et al. revealed 2.39 times enhancement in microhardness and two times improvement in resistance to wear compared to base material [96].

The type of interface between component layers plays a significant role in determining the grain size in the constituent layer, which can be classified into three categories: coherent interface, semi-coherent interface, and interface with a transition layer on a microscopic scale. Wiecinski et al. [112] produced CrN-TiN layered design coatings with coherent interfaces, Ti-TiN layered design coatings with semi-coherent interfaces, and Cr-CrN layered design coatings on the surface of Ti-6Al-4V using the interface of Cr2-N transition layer. The Cr-CrN layered design cladding demonstrated the smallest grain size among coatings with the same component layer thickness due to the Cr2-N transition layer, which effectively impedes the growth of columnar crystals. Conversely, the CrN-TiN layered design coating displayed the largest grain size due to its low-strain coherent interface, which promotes grain coarsening. Similarly, the Ti-TiN layered design coating had a larger grain size due to the low strain.

Therefore, employing different types of interface designs within the coating can regulate grain size, allowing for flexibility in adjusting coating performance.

5. CONCLUSIONS AND FUTURE PROSPECTS

The development of new cladding designs for titanium alloys has addressed the challenge of balancing wear resistance and toughness, which has traditionally been a trade-off in single homogeneous cladding designs. These new designs, inspired by high-performance natural materials, include layered, multiscale, and gradient cladding. However, the current limitations of these designs include a relatively basic microstructure design and a reliance on a single mechanism for strengthening and toughening. As a result, there may be limitations to further improvements in wear resistance, toughness, and hardness. Future research in this area should aim to address these limitations and explore new pathways for improving the wear resistance of titanium alloys.

5.1 Application of intelligent manufacturing technique in the cladding process

Conventional surface modification techniques are utilized to increase the wear resistance of titanium alloys by producing coatings with superior toughness and hardness. However, the creation of coatings with precise spatial designs is a complicated process that restricts their applicability in industrial settings. Hence, advanced manufacturing technologies are needed to produce wear-resistant coatings with suitable designs and shapes. In recent years, 3D printing additive manufacturing technology has emerged as a promising solution to produce coatings with higher toughness and hardness. This technology offers precise control and design of microstructure, making it more efficient than traditional preparation methods. Moreover, 3D printing technology can produce near-net-shape products, eliminating the need for additional material processing and increasing production efficiency.

5.2 Optimization of the process parameters

To create resistant-to-wear cladding with better toughness and hardness, multiscale strengthening and toughening based on bionic structural design can be used. As a result, interface structure, various morphologies, different elements, and various levels in the cladding must be enhanced to increase coating efficiency. New structural coatings, depending on particular application circumstances and performance criteria, should be designed simultaneously to broaden the application regions of titanium alloy coating.

5.3 Application of numerical simulation technology

For material research and development in the past, the "propose hypothesis-experimental verification" process was widely utilised. This research approach takes longer time and effort to complete the growing industrial demand for novel materials. Numerical simulation and computation have become an essential aspects of research in materials due to the rapid advancement of computer technology. To analyse the coating structural design and mechanical features simulation, numerical simulation and calculation analysis may be employed, which will reduce the limitations of experimental settings. The authors propose a technical road map for the production of resistant-to-wear coatings with superior toughness and hardness on the surface of titanium alloy based on the above description.

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