Industrial Application of Laser Cladding for Enhanced Properties

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ABSTRACT Laser cladding (LC) has become a revolutionary surface engineering technology for reducing corrosion, wear, and material degradation in key components like pipes, valves, and structural fittings. This review provides an in-depth overview of the latest developments in LC, with a special emphasis on the integration of high-entropy alloys (HEAs) as novel cladding materials. HEAs are capable of providing better mechanical strength, thermal stability, and corrosion resistance than traditional alloys and thus are exciting material candidates for future industrial coatings. The article also points to the use of LC across aerospace, automotive, energy, and biomedical industries, highlighting its capability to produce defect-free, high-performance coatings with minimal thermal distortion and high geometric control. In addition, the review points out existing challenges in LC—namely non-uniform clad quality, initial capital costs, and industrial-scale application of HEA-based coatings—towards establishing research directions for the future like process control by AI, in-process monitoring, and material design. By filling these gaps, the research contributes rich insights into the contribution of LC in lengthening the functional life of components, fostering sustainability, and innovation in advanced manufacturing.

Keywords: Laser Cladding (LC); Corrosion Resistance; Wear Resistance; Industrial Coating; Material Degradation; Surface Engineering; Tension Cracks; Sustainable Manufacturing; High-Precision Coatings.

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1. Introduction

High entropy alloys (HEAs) have gained significant technical interest in the last few years as next generation materials for surface engineering, particularly for use in laser cladding[1]. HEAs differ from standard alloys with one, or two, principal elements; they are composed of five or more major elements in near equiatomic proportions. The compositional structure of HEAs provides thermal stability, high hardness, wear resistance and corrosion resistance, and mechanical performance in extreme conditions, which are desirable in extreme operational environments typically experienced in aerospace, automotive, marine, and biomedical engineering [2]. The process of laser cladding allows HEAs to provide these advantages in a combined benefit, as high energy density, rapid solidification, and material precision enables the construction of quality coatings with fine microstructures and robust, metallurgical bonds[3]. With increased efficiency, laser cladding also prevents dilution and elemental segregation, which is advantageous in maintaining the complex phase composition characteristic of HEAs[4]. The capability to produce laser cladded HEA coatings (LC-HEACs) represents the first significant leap forward in light of the long-standing consideration of HEAs in materials engineering and offers greater performance than traditional cladding materials for hardness, erosion, and thermal stability, and these developments suggest that LC-HEACs can significantly enhance the durability and longevity of critical components in industrial contexts[5].

Although there are well-known benefits and increased interest for HEA based laser cladding, there are some barriers that prevent its wider industrial implementation[6]. One of the primary barriers impeding implementation is ensuring homogeneous elemental distribution in the deposition, which can critically determine phase formation, hardness, and corrosion resistance[7]. Furthermore, some HEAs use costly rare or refractory elements, which can prevent broader industrial use. Another barrier is the difficulty in fine tuning process parameters of laser systems (i.e. laser power, scanning speed, and powder feed rate) to prevent defects such as porosity or cracks[8]. Additionally, there is limited real-time monitoring and feedback control, which can lead to a significant disparity in coating quality. Proposed future work to address these barriers includes exploring AI and machine learning algorithms to create intelligent, closed-loop control of the laser cladding process[9]. With these types of systems, processing parameters could adjust automatically and in real-time, providing a more consistent and defect-free coating [10]. Additionally, hybrid manufacturing such as using HEAs and laser-directed energy deposition (LDED) can provide exciting possibilities for fabrication of functionally graded materials with desired performance properties[11]. Expanding research in these contexts will be a key course of action needed to establish LC-HEAC as a viable solution for high-performance industrial applications[12]. High-entropy alloys (HEAs) offer superior corrosion resistance, thermal stability, and wear properties, making them ideal for laser cladding. However, challenges remain in cost, uniformity, and process control, requiring further research into AI integration and hybrid manufacturing techniques[13].

Laser cladding has numerous uses but the most important one is in surface hardening also known as hard facing. [14]. By depositing a wear-resistant layer on a substrate, the technology improves the surface hardness of components, particularly alloy steels [15]. For instance, low carbon steel alloy steel weld cladding increases surface hardness provided amount of heat input [16]. The process involves the permanent joining of two dissimilar metallic materials—a substrate and a clad material—through coalescence formation [17]. However, a significant number of problems resists the achievement of 100 % first pass weld cladding and these include formation of crack caused heat induced difference in the rate of contraction between the substrate and the cladding material [18]. These include: avoiding elements which cause formation of cracks, applying buffer layers and utilize tubular electrode with the aid of preheating [19]. Laser cladding also has unique benefits when applied to a concept like the rapid prototyping and additive manufacturing. [20]. By surpassing the constraints inherent in traditional aluminum process, the use of lasers facilitates the creation of creative buildings effectively rated parts, and renovated portions [21]. Coatings to this technology offer a magnified capability in thermal control, shorter manufacturing time, and better mechanical performance, making it highly useful in areas of high precision and reliability [22].

In light of the contemporary trends in advancement of nautical sectors or demand for elements with resistant to corrosion, the use of lasers is considered to be among the most significant innovations in surface technology. SS equipment parts, structures, and systems operating in seawater environment are highly susceptible to corrosion that results to materials failure, cost implications and safety concerns [23]. Current surface technologies like laser cladding is a good way of solving corrosion problems by changing the surface characteristics and composition of the material [24]. High-entropy alloys (HEAs) are gaining curiosity as innovative compounds for surface enhancement due to their exceptional properties, including their ability to prevent erosion, attrition, and exceptional ability [25]. Laser cladding is particularly suited for preparing HEA coatings due to its high energy density, adjustable dilution rates, and rapid processing speeds [26]. Laser cladding is superior to common coating techniques in that the elements are distributed evenly and the problem of element segregation does not occur, greatly improving the corrosion properties of coatings [27]. Furthermore, I think that the prospects are to exploited the ability of HEAs to create a ‘cocktail ‘of elements that improve anti-corrosion properties of the coatings, the selection of elements with enhanced properties for use in the coatings [28].

This review presents a comprehensive and integrated analysis of laser cladding (LC) technology with a special emphasis on the application of high-entropy alloys (HEAs), a topic that has received limited consolidated attention in previous literature[29]. While earlier reviews tend to address either the technical mechanisms of laser cladding or the general performance of HEAs, this work bridges both areas by focusing on the synergistic potential of LC-HEACs (Laser Cladded High-Entropy Alloy Coatings. This combination offers significant improvements in wear resistance, corrosion resistance, and thermal stability across diverse industrial sectors such as aerospace, automotive, biomedical, and energy[30]. Furthermore, the review highlights the comparative advantages of LC over traditional coating methods and introduces emerging trends such as the integration of artificial intelligence (AI) for real-time process control, parameter optimization, and defect minimization [31]. By identifying current research gaps—including uniform element distribution, cost-efficiency, and advanced process modelling—this study provides a forward-looking perspective on how LC-HEA systems can evolve through interdisciplinary research. As such, this review not only summarizes current advancements but also serves as a strategic framework for future investigations, offering valuable insights to researchers, engineers, and decision-makers in the field of surface engineering and advanced manufacturing[32]. As a result, this review not only summarizes the state of the art but has also developed an outline for future work and will offer important reference points for researchers, engineers and policy-makers working in the fields of surface engineering and advanced manufacturing.

1.2 Laser Cladding Technology

Techniques for laser deposition, such as laser surface alloying (LSA) [33], laser remitting [34], High-energy density, high solidification rates, minimal dilution, improved metallurgical bonding, nominal distortion in clad geometry, fewer crack gaps, mobility regarding the possibility of applying it in entirely computerized mode, and the possibility to produce siding with irregularities structure and greater surface attributes as erosion, burning, along with durability against wear represent a few during the explanations why laser cladding (LC) has grown promptly in the past couple of decades [35]. A high-intensity laser beam irradiation is used to facilitate the interaction between the laser beam and the substrate in LC, a multidisciplinary manufacturing process that melts the clad material and deposits it onto the substrate, as shown in Fig. 1. The process of laser-material interaction is shown in Fig. 2. After the substrate was mixed with the clad material, the energy it had absorbed caused it to melt and then re-solidify. High-energy density is used to evaluate the laser radiation [36] [37]. The clad material's quick rate of quenching produces hard phases and an ultrafine microstructure. During this process, argon is supplied as a shielding gas to stop oxidation, inclusions, and other flaws in the clad. [38], [39], [40].

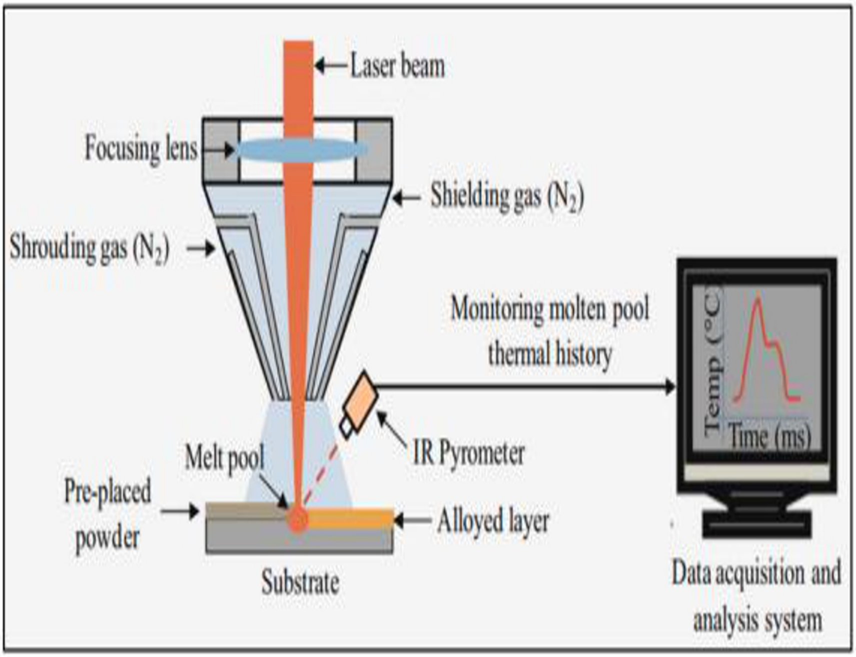

Fig. 1. Diagrammatic illustration of laser cladding technique in which the powder is pre-placed on the substrate surface while an inert environment is created by the shielding gas from the coaxial nozzle.

The four main areas of laser cladding are the base/substrate zone, the interfacial/bounding zone (IZ/BZ), the heat-affected zone (HAZ), and the cladding zone (CZ). One of the primary advantages of the LC technique is its restricted distortion and small HAZ, that's prohibit metallurgy alteration to the material being examined [41], [42], [43]

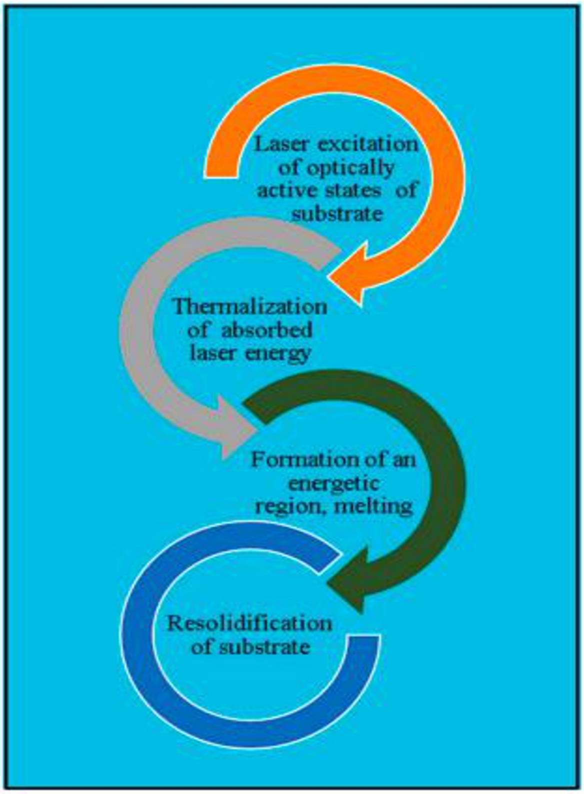

Fig. 2. The energy from the laser beam was absorbed to create a melted area, which was then resolidified when the laser beam moved away. This flow diagram illustrates the many stages of the laser-material interaction during the LC process.

One promising method that is frequently used for the synthesis of HEACs is LC. Comparing this method to more traditional methods for HEA preparation, like casting, magnetron sputtering, plasma arc cladding, and the electrospark process, revealed improved surface characteristics. Using these methods, HEAs were applied layer by layer to the various substrates, creating clads that ranged in thickness from a few microns to several millimeters. [44].

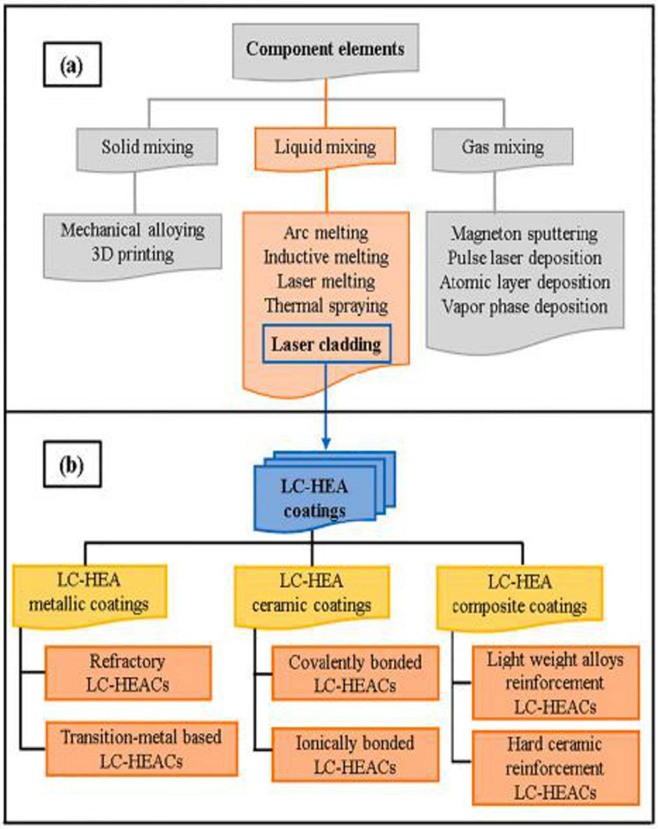

Fig.3 (a) HEA synthesis pathways where laser cladding falls under liquid mixing; (b) LC-HEAC classification according to element kinds

As depicted in Figure 3b, LC-HEACs are categorized into three distinct categories according to the literature that has been published up to this point. Regarding metallic coatings, LC-HEA-based coatings are divided into two categories: transition metal-based LC-HEACs and laser-cladded refractory high entropy alloy coatings (LCRHEACs). Based on transition metals, LC-HEACs contain transition elements such as Al, Cr, Co, Mn, Cu, Ni, Fe, and Ti. Phase Development and Characteristics of Laser Cladded Al2CrFeNiMo x High-Entropy Alloy Coatings | Journal of Thermal Spray Technology However, LC-

RHEACs are made up of elements including Nb, W, Zr, V, Hf, and Mo that melt at high temperatures. [45]. HEA materials are combined with oxygen, boron, or any other element that has a negative charge in order to create ionic or covalent bonds in ceramic-based coatings that are manufactured using LC-HEA. Al, Cr, Ti, Nb, and Zr are some of the elements that are present in these claddings. These elements have a significant affinity with borides, carbides, or nitrides [46]. HEA components serve as a binder or matrix in LC-HEA-based composite coatings, which are reinforced with ceramic particles (TiN, NbC, TiC) or lightweight alloys (Al, Mg). [47], [48], [49]. According to the current research that is being conducted in the subject of laser surface engineering, this classification system will be developed even further in the future. There is a distinction among LC and LSA:

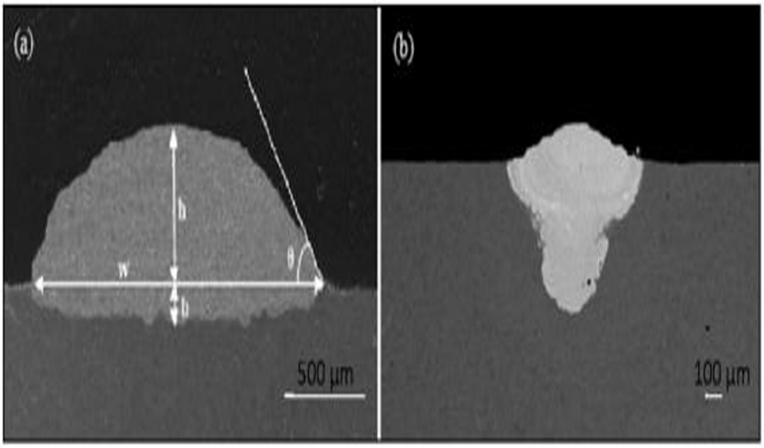

Fig. 4. Scanning electron micrographs illustrating the distinction between the clad geometry of LC and LSA

The preparation procedure, which entails the mingling of the clad element with the base, is one of the many major variations in the LC along with an LSA. It can be expressed by means of diluting percent and means the proportion of the length of the clad

(d) to the general dimension of the clad, that is, the sum of the height of the clad (h) when the depth of the clad (d), as illustrated in Figure 4. It is unattainable to prevent the incidence of dispersion when employing such as regarding these techniques. The LSA technique, in contrast, permits a considerably higher their level of attenuation as opposed to the LC tactic. The interface of the cladding exhibits a lower level of diffusion, as seen in Figure 4a. Furthermore, the dilution of laser clad with excellent interfacial bonding can be decreased to 10% by adopting optimised laser processing conditions. This is possible [50]. On the other hand, there was no discernible difference that was reported (refer to Figure 4b), which also demonstrated that the dilution percentage of the LSA technique is more than that of the LC technique [51]. It is important to point out that the LC and LSA are not very different from one another, and that the latter has not been defined in a precise manner according to the literature that has been documented[52].

2. The process of laser cladding

For a wide range of industrial applications, the laser cladding method is of utmost significance. This method makes use of a variety of nozzles, each of which generates a laser beam in a continuous manner. Furthermore, the laser beam interacts with a variety of particle mixtures, resulting in the melting of the particle and the formation of a layer of powdered material on the top layer [53]. It is also referred to as hard confronting or appearing and it is designed to improve the features of the base (base metal). The procedure is conducted using such as a pulse of laser energy or a spark as a means of heating [54]. Prior to being ground to achieve the final measurement, the infill material utilized in the process is applied layer by coating until the amount needed is addressed [55]. Laser cladding offers numerous advantages over typical treatment methods[56]. Laser cladding exhibits significantly superior efficacy in comparison to other methods. It offers the potential to create an innovation that is capable of rebuilding. The approach has been employed for fixing physical systems [57].

Table 1. Types of Clad Materials

Powdered metals	Chrome base, Nickel base, Cobalt base, Fe base
Powdered ceramics	WC, SiC, TiC, Al_2O_3, ZrO_2

Despite the fact that there is numerous other methods requiring further time and resources, laser cladding has a viable alternative to dispersion approaches[58]. There is a diverse selection of substrate materials, including steel made from carbon, element metals, stainless steel, or nonferrous alloy elements. Table one illustrates that there exist two separate kinds of clad fabrics. The cladding material is inserted onto the base material, as well as melt ponds are formed utilizing the pre-placed power skills, blowing or extruded powdered substance, and cables feed[59]. The laser cladding is subject to a variety of process variables. Pre-powder thickness, powder flow rate, nozzle angle, stand-off, laser energy, laser spot size, laser scanning speeds, or comparable work-piece motion speed are the main parameters. The relationship between cause and effect for the laser cladding process is depicted in Figure 2, which groups the parameters of the procedure into the following five main categories: variables of the machine Features of the laser beam, the products, the laser clad, and the cladding particles [60]. In order to optimize a procedure, it is imperative that you have legitimate oversight of the method's settings. Laser cladding is employed for rapid development, restoration, and healing, in addition to the coating. In Table 2, an overview of the many possibilities is presented [61].

Table 2. Application areas of different laser cladding materials

S. No.	Coating Material	Applications	Authors	Concluding Remarks
1	Ni-base superalloys	Blades for turbines, components for mining machines, and air folds	Damboreana et al. [62], Wang et al. [63], Xue and Isdam[64], Mazumder et al.[65], Xue et al. [66], Bohrer et al.[67], Gaumann et al. [68]	Researchers observed improvement in the fatigue endurance and service performance of cladding of nickel-based superalloys compared with conventionally processed parts.
2	Ni-Cr3-C2	Well drilling and oil extraction equipment	Katipli et al. [69]	After doing research, the authors discovered that coating offers superior erosion resistance in the components as compared to the substrate.
3	Inc625-CrC	Gas turbine airfoil thermal barrier	Gaumann et al. [70]	It was discovered that the covering and substrate materials bonded well.
4	Stellite 6, Stellites	Seal runner, gate valve, torsion shafts, injection molds, and extruder parts	Bruck[71], Mazumder et al. [72]	After doing research, the authors discovered that coating offers superior erosion resistance in the components as compared to the substrate.

S. No.	Coating Material	Applications	Authors	Concluding Remarks
5	316L	Blade integrated disks, injection molding tools, turbine blades	Fessler et al. [73], [74]	Researchers discovered that the laser cladding process was causing thermal strains in the components.
6	316L-Stellite12	Functionally graded materials (3D objects)	Yakovlev et al. [75]	The authors used laser cladding technique to successfully create the FGM structures.
7	316L-Stellite12-Fe-Cu-WC/Co-CuSn-bronze	Components of cooling systems in International Thermonuclear Experimental Reactor	Yadroitsava et al. [76]	It was found that adding Fe-Cu-WC/Co-CuSn-bronze to 316L improved the coatings' smoothness..

S. No.	**Coating Material**	**Applications**	**Authors**	**Concluding Remarks**
8	Al-Ti	Cutting tools, inserts, diffusion barriers in semiconductor technology	Katipli et al. [77]	The laser cladding technique revealed that coatings were quite effective at preventing wear.
9	Al-Cu alloy	Automotive industry	Dubourg et al. [78]	By laser cladding Al-Cu alloy, researchers were able to create extremely dense coatings that are appropriate for the automotive sector.
10	Al-Si	Cylinder heads and blocks	Mazumder et al. [79]	The authors noticed that hardness increases when Si content is added to Al.
11	Al/Si-TiC	Automotive industry	Dubourg et al. [80]	It was found that adding Si and TiC components to Al greatly increased its adhesive wear resistance.
12	Cu-Ni	Engine components, ceramic turbine components, direct metal tools, drug	Shin et al. [81]	Researchers discovered that the component's overall coefficient of thermal expansion was negative.

S. No.	Coating Material	Applications	Authors	Concluding Remarks
		delivery devices, armor and armament components, building blocks for temperature-insensitive structures		
13	Ti6Al4V	Large aerospace components, hollow motorcycle engine stems	Arcella et al. [82], Capshaw	It has been found that parts produced by laser cladding technique were better than that of cast and wrought iron products.
14	TiC–i	Propulsion system and airframe of space planes	Liu et al. [83]	The authors found that the TiC-Ti laser cladding layer successfully inhibits the development of cracks.
15	TiC-90MnCrV8	Tools and molds	Axen et al. [84]	Researchers found that as the amount of carbide increases, the coefficient of friction drops.

S. No.	Coating Material	Applications	Authors	Concluding Remarks
16	WC-20Ni4Mo	Teeth of rock bits, cutting tools	Beidi et al. [85]	It was discovered that laser cladding of WC-20Ni4Mo coatings greatly enhanced the hardness of rock bits and cutting tools.
17	WC-NiCrB	Oilfield and forestry industries	Marchione et al. [86]	Researchers found that alloy coatings improved erosive wear resistance.
18	H13-Ni/Cr alloy-TiC	Mold inserts	Jiang et al. [87]	The authors discovered that coarse grains were formed as a result of the heating generated during the laser cladding process.
19	H13 tool steel	Molds and dies	Hu et al. [88]	Coating was found to increase the surface's hardness.
20	CPM 9V tool steel, CPM 15V tool steel	Rotary cutting dies	Rafiaei et al.[89], Xue and Islam [90]	The coating produced by the laser cladding process increased the resistance to abrasive wear.
21	Rene 80, Inc625	Turbine parts	Mazumder et al. (Mazumder et al., 1997)	The authors discovered that in order to get a good bonding of the deposited layer, the substrate has to be remelted.
22	Cr-CrB2, Mo-MoB	Automotive, aerospace, paper, and plastic	Rajput et al. [92]	Researchers found that chromium-based coatings improved the steel substrate's resilience to erosion and sliding wear.

S. No.	Coating Material	Applications	Authors	Concluding Remarks
		industries		
23	Zn-Al	Propeller and drive shafts, engine components	Carvalho et al. [93]	Strong metallurgical bonds were formed between the substrate and the coatings produced by laser cladding.
24	YPSZ, YPSZ-Al_2O_3	Gas turbine engines	Jasim et al. [94]	The researchers concluded that it was possible to produce two layers of thermal barrier coating on gas turbine engines, each with a distinct topography, after conducting their examination.
25	AISI 410	Valve seat	Kathuria et.al [95]	The authors' findings showed that coatings produced by laser cladding on valve seats were sound, with little distortion or dilution.

3. Industrial Application of Laser Cladding

Laser cladding assumed a major role in surface engineering technologies that aim to enhance properties of shield, deposition and improve mechanical properties, wear resistance and anti-corrosion properties [96]. Laser energy can be delivered precisely with minimal dilution and stress, and microstructure manipulation makes it applicable in aerospace, automotive, and energy manufacturing [97]. The following subtopics bring forth the best understanding of laser cladding with emphasis on aerospace industry [98].

3.1 Aerospace Industry

Laser cladding is quickly growing in the aerospace industry because of its potential for repairing costly apparatuses, enhancing material characteristics and increasing apparatus service times [99]. Both turbine blades and landing gears as well as other crucial parts of the engine operate under high temperature, corrosive treatment, or mechanical stress. Laser cladding as a restoration and improvement technique has been found useful in these components [100].

Components in jet engine or any industry are often subjected to conditions such as high temperature, oxidation and wear and tear that over time could lead to depletion of the turbine blades [101]. In contrast to conventional restoration techniques, for example, welding the mentioned organs produce residual stresses and thermal deformations. Compared to that, laser cladding gives a well-planned and ideal manner to mend these components without affecting its strength in a negative way.[102] and/search/ Ni/ based alloy in the repair of Inconel turbine blades. They established the fact that the laser-cladded coating had better adhesion factor, wear resistance as well as mechanical properties at high temperatures than repair welding [103]. The work identified that utilizing cladding process ensured that dilution of base materials was minimal while the microstructures were designed to enhance the functionality of the repaired blades in challenging conditions [104]. Due to friction and wearage, that is more often experienced by components in aerospace systems, their efficiency and safety of operation are compromised. One way out; through laser cladding; where wear resistant materials such as cobalt based and tungsten carbide reinforced materials could be deposited on these components. For instance, [105] examined the application of Stellite 6 coatings for enhancement of wear resistance on aerospace materials. From their study, they showed that laser cladding provided dense and sound material deposits and strong metallurgical bond thereby enhancing the life of the parts. The process also provided the best deposition in the complicated shape that is required for the aerospace parts due to the geometrical shape [106].

Aerospace part corrosion is a major problem when parts are exposed to high humidity or in saline atmospheres. It allows deposition of corrosion-resistant metals including stainless steel and nickel based superalloys to reduce the chance of failure in those sections [107]. only proved the possibilities of using laser cladding employing Inconel 625 to enhance corrosion protection of aluminium aerospace alloys. The investigation showed that cladding created a metallurgically bonded layer of coating with very low porosity and excellent coalescence [108]. The coated components also showed very low propensity for pitting and intergranular corrosion thus making them ideal for corrosive service. Laser cladding also offers important benefits to the enhancement of material characteristics and reducing weight in aerospace parts while maintaining or enhancing the surface characteristics of lightweight substrates. This is more relevant today in light of durability and increased fuel efficiency to invent new materials and parts for the construction of aircraft that have less weight. focussed on the feasibility of laser cladding on titanium alloys which has great importance in aerospace industry due to its desirable strength to weight ratio. In a study they revealed that after laser cladding, these components enhance features include; hardness, fatigue strength, and thermal stability that allows for further use in such important zones notwithstanding weight loss [109]. Laser cladding is also incorporated into the various hybrid manufacturing system like laser-directed energy deposition where cladding and 3D printing are combined [110]. This method also enables the development of intricate geometries and the rehabilitation of substantial elements with enhanced trait behaviors [111]. Studied the prospects of using LDED in repair and fabrication of aerospace parts and components. In their study, they demonstrated the possibility of using this technique to fabricate functionally graded materials and designs to fit the exacting demands of aerospace applications. Laser cladding can be integrated with other manufacturing techniques that are revolutionizing engineering especially the aerospace engineering [112].

3.2 Automotive Industry

The automotive industry requires automotive parts that provide high performance, long endurability, and high anti-wear and anti-corrosion capabilities. Laser cladding satisfies these requirements making it a versatile technology that is widely used to improve engines and other automotive parts [113]. The subsequent subsections elaborate the particular cases and investigations. Crankshafts have very important functions of reciprocating linear movement of the pistons into rotational movements. It means that the material shall possess high wear resistance and fatigue strength as a result of frequent mechanical and thermal loads. applied laser cladding technology using WC-Co based materials to enhance the crankshaft wear. In their study they found that laser cladding of crankshafts improved them by increasing the wear resistance by 25% as opposed to more conventional manufacturing processes. Each of these results hints at the feasibility of using laser cladding to increase the lifetime of the engine parts [114].

Piston rings and cylinder liners are subjects of high friction and high temperatures. Studies by [115] demonstrated that laser cladding with Ni-based alloys significantly enhanced the wear resistance and hardness of piston rings. The laser-clad coatings reduced friction coefficients by 30%, improving engine efficiency. Similarly, Xinlin Wang et.al [116] applied laser cladding to cylinder liners, achieving a substantial increase in thermal resistance and reducing wear rates by 20%. Laser cladding has proven effective in refurbishing valve seats and guides, which endure high impact and thermal stresses. According to Maria Bogdan et al. [117], laser cladding of Co-based alloys for valve seats, improved hardness and reduced thermal cracking were reported. It also revealed a decrease in the amount being spent on maintenance because of the duration of the components [118].

Subassemblies of gear systems in car transmissions are confronted with highly Mechanical loads and wearing out. Chuang Guan as part of the research demonstrated that laser cladding can enhance the surface hardness and fatigue limit of gear systems. The study also revealed that laser cladding extended the life of gears by 35% relative to a traditional treatment of the gears. Due to this, brake discs demand supremacy in terms of wear and heat treatment for car safety purposes [119]. The application of laser cladding with the ceramic reinforced metal matrix composites in improving brake disc ability. The results revealed that the application of the technique enhanced braking with the least thermal cracking, which makes it a potential substitute to regular manufacturing processes [120].

3.3 Oil and Gas Industry

Since corrosion is a major problem in the oil and gas industry, pipelines, valves, and other instruments are in the line [121]. It has been possible to use laser cladding to transfer alloys with inherent protection from corrosion on the surface of these parts. Laser cladding of stainless steel and Ni-based materials with increased pipeline material life in conditions of high salinity and aggressive chemise [122]. In the same manner, the use of Co-based alloys in cladding activities to minimize effects of H2S on corrosion in drilling processes. Equipment in use in the extraction of oil and gas experiences a great level of wear since it has to deal with abrasive material, high pressure and temperature variations [123]. Laser cladding provides a sound procedure for forming hard-faced layers by using materials such as tungsten carbide and chromium carbide. According to [124], cladding with tungsten carbide composites improved the wear resistance of drill bits by up to 45% compared to traditional methods. Another study by[125] offered improved ability to withstand wear in the impellers of used pumps and helped cut on the expenses incurred on maintenance [126].

The high working temperatures characteristic of several oil extraction processes requires materials with high thermal resistance. Laser cladding of Ni-based superalloys has been reported to possess enhanced mechanical properties as those of deposited metals at high temperatures. For instance, observed notable thermal performance enhancement when NiCrAl alloys were used on heat exchangers working in offshore platforms. Apart from having excellent thermal characteristics, these materials can also endure thermal fatigue [127]. Another undesirable effect observed in the oil and gas industry is fatigue failure that affects rotating and cyclically loaded members. Laser cladding provides a technique of eliminating fatigue crack initiation mainly because of the formation of smooth and dense surface. In a study by [128], By cladding the drill pipes with Ti-based alloys it was possible to extend the fatigue life of the pipes by about 60% [129]. This improvement was said to have been achieved as a result of minimization of surface defects and generation of compressive residual stress during cladding. One of the significant benefits of laser cladding is the potential to restore and reconstruct costly functional parts properly [130]. As compared to the IWC method where worn parts are removed before other brand new ones are fitted, laser cladding offers localized material depositions to bring back its actual size and properties [131].

The study on Laser Cladding of Inconel 718 Alloy for the repair of Off shore Turbine Blades. This had the dual advantage of minimising costs and decreasing time lost in important processes [132]. One typical problem associated with flow of fluids containing solid particles is the erosion resulting from their impact in pipelines used in the oil and gas industries [133]. Moreover, experimental and theoretical analysis to reduce the wear of components due to erosion has been done; laser cladding with Stellite alloys successfully tackles this problem [134]. A study by Davis Vannasing it was shown that application of Stellite 6 cladding decreased the erosion rate of pipeline bends by approximately 70% and, therefore, increasing their service life. Hydrogen embrittlement therefore remains a significant concern in high pressure gas contexts especially in ultra-deep water conditions [135]. Laser cladding has been used to deposit material that is resistant to Hydrogen diffusion and cracking. Overview of an application of duplex stainless steels for cladding of subsea connectors demonstrating a good resistance to hydrogen induced cracking after long periods of exposure [136].

3.4 Biomedical Engineering

Application of Ti6Al4V alloy cladding for enhancement of compatibility of medical instruments. Through strength and corrosion resistance, Ti6Al4V has found practical applications in manufacture of orthopedic and dental implants [137]. But, laser cladding was used to perform its surface with enhanced characteristics for better affinity with the biological tissues. This technique improves the cells attachment features and minimizes the chances of implant rejections and therefore can be considered as one of the most likely future developments of medical devices. In applications where the implant is subjected to heavy stress there is always the problem of wear and corrosion which greatly reduces the life expectancy of the implant. [138]. Laser cladding process for the deposition of cobalt-chromium (Co-Cr) alloys on orthopedic implants: A review. This study showed that the surfaces treated by laser cladding showed better wear properties and constant corrosion characteristics than the implants treated by using conventional ways. This advancement minimizes implant replacement operations while improving patient results [139].

With implant therapy one of the difficulties in oral surgery is achieving anti-sepsis after the procedure has been completed.[140] investigated the application of cladding by laser, to develop layered coatings of silver-added titanium for operation implant apparatus. The current coatings were proved to possess high antibacterial efficacy and biocompatibility [141]. They are essential for the prevention of implant-borne infections in particular. The newest trends in laser cladding are its combination with the methods of additive manufacturing to create individual medical implants. Long Bai et al.[142] emphasized that using the laser cladding technique, successive layers of biomaterials can be applied to create an implant tailored for the individual patient. This is especially applicable for intricate surgical procedures where standard implant dimensional specifics do not meet anatomical considerations. Many medical devices and implantations need some form of refitting and repair due to regular wear or damage. Consequently, laser cladding proved to be a low cost option for repairing these components [143]. Laser cladding was applied for repairing tools used in surgeries and dental equipment as Toyserkani pointed out that their surfaces get worn out. Besides, this approach will also lessen wastage in the healthcare sector in addition to elongating the life cycle of a medical device [144].

3.5 Tool and Die Industry

Laser cladding has now become one of the most recognized progressive processes in the system of modern manufacturing since it allows improving the characteristics of materials and rejuvenating industrial products [145]. Its influence is most keenly felt in tool die making industry where tooling for creating parts, components and tools are required to be strong, fast, accurate, and efficient all the time. In this case, this technology comes with enhanced wear resistance, surface hardening capability, better corrosion protection and thermal stability, more so with the added advantage of cost-effective repairs [146]. Through recent developments, laser cladding has the capacity of bringing about a revolution on the improvements of tool and die systems. In this article the author examines the real-world use of Laser cladding employed in the tool and die industry with particular focus on advantages of Laser cladding and disadvantage [56].

Durability is a basic characteristic of tool and die parts since they are subjected to mechanical and thermal stresses, wear, abrasion and possible repeated use. Practical application of laser cladding establishes wear resistance by developing metallurgical bond between the substrate and clad material to offer a strong layer to withstand the abrasive forces [147]. In its research, conducted a relevant experiment successfully using laser cladding on die-casting molds, which enhances significantly its wear – resistant performance. The treated tools were shown to work for longer periods before they needed to be maintained or replaced [148]. The application of cobalt-based alloys on steel dies through laser cladding, revealing remarkable improvements in performance during high-stress applications. These findings underscore the ability of laser cladding to optimize wear resistance, minimizing operational downtimes and reducing costs [65].

Carburizing and Martensitic hardening is employed in the tool and die applications mainly used in surface hardening purposes to have hard and rigid external look of a component so as to bears mechanical loads while the center of the component is made ductile. This technique provides for the ability to apply a layer of hard material-like tungsten carbide or some ceramic matrix composite-on to the surface and obtain an order of magnitude increase in hardness [149]. investigated the responses of tool steel to tungsten carbide deposition by laser cladding. The components which are subjected to the present inventive method were found to have enhanced surface hardness by 45% in comparison with the untreated components [150]. The latter helped a great deal in increasing the cutting efficiency and as well as the usage of the tools. Laser cladding has been used as a surface-hardening technology in industries which need high level accuracy and hardness such as manufacturing and machining industries [151].

Corrosion is a major problem in tool and die industry especially in parts experiencing chemically reactive atmosphere or wet environment [152]. Successful improvement of corrosion resistance is one of the ways by which laser cladding corrects this by applying materials like nickel based superalloys to the substrate [153]. Nickel based superalloys in improving the corrosion resistance of forging dies. Their work proved this to be the case but also showcased how while laser-clad components had a significantly lower corrosion rates they were less likely to require maintenance and would last longer in the field. This application has been exceptional in the automotive and aerospace industries where tools and dies undergo corrosion agents [154].

Laser cladding has a wide range of uses, the most efficient of which are the renewal of worn or damaged details. Since the laser cladding process retains the original geometry and material characteristics free from distortions, the component does not require complete rebuilding but only the targeted addition of material, of which reduction in both waste and cost are tangible benefits [155]. Laser cladding for repair of stamping die, demonstrating that the process returned the structural characteristics and performance of the parts with a minimal distortion. Applying laser cladding, repair costs were decreased up to 40% compared to other kinds of welding [156]. This application is in compliance with Resource efficiency and Sustainable resources since it reuses components whilst considering sustainability in the process.

It means that thermal stability becomes an especially important characteristic for tools and dies that work at high temperatures, for example, in forging- or casting-related operations. Laser cladding also improves thermal properties by coating heat resistant alloys on to the component to minimize or eliminate heat cracking and component fatigue [157]. have examined the use of heat-resistant alloy deposit on hot forging dies by laser cladding. They showed in their work that thermal cracking was also reduced, thereby helping dies to withstand long periods of heat exposure. Of all the applications Formula LITE is particularly beneficial to industries with high temperature applications like heavy equipment manufacturers. However, there are several constraints inherent with the use of laser cladding in the tool and die industry. There are also questions connected to the identification of materials that can be used as cladding. Said that the differences in the coefficients of the thermal expansion between the substrate and clad material may have an adverse impact on the adhesion [158]. Consequently, while selecting the materials and elaborating the process, pertinent risks must be avoided or minimized. Laser cladding equipment itself is expensive at the initial level and may prove prohibitive to entry for new smaller organizations. What makes laser cladding even more expensive is the need for specialized operators to achieve the micrometer-premium accuracy required for the process. It could also be possible to expand the application of this technology by addressing such challenges through workforce training programs, and establishment of cheaper equipment manufacturing systems [159].

Table 3. Industrial Applications of Laser Cladding

Industry	**Application**	**Enhanced Properties**	**Materials Used**	**Laser Type**
Aerospace	Repair of turbine blades and engine components	Wear resistance, thermal stability, corrosion resistance	Nickel-based alloys, titanium alloys	Fiber Laser, CO_2 Laser
Automotive	Coating of engine parts, gears, and shafts	Hardness, fatigue resistance, wear resistance	Steel, aluminum alloys	Diode Laser, Fiber Laser
Energy (Power Plants)	Repair and enhancement of boiler tubes, turbine components	High-temperature resistance, erosion resistance	Stainless steel, Inconel	Nd:YAG Laser, Fiber Laser
Oil & Gas	Coating of drill pipes, valve seats, and pump components	Abrasion resistance, corrosion resistance	Carbides, superalloys	High-power CO_2 Laser
Medical	Production of biomedical implants, dental tools	Biocompatibility, surface hardness	Titanium, cobalt-chromium alloys	Fiber Laser, Nd:YAG Laser
Mining	Restoration of worn-out mining equipment	Abrasion resistance, impact strength	Tungsten carbides, steels	Diode Laser
Tooling Industry	Coating of cutting tools, molds, and dies	Surface hardness, wear resistance	Hard-facing alloys, carbides	Solid-state Laser

Marine	Repair of propellers and rudders	Corrosion resistance, impact toughness	Copper-nickel alloys, stainless steel	CO_2 Laser, Fiber Laser
Electronics	Coating for semiconductor manufacturing tools	Precision, wear resistance	Ceramic-metal composites	Ultrafast Lasers

The given table explains the use of laser cladding for different verticals of industry and emphasizes how this technique causes improvement in material characteristics. In aerospace, it reconditions turbine blades and other hardware for enhanced wearing as well as corrosion protection using fibre and carbon dioxide lasers [160]. Auto industry uses cutting tool for applying coat to the engine parts and gears, increasing the hardness and fatigue strength by using diode and fibre laser. The energy sector benefits from enhanced boiler tubes and turbine components using Nd: YAG and fibre lasers, while the oil & gas industries use cladding for abrasion resistant on Drill Pipes with high powered CO_2 lasers [161]. Medical uses include biocompatible implants with fibre and Nd: Abrasion-resistant coatings for mining and tooling industries while applications of YAG lasers. Restressed concrete, electronics, rapid prototyping, and marine industries extensively apply laser cladding to achieve high accuracy and corrosion protection [162].

4. Conclusion

The industrial use of laser cladding (LC) has become a revolutionary solution for various industries such as aerospace, automotive, oil and gas, biomedical, and tooling industries. LC facilitates the localized deposition of material with minimal thermal distortion that improves surface properties such as wear resistance, corrosion protection, and mechanical integrity. Specifically, the incorporation of high-entropy alloys (HEAs) into laser cladding has brought a new paradigm in surface engineering because of their excellent hardness, thermal stability, and erosion and chemical degradation resistance. These innovative coatings have demonstrated high potential to prolong the service life of high-value components like turbine blades, valve seats, molds, and biomedical implants. In the defense and aerospace industries, LC enables the refurbishment of key components without losing dimensional tolerances. In biomedical applications, HEA-coated implants exhibit enhanced bio-compatibility and lower degradation rates.

In addition, the application of artificial intelligence and real-time process monitoring has notably improved cladding consistency and control over microstructure, enhancing process repeatability and cost-effectiveness. Notwithstanding these achievements, problems persist that require research in the future. Particularly, realizing homogeneous element distribution in HEA cladding, reducing residual stresses, and enhancing adhesion of multilayer coatings are persisting issues. Intelligent control of thermal gradients during cladding, discovery of new HEA compositions for specific application performance, and hybrid manufacturing methods such as laser-directed energy deposition (LDED) combined with LC are topics of future research. In addition, the emergence of in-situ diagnostics and adaptive AI-driven process controls would be able to revolutionize cladding accuracy and reduce defects. With sustainability and material efficiency being industry watchwords, laser cladding—particularly with HEAs—is poised to be a critical component of next-generation manufacturing and repair technology.

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Disclosure of Interest

The authors affirm that none of their personal connections or conflicting financial interests might have influenced the work described in this paper. **Aishwarya Dhoot** writing– original draft, Data collection, Conceptualization. **Dr.S.S.Bhavikatti** provided Supervision throughout the work and **Kedarnath Chaudhary** was involved in conceptualization of study and data collections.

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