

# A Sustainable Development Perspective and Evaluating the Impact of Laser Cladding Parameters on Mild Steel

Sujeet Kumar<sup>1\*</sup>, Sandeep Karnwal<sup>2</sup>, Sujeeth Swami<sup>3</sup>, N. Punitha<sup>4</sup>, S. Padmanabhan<sup>5</sup>, V. Vijayan<sup>6</sup> and S. Baskar<sup>7</sup>

<sup>1</sup>IIMT University Meerut, Ganganagar, Meerut, U.P. - 250001, India, [sujeetk65@gmail.com](mailto:sujeetk65@gmail.com)

<sup>2</sup>Assistant Professor, Department of Mechanical Engineering IIMT University Meerut-250001 Uttar Pradesh, [sandeepkarnwal@iimtindia.net](mailto:sandeepkarnwal@iimtindia.net)

<sup>3</sup>Assistant Professor, Department of Mechanical Engineering, New Horizon College of Engineering, Bangalore, Karnataka, Pincode-560103, India, [sujeeth89@gmail.com](mailto:sujeeth89@gmail.com)

<sup>4</sup>Associate Professor, Department of Physics, St. Joseph's College of Engineering, Chennai - 600119, [punithasan@gmail.com](mailto:punithasan@gmail.com)

<sup>5</sup>Professor, School of Mechanical and Construction, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi, Chennai- 62.

<sup>6</sup> Professor and Head - CFRD, K. Ramakrishnan College of Technology, Trichy, Tamilnadu, India.

<sup>7</sup> Assistant Professor, Department of Automobile Engineering, Vels Institute of Science, Technology and Advanced Studies, Chennai

**Abstract.** Mild steel is a popular material used in various applications due to its excellent machinability, strength and durability. Mild steel is one of the most affordable materials available, making it an excellent choice for budget-conscious projects. Regrettably, Mild steel is not typically used in some industries due to its low strength-to-weight ratio and limited corrosion resistance. AISI 1020 steel is relatively soft and has limited wear resistance compared to other types of steel, particularly those with higher carbon content. This review paper discusses the profitable and successful approach to enhance the service life and utility of the mild steel machinery components. Various investigators have put their effort into developing different methods to improve the properties of the mild steel components. The laser cladding process is developed by the melting of the preplaced coating layer with the surface of the substrate simultaneously which is able to prevent direct contact with the environment. The present review paper discussed in detail the impact of various parameters of laser cladding process and variation of the coating materials on the surface properties and microstructure of mild steel. Some challenges and remedies are also discussed in the paper. This review paper focused on some potential uses of the laser cladding process in diverse industries.

## 1 Introduction

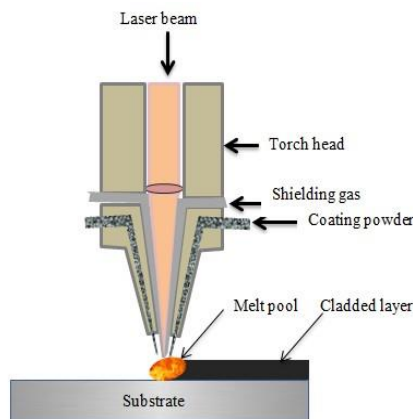
Mild steel is a strong and durable material, making it suitable for use in a variety of construction and manufacturing applications. Mild steel can be easily machined and turned into various shapes and sizes, making it ideal for use in machinery and gas industries field [1]. AISI 1020 steel is often used to make shafts and axles due to its strength and durability. The excellent machinability of AISI 1020 steel makes it a popular choice for the manufacture of gears. Gears are critical components in many types of machinery and require a material that can be easily machined and withstand high stresses and wear. Nevertheless, the applications of mild steels can be restricted due to the low hardness, poor tribological properties and bad corrosion performance [2, 3]. Therefore, lots of surface modification processes are employed by the many research groups to enhance surface properties of mild steel that expanded its industrial applications and machineries fabrication. The major surface properties enhancing methods are follows: Thermal treatment, surface coating and thermo chemical [4, 5]. Thermal treatment processes are induction hardening and flame hardening. These hardening processes enhance microstructure and do not effect on surface chemistry. Thermal treatment process is not suitable for the steel containing carbon content < 0.35%. Therefore, this process is not suitable for low carbon steel (mild steel) [6]. There are following thermochemical processes such as nitriding, carburizing, boriding which are used to enhance the surface properties of the materials. The thermo chemical process modifies the surface chemistry and microstructure but this process are limited used in some industries due to high temperature process. In this process, high temperature is applied to enhance the properties of the components but due to high temperature, oxidation or distortion may occur [7]. Surface coating technology aims to enhance the oxidation resistance, microhardness, wear resistance and corrosion resistance properties of a substrate by applying a layer of robust materials onto its surface. This process involves depositing a coating that provides an additional protective barrier, effectively increasing the substrate's durability and lifespan. There are following coating processes which are most frequently used such as physical vapour deposition, cladding, thermal spraying, chemical vapour deposition, thermo-reactive deposition and weld overlays [8, 9]. The coating process CVD and PVD provide a thin layer of the coating materials onto the surface of the substrate which may fail due to higher working

\* Corresponding author: [sujeetk65@gmail.com](mailto:sujeetk65@gmail.com)

load conditions. The CVD process is also a slow process as compared to the other surface coating process. Thermal spraying can result in the formation of porosity in the coating due to the rapid solidification of the sprayed particles. Additionally, high-temperature spraying can lead to oxidation of the sprayed material, affecting the coating quality [10]. Therefore, cladding processes such as plasma transferred arc cladding, gas tungsten arc cladding and laser cladding are employed to deposit the hard and thick coating layer onto the substrate surface. Thick coating layers deposited by these coating processes not only provide the mechanical properties but also enhance the surface dependence properties such as corrosion resistance, wear resistance so that the components are able to withstand in severe working conditions [11]. Various cladding processes and its parameters influence the surface properties of mild steel. Among these cladding processes laser cladding gives better surface finishing, excellent surface properties, controlled thickness and voids free coating layer. The focused laser beam provides precise and localized heat input, minimizing the heat-affected zone (HAZ) and reducing distortion or damage to the surrounding areas of the component. [12]. The surface properties of mild steel not only depend on the parameters of the cladding process but also depend on the coating materials and its composition. The present review paper systematically discusses the effect of various parameters of laser cladding implemented to improve the surface properties of mild steel. This review paper also focused on the effect of coating materials and its composition on the microhardness, corrosion resistance and wear rate of the mild steel substrate. The influence of coating materials and its variation on the geometry of the laser cladded layer on mild steel is also explored in detail. The industrial applications of the laser coated mild steel are also discussed in the last sections of this paper.

### 1.1 Laser cladding process

Nowadays, various industries are increasingly adopting laser cladding techniques to enhance the surface properties of components and for component repair. In laser cladding technique a laser beam with certain energy is used to melt the coating materials and substrate surface. The laser beam is focused onto the substrate, and as the beam scans across the surface, it rapidly heats and melts the material. The molten material then solidifies and bonds to the substrate, forming a new layer or coating. The protection of the melt pool is provided by the shielding gas. The process parameters of the laser cladding are size of laser beam, scanning speed, flow rate of shielding gas, laser powder and feed rate of coating powder [13, 14]. These parameters strongly influence the coating geometry, microstructure and surface properties of the coated mild steel.



**Fig. 1.** Schematic diagram of laser cladding process with direct powder feeding arrangement.

The methods of the laser cladding process depend on the feeding method of coating materials. There are four methods to feed the coating materials in the laser cladding technique.

### 1.2 Paste form feeding

In laser cladding, paste form feeding refers to the method of delivering the cladding material in the form of a paste or slurry. a paste is used, which consists of fine particles of the cladding material mixed with a binder or carrier medium. The paste is typically composed of metal powders or ceramic powders suspended in a liquid binder. The binder serves multiple purposes, such as providing a medium for transporting the particles to the laser interaction zone, aiding in the adhesion of the particles to the substrate, and controlling the viscosity and flow properties of the paste [15].

### 1.3 Preplaced powder technique

The preplaced powder technique is a method used in laser cladding to deposit a layer of material onto a substrate. It involves prepositioning a layer of coating powdered material onto the substrate surface before the laser cladding process

begins. The preplaced powder technique is commonly used in applications where precise control over material composition, bonding strength, or the creation of graded structures is important [16].

#### **1.4 Wire feed method**

The wire feed method is a technique used in laser cladding to deposit material onto a substrate using a continuous wire feedstock. In this method, a wire of the cladding material is fed into the laser interaction zone, where it is melted and fused with the substrate. A suitable wire feedstock is chosen based on the desired material properties and application requirements [17].

### **2 Powder injection method**

The powder injection method is a technique used in laser cladding to deposit material onto a substrate. In this method, fine powder particles of the cladding material are injected into the laser beam where they are melted and fused with the substrate. The powder is injected into the laser cladding system using a powder feeding mechanism. The powder is typically delivered through a nozzle or an injector, which is positioned near the laser interaction zone [18]. The powder injection method in laser cladding offers several advantages: the powder injection method allows for the use of a wide range of materials, enabling the deposition of different alloys, composite materials, or even multiple materials in a single process. The powder injection method can achieve high deposition rates, making it suitable for applications that require efficient and rapid cladding. These are some of the common types of laser cladding techniques based on the feeding method. Each method has its advantages and is suitable for specific applications, depending on factors such as material properties, coating requirements, and the desired outcome.

#### **2.1 Factors that affect the laser cladding quality**

There are various factors that affect the coating quality, coating properties of the laser clad layer. Fig. 2 also shows the various factors that influence the laser cladding quality, surface properties.

#### **2.2 Selection of substrate Material**

The composition and properties of the substrate material, such as its composition, hardness, and thermal conductivity, can influence the interaction between the cladding material and substrate. Proper matching of substrate and cladding material can enhance the bonding strength and overall performance of the cladding layer [19].

#### **2.3 Cladding Material**

There are several factors of cladding powder such as size, injection angle, feed rate and composition that affect the surface properties of laser cladding. The selection of the cladding material, whether it be metal alloys, ceramics, or composites, holds substantial importance as it profoundly influences the properties exhibited by the cladding. This decision significantly impacts the performance, functionality, and overall quality of the cladding in its intended application. Different materials offer varying levels of hardness, corrosion resistance, wear resistance, thermal conductivity, and other desired characteristics.

### **3 Process Parameters of laser**

Laser cladding process parameters, including laser power, scanning speed, spot size, powder feed rate and standoff distance directly influence the properties of the cladding. These parameters control factors such as heat input, solidification rate, dilution, and microstructure formation, which ultimately impact the properties of the cladding layer [20, 21]. Melting of the coating materials is done using a laser beam in laser cladding method. Beam diameter influences the heat distribution and energy density. A smaller beam diameter leads to higher energy density, resulting in deeper penetration and finer microstructure. However, a larger beam diameter provides better stability and wider melts pool coverage [22].

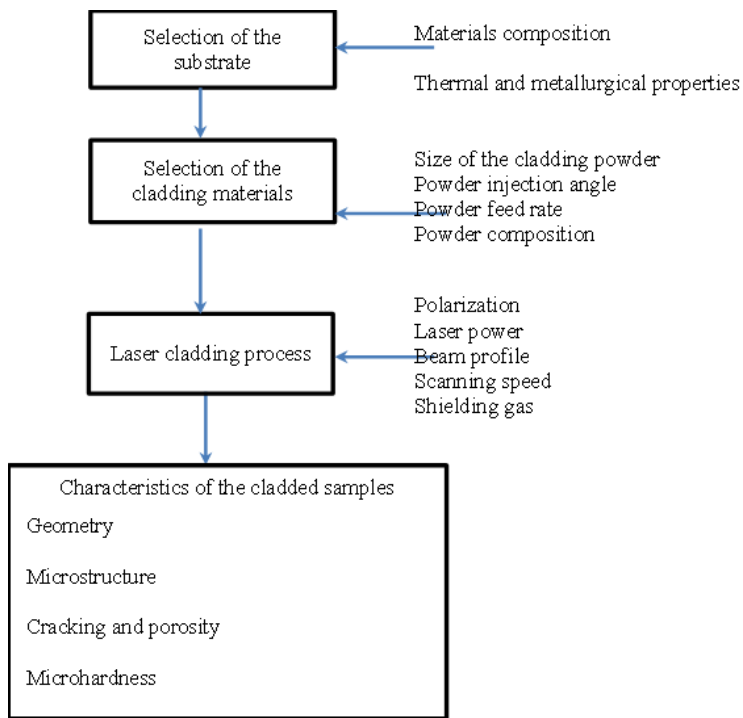


Fig. 2. General line diagram of the factors of, coating materials, substrate and laser cladding affecting the quality and properties of the deposited cladding layer.

## 4 Different coating materials deposition on mild steel substrate by laser cladding

### 4.1 SiC coating

SiC is commonly employed as a coating material to effectively augment the microhardness and wear resistance properties of mild steel. Once the hard SiC coating is applied onto the mild steel components, it significantly enhances their overall hardness so that the components can able to withstand extreme heat and maintain their structural integrity, also making them suitable for applications in harsh environments with elevated temperatures, such as gas turbines, aerospace components, and heat exchangers [23]. Many research groups have used SiC as reinforcement materials and deposited them with matrix materials. In this paragraph, authors discussed the influence of the variation of wt.% of SiC and also explored the effect of laser cladding parameters. In this respect, Majumdar et al. [24] developed two layers of Fe-SiC coating on the mild steel surface using a CO<sub>2</sub> laser cladding process. The top layer of the composite had a composition of 85% Fe and 15% SiC, while the bottom layer had 95% Fe and 5% SiC. The microstructural study of the composite layer revealed the presence of dispersed SiC particles within a matrix composed of ferrite and iron silicide (Fe<sub>2</sub>Si). It was observed that the SiC particles underwent partial dissociation, with a greater degree of dissociation observed in the lower layer as compared to the upper layer. The surface layer exhibited the highest area fraction of particles, while the fraction decreased gradually with increasing depth. According to the findings, the microhardness was observed to reach its highest value at the uppermost surface of the coating, gradually decreasing towards the substrate zone. It was also emphasized that the microhardness and wear resistance of the coating primarily rely on two key factors: the presence of the SiC phase and the refinement of the grain structure. Abbas and Ghazanfar [25] deposited the coating of stainless steel and stainless steel + SiC on mild steel using the same parameters of laser cladding. It was tried to show the influence of SiC on the surface properties of En3b mild steel. The microhardness values were found very high for the coating deposited using stainless steel with SiC reinforcement. The wear rate is also found very low for the coating of stainless steel + SiC as compared to the coating layer of only stainless steel. From the above study, it is found that the microhardness and wear resistance of the coating is strongly influenced by the dispersion and composition of the hard phases SiC coating powder in the cladded layer.

## 4.2 TiC coating

TiC is an extremely hard material with a high level of hardness, approaching that of diamond. This hardness provides excellent wear resistance, making TiC coatings highly desirable for applications where components are subjected to abrasive wear, erosion, or sliding contact with other surfaces. Han et al. [26] developed the TiC coating layer by in-situ method. It was observed that the high temperature of laser cladding helps to in-situ formation of TiC by combining the Ti with graphene and graphite. The graphite provides more carbon than the graphene which results in higher formation of the TiC phase in the coating layer of graphite as compared to graphene coating. Therefore, the formation of TiC contributes to high hardness in the both types of coating layer but the graphite coating provides higher microhardness as compared to the graphene coating. El-Labban et al. [27] deposited TiC reinforced coating layer on low carbon steel at different power of laser cladding. Observations revealed a noticeable trend where an increase in laser power corresponded to an augmentation in both the width and depth of the affected area. The microhardness of the coating also increases with decreasing the laser power. It was reported that the wear resistance was 25 times higher as compared to low carbon steel. Emamian et al. [28] synthesized the TiC-Fe coating layer by in-sit method using various parameters of laser cladding. The reported findings indicated a correlation between the volume fraction of TiC and the microhardness as well as the wear resistance of the deposited coating. Increasing the volume fraction of Ti-C in the coating powder was found to directly correspond to a higher fraction of TiC in the resulting coating layer. This increase in TiC content was found to significantly contribute to enhanced microhardness and wear resistance properties. Chen et al. [29] developed the coarse TiC coating layer on low carbon steel using laser cladding and explored the variation of influence of volume fraction of TiC on microhardness and microstructure of the TiC/H13 coating. It was observed that due to slow scanning speed the coarse TiC particles melted and formed different shapes of fine TiC particles. It was also reported that the microhardness increases with increasing the ceramic content in the coating layer.

From the above reviews, it is concluded that the volume fraction of the hard phases (TiC) in the cladded layer also influences the surface properties. The laser cladding provides fine microstructure due to rapid cooling rate which is responsible for the high microhardness and wear resistance. The higher volume fraction present in the cladded layer facilitates the higher microhardness and wear resistance while lower volume fraction responsible for lower microhardness.

## 4.3 TiB<sub>2</sub> Coating

In this paragraph, the influence of the TiB<sub>2</sub> on the surface properties is discussed in detail. TiB<sub>2</sub> gained more attention as a reinforcement material for the steel substrate due to its high hardness, high melting temperature and excellent tribological properties [30]. Du et al. [31] developed the TiB<sub>2</sub> coating layer on a mild steel substrate using a laser cladding process. In this research paper, TiB<sub>2</sub> was synthesized by in-situ method using coating powder such as ferrotitanium and ferroboron. The coating was done by overlapping 30 % of every track using laser cladding. It was reported that the coating layer formed a hard phase TiB<sub>2</sub> (blocky shape) in the coating layer. The coating layer is found free from any defects such as porosity, voids and interfacial gaps. Ductile  $\alpha$ -ferrite and blocky TiB<sub>2</sub> formed because of the synergetic effect of coating materials and laser power. Therefore, high hardness and improved wear resistance were found. Du et al. [32] effectively utilized the laser cladding technique to create a composite coating of TiB<sub>2</sub> reinforced Fe-based material on a low carbon steel substrate. This process involved using affordable Fe-Ti alloy powder, Fe-B alloy powder, and Fe powder as precursor materials. Through an in situ reaction, the composite coating exhibited uniformly dispersed, finely shaped hexagonal TiB<sub>2</sub> particles. As a result of this reaction, the composite coating demonstrated significantly enhanced hardness and wear resistance in comparison to the original substrate. Tang et al. [33] investigated the composite coating of TiB<sub>2</sub>-inconel 718 on low carbon steel using different input energy of laser cladding. It was reported that as the input energy (E) decreases, the experimental findings indicate a reduction in the dilution rate and a corresponding increase in the contact angle. With an increase in the cooling rate, the composite coating exhibits a decrease in both the primary dendrite arm spacing (PDAS) and the Laves content. Consequently, this decrease contributes to an increase in microhardness and an overall enhancement in tribological properties. Furthermore, a notable change in the wear mechanism was observed, transitioning from severe multi-plastic deformation wear, adhesive wear, and oxidative wear to a more moderate abrasive wear phenomenon.

## 4.4 TiB<sub>2</sub>-TiC coating

In this paragraph, authors discussed the factors that influence the coating quality and surface properties of the deposited layer. Masanta et al. [34] enhanced and compared the surface properties of mild steel and stainless steel by synthesising the TiB<sub>2</sub>-TiC-Al<sub>2</sub>O<sub>3</sub> using TiO<sub>2</sub>-Al-B<sub>4</sub>C coating materials. The coating layers were deposited on mild steel and stainless steel using fixed composition of coating materials and different scanning speed of the laser cladding to show the influence of the scan speed on the surface properties of these coatings. It was reported that the size and microstructure features strongly depend on the solidification rate, temperature gradient and cooling rate. The microstructure of the coating is refined higher in for the mild steel as compared to AISI 304 stainless steel. The microhardness value increases with increasing laser scan speed and the same trends were observed for both substrates. The wear rate also enhances with enhancing the laser scan speed for both substrates. Li et al. [35] deposited the ceramic coating of TiB<sub>2</sub>-TiC-Al<sub>2</sub>O<sub>3</sub> on the carbon steel by laser cladding technique. It was reported that the coating layer deposited using various compositions of coating powder with fixed process parameters of laser cladding. It was observed that the microhardness of the coating

layer was found higher for the coating deposited using lower  $\text{Al}_2\text{O}_3$ . The formation of the hard phases  $\text{TiB}_2$ ,  $\text{TiC}$  and  $\text{Al}_2\text{O}_3$  are responsible for achieving higher microhardness and lower wear rate. Due to similar physical and mechanical properties of  $\text{TiB}_2$  and  $\text{Al}_2\text{O}_3$ , the presence of these particles leads to an enhanced coupling effect, resulting in increased hardness and breaking strength of the cladding layer. The rapid condensation process during laser cladding contributes to refining the crystal grains and achieving a smaller and more uniform distribution of the hard particle phase within the cladding layer. This refinement of the microstructure, along with the in-situ self-generated reinforcing phase, significantly strengthens the cladding layer by interacting with the solidified structure and promoting fine-grain strengthening. Overall, these factors contribute to an overall increase in the hardness of the cladding layer. Masanta et al. [36] enhanced the surface properties of AISI 1020 steel by in-situ synthesizing the  $\text{TiB}_2$ - $\text{TiC}$ - $\text{Al}_2\text{O}_3$  coating using laser cladding. The coating materials were taken with a fixed composition of Al,  $\text{TiO}_2$ ,  $\text{B}_4\text{C}$  while the laser process parameters changed to show the influence of process parameters of laser cladding on the microhardness and wear resistance. It was reported that the coating deposited at lower scan speed contains some porosity. The reason for the porosity is the inclusion of gases inside the coating layer due to attain higher temperature at the time of cladding. With increasing scan speed the heat input decreases, therefore the porosity is eliminated and provides a smooth coating layer. The microhardness was found higher for the coating deposited at higher scan speed and decreases with decreasing scan speed. The wear rate found higher for the coating deposited at lower laser power as compared to the coating deposited at higher laser power. The wear rate also depends on the applied normal load and it increases with increasing normal load.

#### 4.5 WC coating

WC is an extremely hard material used for its exceptional wear resistance. Coating on mild steel with WC expressively improves its capacity to withstand erosion, abrasion, and friction. In this respect, many research groups have used WC ceramic materials as reinforcement materials on the mild steel substrate. Zhenda et al. [37] investigated the surface properties of WC-Ni coating deposited on mild steel using a powder feeding system of laser cladding. The composite coating exhibited superior wear resistance compared to conventional metal materials. The notable enhancement observed in the aforementioned properties was primarily attributed to the laser cladding process. This process facilitated the uniform distribution of hard WC particles embedded within a resilient fine-dendritic Ni-based alloy matrix, leading to the desired improvements in the material's characteristics. The combination of these factors contributed to the enhanced wear resistance of the composite coating. Zhou et al. [38] analyzed the crack behaviour of the WC-Ni coating deposited on mild steel using laser cladding technique. It was reported that crack formation initiated at the interface between the cladding layer and substrate, subsequently propagating through the cladding layer. This occurrence was attributed to the dissolution of the WC particles, which played a role in the progression of crack formation within the coating. The laser scanning speed and powder flow rate increased as the preheated average temperature of the substrate during Laser-Induced Hybrid Rapid Cladding (LIHRC) increased. This implies that higher substrate temperatures result in faster laser scanning and powder deposition rates. The higher laser scanning speed resulted in a decrease in the dissolution of WC (tungsten carbide) particles. This is beneficial because it helps reduce the porosities in the composite coatings formed during LIHRC. Reduced porosities contribute to the overall quality and integrity of the coatings. Li et al. [39] developed the WC-Ni- $\text{La}_2\text{O}_3$  on the steel using a laser cladding process. It was reported that an ultrasonic vibration device was used during the cladding process with different power [40-44]. The crack formation was investigated and reported on the propagation direction of a transverse crack within a composite coating and its interaction with the coating-matrix interface. The crack was observed to propagate towards the interface, causing the splitting of WC particles along its path instead of bypassing them. This behaviour was primarily attributed to the thermal mismatch that existed between the composite cladding coatings and the matrix material. The differential expansion and contraction rates during thermal cycling contributed to the initiation and propagation of cracks within the coating. The addition of  $\text{La}_2\text{O}_3$  reduces the tendency for cracking, but there is a limit to its effectiveness (0-0.7%). After surpassing this content range, crack formation in the coating layer resumes. In the absence of assisted ultrasonic vibration, columnar dendrites formed at the bottom of the cladding coating, resulting in the dissolution, combination, crystallization, and aggregation of WC ceramic particles [45-49]. However, when ultrasonic vibration was introduced, the dendrites present in the cladding layer were disrupted, leading to a noticeable refinement of the grains. Additionally, it was reported that the ultrasonic vibration device facilitated the uniform distribution of WC particles throughout the coating layer, resulting in improved microhardness and enhanced wear resistance. Acker et al. [40] deposited the thick coating layers of WC with Ni matrix on low carbon steel using laser power. The coating is also deposited at three different particle sizes of the WC and different volume fractions of the coating powder. There is no observed correlation between the increase in hardness and the size of the reinforcing particles because the internal stress was not affected by the size and concentration of the particles. It was noticed that the addition of even a small concentration of carbides leads to a significant improvement in the wear resistance of the Ni-based coating.

#### 4.6 Applications of coated mild steel

Applying  $\text{TiB}_2$ ,  $\text{TiC}$ ,  $\text{Al}_2\text{O}_3$ , WC ceramic with the matrix material act as a barrier between the steel surface and the corrosive elements, providing effective protection against corrosion. This facility makes it valuable for components exposed to corrosive conditions, such as marine applications, chemical processing equipment, and automotive parts. Coating mild steel with  $\text{TiB}_2$  can significantly improve its resistance to friction, erosion and abrasion [50]. This makes it



suitable for applications involving high wear and sliding contact, such as bearings, cutting tools, punches and gears.

## 5 Conclusion

It was concluded from literature review that the smooth and defect free coating layer can be deposited by laser cladding using optimized laser parameters such as laser powder, scan speed, laser spot. Based on the aforementioned review of the research papers, the following conclusion can be drawn:

1. The incorporation of ceramic phases such as TiC, WC, and TiB<sub>2</sub> significantly improves both the microhardness and wear resistance of the coating layer deposited by laser cladding process on the mild steel substrate.
2. The fraction and distribution of the coating materials, especially ceramic phases in the coating layer, strongly influence the microhardness and wear properties of the new deposited layer. It is important to note that a higher volume fraction of ceramic phases within the clad layer results in increased microhardness and wear resistance. The presence of a larger volume fraction of ceramic phases enables a greater amount of the added material to contribute to the microstructure, thereby enhancing the material's overall strength and resistance to wear.
3. The addition of La<sub>2</sub>O<sub>3</sub> serves as a transformative agent, effectively converting a coarse grain structure into a refined and fine grain structure. This remarkable outcome is achieved through the formation of dense and compact dendrites or granular dendrites, which play a crucial role in the structural refinement process and reducing cracking tendency.
4. The size, microstructure characteristics, microhardness values and wear resistance are influenced by the solidification rate, temperature gradient, and cooling rate. One of the key factors contributing to these desirable properties is the rapid cooling rate associated with laser cladding. This rapid cooling rate promotes the formation of refined microstructure which enhances the substrate microhardness and wear resistance.

## References

1. L. Ding, H. Shengsun, Q. Xiumin and S. Junqi, "Effect of aging treatment on microstructure and properties of VN alloy reinforced Co-based composite coatings by laser cladding," *Mater. Characte.*, **129**, pp. 80-87, (2017).
2. H. Zhang, Z. Yong, Z. Zengda and W. Dongting, "Microstructures and properties of low-chromium high corrosion-resistant TiC–VC reinforced Fe-based laser cladding layer," *Journal of Alloys and Compounds*, **622**, p. 62-68, (2015).
3. P. Farahmand and K. Radovan, "Corrosion and wear behavior of laser clad Ni–WC coatings." *Surf. Coat. Techn.*, **276**, pp. 121-135, (2015).
4. M. Prince, A. J. Thanu, and P. Gopalakrishnan, "Improvement in wear and corrosion resistance of AISI 1020 steel by high velocity oxy-fuel spray coating containing Ni-Cr-B-Si-Fe-C," *High Temp. Mater. Proc.*, **31**, pp. 149–155, (2012).
5. S. I. Neife, V. S. Aigbodion and C. A. Mgbemene, "High-temperature thermal treatment of co-deposition of Zn-10ZnO-25Ant hill particulate composite coating on mild steel," *Inter. J. Adv. Manufa. Techno.*, **95**, pp. 4371-4381, (2018).
6. P. Gopalakrishnan, P. Shankar, R.V. Subba Rao, M. Sundar and S. S. Ramakrishnan, "Laser surface modification of low carbon borided steels," *Scripta Materialia*, **44**, 5, pp. 707-712, (2001).
7. R. Iakovou, L. Bourithis, and G. Papadimitriou. "Synthesis of boride coatings on steel using plasma transferred arc (PTA) process and its wear performance," *Wear*, **252**, 11-12, pp. 1007-1015, (2002).
8. G. R. C. Pradeep, and A. Ramesh, "Comparative study of hardfacing of AISI 1020 steel by three different welding processes," *Global Journals of Research in Engineering* **13**, A4, pp. 11-16, (2013).
9. M. Chhowalla, K.B.K. Teo, C. Ducati, N.L. Rupesinghe, G.A.J. Amaratunga, A.C. Ferrari, D. Roy, J. Robertson, G. A. J. "Growth process conditions of vertically aligned carbon nanotubes using plasma enhanced chemical vapor deposition," *Journal of Applied Physics*, **90**, 10, pp. 5308-5317, (2001)
10. G. R. Heath, P. A. Kammer, and M. M. Stack, "The high temperature erosion/corrosion behavior of industrial thermally sprayed coatings," *In ITSC*, pp. 29-37. ASM International, (1996).
11. A. Zikin, E. Badisch, I. Hussainova, C. Tomastik, and H. Danninger, "Characterisation of TiC–NiMo reinforced Ni-based hardfacing," *Surface and Coatings Technology*, **236**, pp. 36-44, (2013).
12. A. K. Das, "Effect of rare earth oxide additive in coating deposited by laser cladding: A review," *Materials Today: Proceedings*, **52**, pp. 1558-1564, (2022).
13. R. A. R. Rashid, S. Abaspour, S. Palanisamy, N. Matthews, and M. S. Dargusch, "Metallurgical and geometrical

- characterisation of the 316L stainless steel clad deposited on a mild steel substrate," *Surf. Coat. Technol.*, **327**, pp. 174-184, (2017).
14. V. Fallah, S.F. Corbin and A. Khajepour, "Solidification behaviour and phase formation during pre-placed laser cladding of Ti45Nb on mild steel." *Surf. Coat. Technol.*, **204**, 15, pp. 2400-2409, (2010).
  15. A. K. Das, "Recent trends in laser cladding and alloying on magnesium alloys: A review," *Materials Today: Proceedings*, **51**, pp. 723-727, (2022).
  16. G. Han, and Y. Zhang, "Microstructure and Corrosion of Laser Cladding Coatings on Titanium Alloy with Nd2O3," *J. Engin. Materi. Techno.*, **143**, 1, (2021).
  17. M. B. Rodrigues, R. G. N. Silva, M. Pereira, R. H. G. E. Silva, and E. W. Teichmann, "Effect of dynamic wire feeding on deposition quality in laser cladding process." *Journal of Laser Applications*, **32**, 2, p. 022065, (2020).
  18. O. S. Fatoba, E. T. Akinlabi, S. A. Akinlabi, and S. Krishna, "Influence of rapid solidification and optimized laser parameters relationship on the geometrical and hardness properties of Ti-Al-Cu coatings," *Materials Today: Proceedings* **18**, pp. 2859-2867, (2019).
  19. L. Han, K. M. Phatak, and F. W. Liou, "Modeling of laser cladding with powder injection," *Metallurgical and Materials transactions B*, **35**, pp. 1139-1150, (2004).
  20. T. Wu, W. Shi, L. Xie, M. Gong, J. Huang, Y. Xie, and K. He, "Effect of preheating temperature on geometry and mechanical properties of laser cladding-based stellite 6/WC coating." *Materials*, **15**, 11, p.3952, (2022).
  21. X. Xu, G. Mi, L. Chen, L. Xiong, P. Jiang, X. Shao and C. Wang, "Research on microstructures and properties of Inconel 625 coatings obtained by laser cladding with wire," *Jour. Alloys Compou.*, **715**, pp.362-373, (2017).
  22. L. H. R. Apolinário, E. A. Torres, H. R. Araújo, A. D. A. Vicente, and T. F. D. A. Santos, "Effect of laser cladding parameters in NbC reinforced 316L austenitic stainless steel composite depositions on a mild steel," *The International Journal of Advanced Manufacturing Technology*, **122**, 7-8, pp. 3095-3113, (2022).
  23. A. Woldan, J. Kusiński, and E. Tasak, "The microstructure of plain carbon steel laser-alloyed with silicon carbide." *Materials chemistry and physics*, **81**, 2-3, pp. 507-509, (2003).
  24. J. D. Majumdar, B. Ramesh Chandra, A. K. Nath, and I. Manna, "Studies on compositionally graded silicon carbide dispersed composite surface on mild steel developed by laser surface cladding," *Journal of Materials Processing Technology*, **203**, 1-3, pp. 505-512, (2008).
  25. G. Abbas, and U. Ghazanfar, "Two-body abrasive wear studies of laser produced stainless steel and stainless steel+ SiC composite clads," *Wear*, **258**, 1-4, pp. 258-264, (2005).
  26. T. Han, M. Xiao, Y. Zhang, and Y. Shen, "Effects of graphite and graphene spatial structure on the TiC crystal structure and the properties of composite coatings." *Surf. Coat. Technol.* **377**, pp. 124909, (2019).
  27. E. Labban, F. Hashem Essam Rabea Ibrahim Mahmoud, and Ali Algahtani, "Microstructure, wear, and corrosion characteristics of TiC-laser surface cladding on low-carbon steel," *Metallur. Mater. Transac. B*, **47**, pp. 974-982, (2016).
  28. A. Emamian, "In-situ TiC-Fe deposition on mild steel using a laser cladding process," (2011).
  29. H. Chen, Y. Lu, Yunsen Sun, Y. Wei, X. Wang and D. Liu, "Coarse TiC particles reinforced H13 steel matrix composites produced by laser cladding," *Surface and Coatings Technology*, **395** pp. 125867, (2020).
  30. R. Anandkumar, A. Almeida, R. Colaço, R. Vilar, V. Ocelik and J. Th M. De Hosson, "Microstructure and wear studies of laser clad Al-Si/SiC (p) composite coatings." *Surfa. Coati. Techno.*, **201**, 24, pp. 9497-9505, (2007).
  31. B. Du, Z. Zou, X. Wang and S. Qu, "Laser cladding of in situ TiB2/Fe composite coating on steel," *Applied Surf. Scien.*, **254**, 20, pp. 6489-6494, (2008).
  32. B. Du, Z. Zou, X. Wang and S. Qu, "In situ synthesis of TiB2/Fe composite coating by laser cladding," *Materials Letters*, **62**, 4-5, pp. 689-691, (2008).
  33. B. Tang, Y. Tan, Z. Zhang, T. Xu, Z. Sun and X. Li, "Effects of process parameters on geometrical characteristics, microstructure and tribological properties of TiB2 reinforced inconel 718 alloy composite coatings by laser cladding," *Coatings*, **10**, 1, p. 76, (2020).
  34. M. Masanta, S. M. Shariff, and A. Roy Choudhury, "A comparative study of the tribological performances of laser clad TiB2-TiC-Al2O3 composite coatings on AISI 1020 and AISI 304 substrates," *Wear*, **271**, 7-8, pp. 1124-1133, (2011).



35. Z. Li, M. Wei, K. Xiao, Z. Bai, W. Xue, C. Dong, D. Wei and X. Li, "Microhardness and wear resistance of Al<sub>2</sub>O<sub>3</sub>-TiB<sub>2</sub>-TiC ceramic coatings on carbon steel fabricated by laser cladding," *Cerami. Internati.*, **45**, 1, 115-121, (2019).
36. M. Masanta, S. M. Shariff and A. Roy Choudhury, "Tribological behavior of TiB<sub>2</sub>-TiC-Al<sub>2</sub>O<sub>3</sub> composite coating synthesized by combined SHS and laser technology." *Surf. Coati. Techno.*, **204**, 16-17, pp. 2527-2538, (2010).
37. C. Zhenda, L. Leong Chew and Q. Ming. "Laser cladding of WC-Ni composite." *J. mater. Proce. Techno.* **62**, 4, 321-323 (1996).
38. S. Zhou, X. Zeng, Q. Hu, and Y. Huang, "Analysis of crack behavior for Ni-based WC composite coatings by laser cladding and crack-free realization," *Applied Surface Science*, **255**, 5, pp. 1646-1653, (2008).
39. M. Li, Q. Zhang, B. Han, L. Song, G. Cui, J. Yang and J. Li, "Microstructure and property of Ni/WC/La<sub>2</sub>O<sub>3</sub> coatings by ultrasonic vibration-assisted laser cladding treatment." *Opti. Lasers in Enginee.*, **125**, p. 105848, (2020).
40. K. V. Acker, D. Vanhoyweghen, R. Persoons, and J. Vangrunderbeek, "Influence of tungsten carbide particle size and distribution on the wear resistance of laser clad WC/Ni coatings," *wear*, **258**, 1-4, 194-202, (2005).
41. J Kumaraswamy, Anil K. C., Vidyasagar Shetty & C Shashishekar, Wear behaviour of the Ni-Cu alloy hybrid composites processed by sand mould casting, *Advances in Materials and Processing Technologies*, page 1-17, (2022)
42. Subbian, V., S. Siva Kumar, K. Chaithanya, Sujin Jose Arul, Gopal Kaliyaperumal, and Khan M. Adam. "Optimization of solar tunnel dryer for mango slice using response surface methodology." *Materials Today: Proceedings* **46** (2021).
43. K.C. Anil, J. Kumaraswamy, Akash et al., Experimental arrangement for estimation of metal-mold boundary heat flux during gravity chill casting, *Materials Today: Proceedings*, (2022)
44. Anil, K.C., Kumaraswamy, J., Reddy, M., Prakash, B., Mechanical Behaviour and Fractured Surface Analysis of Bauxite Residue & Graphite Reinforced Aluminium Hybrid Composites, *Frattura ed Integrità Strutturale*, **62** (2022)
45. Satish, S., S. John Alexis, Arun Bhuvendran, Mohanraj Shanmugam, S. Baskar, and V. S. Shaisundaram. "Design and analysis of mild steel mini truck body for increasing the payload capacity." *Materials Today: Proceedings* **37** (2021).
46. J. Kumaraswamy, V. Kumar and G. Purushotham, A review on mechanical and wear properties of ASTM a 494 M gradenickel-based alloy metal matrix composites, *Materials Today: Proceedings*, **37**, pp 2027–2032, (2021).
47. Venkatesh, R., Roshita David, C. B. Priya, M. Aruna, Gopal Kaliyaperumal, N. Mukilarasan, Avinash Malladi, and M. Karthikeyan. "Synthesis and Experimental Thermal Adsorption Characteristics of Epoxy Hybrid Composite for Energy Storage Applications." *Adsorption Science & Technology* (2023).
48. K. Jayappa, V. Kumar, and G. G. Purushotham, "Effect of reinforcements on mechanical properties of nickel alloy hybrid metal matrix composites processed by sand mold technique," *Applied Science and Engineering Progress*, **14**, 1, pp. 44–51, (2021)
49. Prabhakaran, A., K. Sridhivya Krishnan, R. Dhinakaran, S. Baskar, and V. S. Shaisundaram. "Analysis of the efficiency of an automotive alternator by replacing mild steel into aluminum as a material for rotor." *Materials Today: Proceedings* **37** (2021).
50. Srikanth, S., Parthiban, A., Vijayan, V., Dinesh, S., Sathish, S. Experimental Investigation of Nd:YAG Laser Welding of Inconel 625 Alloy Sheet. *Advances in Industrial Automation and Smart Manufacturing. Lecture Notes in Mechanical Engineering*. 21 October 2020 Singapore (2021).