Hard metal-matrix composite coating via laser cladding on engineered surfaces

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Chapter #. Title: Chapter 3. Hard Metal Matrix Composite Coating via Laser Cladding on Engineered Surfaces

Abstract

Laser surfacing is an important and necessary technology that can be used to repair, restore, and enhance the surface properties of parts, making them more durable, resistant, and efficient. The use of tungsten disulfide (WS2) in laser cladding is still in the development and research stage, but the properties and characteristics of WS2 make it a good candidate for laser cladding applications in industries where tribological systems, cutting tools, and thermal management are important. In this chapter, laser cladding of WS2 is carried out using a fiber laser of 400 W power. It is observed that a hard surface coating of WS2 was cladded to the substrate surface. The surface of the cladded surface is characterized in several ways to understand its properties and quality. Some common methods of characterizing a laser-cladded surface include microstructure analysis, hardness, wear testing, and chemical analysis. The microstructure of the cladded surface is analyzed using optical microscopy, and scanning electron microscopy (SEM), to understand the grain size, phase composition, and morphology of the cladded material. The hardness and wear resistance of the cladded surface are measured using techniques Vickers hardness testing, and tribometer testing to understand the mechanical properties of the cladded material. The chemical composition of the cladded surface is analyzed using techniques of energy-dispersive X-ray spectroscopy (EDS) to understand the composition of the cladded material.

Keywords: Laser cladding, Microhardness, Wear, Microstructure, Power density

Introduction

Laser surfacing is a crucial technology for repairing, restoring, and enhancing the surface properties of parts, making them more durable, resistant, and efficient. Tungsten disulfide (WS2) is a promising material for laser cladding applications in industries that require tribological systems, cutting tools, and thermal management. This chapter explores the use of WS2 in laser cladding, using a fiber laser of 400 W power to create a hard surface coating of WS2 on the substrate surface.

Several techniques are used to characterize the properties and quality of the cladded surface. These include microstructure analysis, hardness and wear testing, and chemical analysis. Microstructure analysis is performed using optical microscopy and scanning electron microscopy (SEM) to determine the grain size, phase composition, and morphology of the cladded material. Hardness and wear resistance are measured using techniques such as Vickers hardness testing and tribometer testing to assess the mechanical properties of the cladded material. Finally, energy-dispersive X-ray spectroscopy (EDS) is used to analyze the chemical composition of the cladded surface.

This chapter provides valuable insights into the development and research of WS2 in laser cladding applications, highlighting its potential for use in various industries. The findings of this study could contribute to the development of more durable and efficient parts with improved surface properties.

Chapter 3: Hard Metal Matrix Composite Coating via Laser Cladding on Engineered Surfaces

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3.1 Introduction

In this era, when new materials are being developed to enhance mechanical and tribological properties, laser cladding offers a promising way to achieve this with traditional metals and alloys. The bond strength between the deposited material and the substrate is high, making the cladding durable and long-lasting. Fields like nuclear energy, automobiles, and aerospace use various components subjected to extreme environmental conditions like high temperature, pressure, humidity, etc., that require advanced technologies to meet the desired properties of various materials through cladding (Ritter 1991). In biomedical applications, laser cladding has been used to generate layers having antimicrobial properties (Jianglong 1994). Laser surfacing technology is a type of laser processing that involves using a laser beam to melt and deposit material onto a surface to repair, restore, or enhance its properties. This is typically used to improve the surface properties of a part, rather than adding material to it. Laser surfacing technology has an advantage over other processes like tungsten inert gas and metal inert gas surface modification techniques as it has minimal dilution and less heat input to the material (Corbin 2003, Omar 2022). Mazumdar (2002) studied the compositionally graded silicon carbide dispersed composite surface on mild steel developed by laser surface cladding to study the microhardness, wear, and tribological properties of the clad surface.

It was observed that the friction coefficient of the laser-clad Ni60–WS_2 (nano-Ni encapsulated) coating was reduced significantly (Yuan 2021, Quazi 2016). However, very few works have been performed using continuous fiber laser cladding. Solid lubricant like WS_2 provides excellent wear properties due to their extremely low coefficient of friction (Gupta 2019, Watanabe 2004, Essa 2017). Austenitic steel is widely used in screws, machinery parts, shafts, flanges, and structures (Zangeneh 2017, Elflah 2019).

From the previous research, it is found that most of them are being done on powder-blowing techniques. Only some works are available for the pre-placed powder technique. Fibre laser having superior qualities to traditional lasers offers excellent scope for more research in this field. Negligible works have been performed for preplaced powder technique using a fiber laser. So, the present thesis is based upon the experimentation and investigation of laser cladding of 304 SS with tungsten disulfide using preplaced powder technique. Thus, in the present research, 304 SS surface has been selected as the substrate, and WS_2 powder has been chosen adding material. A continuous wave fiber laser of maximum power 400 W has been used for cladding operation. Cladding of 304 SS using WS_2 powder is expected to provide good wear characteristics and better surface properties like microhardness, less diffusion rate, and clad thickness. The cladding has been performed at different laser power, and the cladding samples have been characterized using FESEM, EDS, metallurgical microscope, Vickers microhardness, and pin-on-disc wear test. The effect of fiber laser power and different feed rate on the formation of metal matrix particulate composite has been investigated in this chapter.

3.2 Materials and Methods

3.2.1 Material selection

A 304 SS substrate with the following chemical composition—Fe-18Cr-8Ni-2Mn-0.75Si0.1N-0.08-C (wt%)—was used for laser cladding studies. Samples were initially cleaned by sandblasting, then washed in an acetone bath. Then the samples were washed using ethanol and dried. The various physical and chemical properties of 304SS are shown in table 1. WS_2 powder with 51.71W-21.67S-20.29O-6.32C (wt. %) was used as the cladding material. Before cladding, FE-SEM Supra 55, make: by ZEISS, Germany, was used to taking FESEM scanning of the powder sample and conducted an EDS analysis of the powder particles. The results are presented in figure 1 with table 2. The average particle size of the WS_2 powder was 40 µm, while the shape of the particles is irregular with sharp edges. This is helpful in the formation of MMC to provide better adhesion and binding of the particulates.

Table 3.1. Various physical and thermal properties of 304 SS substrate

Material	Density (g/cc)	Melting Temp.(^{0}C)	Vickers's Microhardness (HV)	Specific heat capacity(J/g-^{0}C)
304 SS	8	1400-1455	194	0.5

Insert Fig 3.1 Here

Table 3.2. Elemental composition of the tungsten di-sulfide powder

Element	**Weight %**
W M	46.97
S K	17.57
O K	20.90
Na K	9.92
C K	4.65

3.2.2 Experimental setup

The specification of the fiber laser used for the experimentation is shown in Table 3. The laser head is placed in a CNC stage to move up and down to change the laser beam's required diameter. Figure 2 depicts the experimentation setup. To obtain 2-D motion, the work item is held in an X-Y CNC stage. A cylindrical workpiece of diameter 10 mm was held with a fixture on the X-Y CNC table. Table 4 represents the experimental parameter settings for different experiments. The experimental setup consists of the following units Fibre Laser system (SPI make, 400 W), Chiller unit, Laser head (precitec, Germany), XYZ CNC Stage (Siemens), and Argon gas cylinder.

Insert Fig 3.2 Here

Table 3.3 Specification of the Laser system

SPI laser Model No.	SM-S00051
Power, Max	400 W
Focal Length	80 mm
Focal Spot dia.	0.4 mm
SPI laser Model No.	SM-S00051

3.2.3 Experimental Parameters

3.2.3.1 Input Parameters

a) System Parameters: Spot diameter, Scanning speed, Power, Continuous beam, Standoff distance, and Gas supply.

b) Work parameters: Overlapping, Thickness of workpiece, Substrate.

3.2.3.2 Output Parameters: Microhardness, SEM Analysis, wear test, depth of cladding.

Table 3.4 Experimental parameters selected for laser cladding operation

CONSTANT PARAMETERS		**VARIABLE PARAMETERS**	
Workpiece thickness	5 mm	Power	220 – 300 Watt
Workpiece	304 SS		
Clad material	WS_2 powder		
Cladding height	0.7 mm		
Binder	Polyvinyl alcohol	Scanning speed	30 – 50 mm/min
Standoff distance	5 mm		
Beam type	continuous		
Spot size	1 mm		
Argon Gas flow	10 l/min at 1 bar		

3.2.4 Morphology Study

Metallurgical Microscope has been used to study the surface morphology and thickness of the clad layer. The specification of the Metallurgical microscope is Make: Olympus, Model: BH2UMA. The Morphology was studied at 5X magnification to see the presence of pores and cracks in the cladding part.

3.2.5 Microhardness measurement

The microhardness measurement has been performed using a Vickers Microhardness tester. The cladding surface microhardness was measured by applying a load of 5 N for a dwell time of 10 sec. Additionally, the cross-section's microhardness was evaluated to determine how it changed with clad depth.

3.2.6 Analysis of Microstructure

The Microstructure was analyzed using a Supra FESEM machine. The machine specifications are as Model: FE-SEM Supra 55 (Germany) with Air Lock, EDS, EBSD, Resolution: 0.8 nm at 15 kV, 1.6nm at 1 kV, Magnification: 12-1000000X, Acceleration voltage: 100V TO 30 kV, Gun type: Schottky Field Emission Electron Gun, Detectors: SE, In-Lens, BSE, Retractable STEM with the Bright and dark field. FESEM Images were taken at 400 X, 1 KX, and 20 KX magnifications. Images of the top surface, as well as images of the cross-section, were taken. The top surface was analyzed for pore cracks and impurities, while the crosssection was internal cracks and a substrate-clad interface.

3.2.7 Wear test

The wear of the samples has been analyzed using a Pin on Disc wear measuring machine. A wear test has been performed at RT. Some tests have been performed on 5 N loads and some on 10 N loads. Some other parameters include rotation radius (40 mm), RPM (300), Time (1520 min), Load (5-10 N), and Disc Material-EN31.

3.2.8 Experimental Procedure

Before conducting the experiments, several trial experiments were conducted at different process parameters. First, the spot diameter was calculated by scanning a single line beam at different power. Then the average value of the beam diameter was taken at a defocussing distance. The final spot diameter was taken as 1 mm at a defocussing of 5 mm for experimentation.

Insert Fig 3.3 Here

a) Preparation of 4 Wt% Poly Vinyl Solution

For operating, the polyvinyl alcohol was first mixed with water, and a 4 wt% solution was prepared. For making such a solution, the weight of polyvinyl alcohol was selected as 40 mg, and the water was taken as 960 mg. Then they were stirred correctly for 30 minutes to prepare the solution.

b) Applying Clad Layer on 304 SS Plate

The solution prepared was mixed with tungsten disulfide powder, and the mixture was spread adequately on the steel. A pattern of 0.5 mm height was used to provide a uniform-clad height throughout. Then the spread powder steel plate was kept inside a hot air oven at a temperature of 40 ºC for 24 hr. for drying. Slow heating was used to prevent the paste from cracking. **c) Laser Cladding**

Then the pre-decided parameters (Power 220-300 Watt and feed 30-50 mm/min) were fed in the laser CNC, and a cladding experiment was performed. The ambient atmospheric temperature was maintained at 20 ºC. The clad was left in the atmosphere for cooling. Then the clad samples were washed with acetone and polished. Then the samples were cleaned in an Ultrasonic cleaner.

Insert Fig 3.4 Here

3.3 Results and Discussion

3.3.1 Experimental results

After doing the experimental work, the observations were taken down in the form of a table and analyzed for different properties. The observations were done for different morphology and physio-mechanical properties.

Table 3.5 Experimental input and output parameters obtained during experimentation

Sample no.	**Power (Watt)**	**Feed (mm/min)**	**Microhardness ($HV_{0.5kg}$)**	**Wear (µm)**	**Clad thickness (mm)**
1	220	30	404.73	33	0.41
2	220	40	433.90	55	0.37
3	220	50	468.6	41	0.33
4	250	30	454.43	99	0.44
5	250	40	488.83	26	0.39
6	250	50	624.10	38	0.32
7	300	30	552.3	33	0.48
8	300	40	630.27	9	0.43
9	300	50	829.27	97	0.38

3.3.2 Analysis of Clad Thickness

The different thickness of the clad has been obtained at different parameters. Clad thickness is directly proportional to the value of laser power. As the value of power increases, more substrate melts and clad thickness increases. The cladding has been observed to be more successful in sampling some samples in terms of uniformity. Some non-uniform cladding is observed, but the substrate-clad interface is visible. This means the dilution effect is low here. The nonuniform cladding has been observed due to gas evolution while cladding. No visual porosity has been observed on any sample. It shows that preplaced technique resulted in uniform cladding over the whole surface. Some slag-type inclusions have been observed. It can be assumed that the sulfur vapor may have gotten entrapped in the melt pool. The best surface morphology is obtained in clad samples 3 and 7. No visible pores are present in the wrapped samples.

Insert Fig 3.5 Here

Insert Fig 3.6 Here

3.3.3 Microhardness Analysis

Base Material Hardness was found to be around 222.9 HV. As we increase the power, the hardness of the clad surface increases. It can be suggested that more heat input is causing the quenching process to take place resulting in a finer grain structure. Hardness values increase with the increase in speed due to a higher cooling rate. The highest value achieved in hardness is about 829.27 HV which is four times higher than the base material.

Insert Fig 3.7 Here

3.3.4 Microstructural Analysis

At the optimum parameters, the cross-section observed was dense and free from bulk defects such as macro cracks, intermetallic inclusions, etc. There were isolated pores at one or two locations, as seen in figure 8 (a). Few W particles reached deep down to the melt pool due to high density. It can be seen that a uniform-clad substrate has been achieved with significantly less dilution effect. As we have increased the power, a more uniform cladding has been achieved, as seen in figure 8 (b). The clad's microstructure depends on the cooling rate in the melt pool during heating and cooling. When a laser-induced melt pool was formed, temperature gradient and nucleation rate increased at higher power resulting in the finer and uniform cladding.

Insert Fig 3.8 Here

3.3.5 EDAX Analysis

It has been observed that the Metal-Matrix composite consists of Tungsten, Iron, Chromium, and other constituents. The percentage of tungsten is less at higher power concerning lower power. It may be due to more melting of the substrate than at lower power resulting in more dilution and so lesser percentage of tungsten. Most of the samples showed a good percentage of tungsten. Microhardness value has increased about 3-4 times. This indicates the formation of a hard carbide phase and fine-grain strengthening. Sample 3 shows a very high percentage of tungsten as the analysis has been performed in the deeper clad region along the interface. It suggests that the tungsten, a heavier particle, has settled down below in more concentration concerning the surface. The percentage of Iron lies between 40-50%. Most of the sulfur evaporated as expected due to its dissociation at a higher percentage. The presence of oxygen suggests some oxide formation. More shielding should be provided to inhibit the oxide formation, but increasing the shielding gas will blow out the powder from the surface. So, a trade is required between the two aspects.

Insert Fig 3.9 Here

Insert Fig 3.10 Here

3.3.6 Wear Analysis

Initially, the graph showed adverse wear. It occurs because of uneven surfaces. But as the graph proceeds, it generates a good feeling for wearing. All the samples showed excellent results concerning the base material. The average wear rate of the samples is 12-13 times better than 304SS. Thus, the samples fulfill the criteria of a very low-wearing substance. Some samples showed a little higher value. It can be because of improper fixing or testing errors. Variation of wear time along with variation in frictional force with respect to time is presented in figure 10. Few samples showed an exciting result of having a wear rate of 8 micrometers. It can be compared with the wear rates of some High-density polyurethane (HDP) or LDP, which have meager wear rates.

Insert Fig 3.11 Here

3.4 Conclusion and Future Scope

3.4.1 Conclusion

This thesis has studied the microstructure, microhardness, and tribological properties of 304 SS material cladding with tungsten disulfide coating. All the above results showed that the layer could be done successfully on 304 SS having desired surface properties.

1. It can be concluded that the generation of metal matrix composite upon the 304 SS has been successfully achieved, having higher mechanical and other properties
2. The cladding achieved is of height 0.2-0.4 mm on average, which can be considered a good cladding height.
3. Microhardness value shows a modest increase from 222.9 HV (0.5kg) of the substrate to as high as 800 HV (0.5 kg) of the clad layer.
4. Microstructural and EDAX results suggest clad surface-bearing tungsten particles surrounded by other materials. Coatings exhibit fine microstructures with no cracks and pores.
5. The boundary of the clad substrate interface is distinct. It means the dilution effect is significantly less than expected. The straightforward clad substrate interface can be visualized from FESEM images.
6. Wear test results show an excellent response. It has been observed that the wear rate of the clad surface has been drastically reduced concerning the substrate. The low wear value suggests that the surface's tribological properties got enhanced by laser cladding.

3.4.2 Future Scope

Laser cladding offers a promising way to enhance materials' surface and tribological properties. Further work on the process can be done using other techniques like powder blowing, wire feeding, etc. Laser cladding is in the early commercialization stage and offers a revolutionary new manufacturing technique to the industry in the new millennium. Cladding can achieve the desired properties in different fields like automobiles, railways, aerospace materials, etc. Thus, it offers us a bright future.

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