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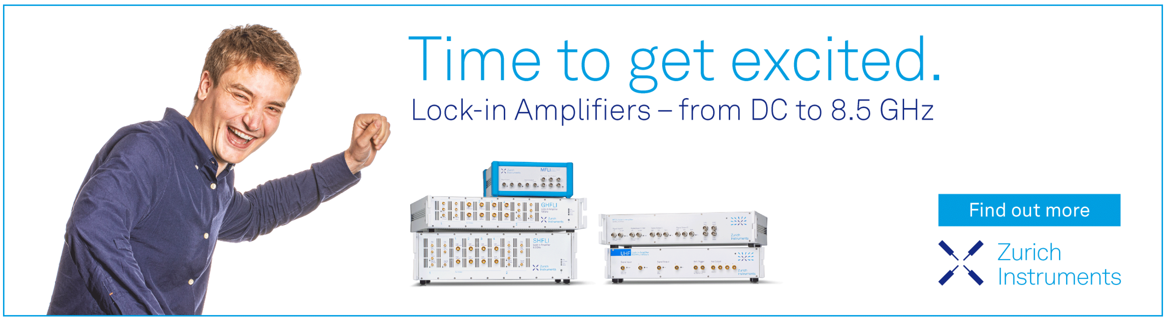

Latest Advancements in the Surface Performance of Microwave Cladding and the Future Scope – A Critical Review

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Abstract. Microwave cladding is a revolutionary, cost-effective technique of enhancing the surface characteristics of metallic components. Microwaves are becoming increasingly popular because they aid in the uniform heating of materials on a molecular scale. Partially diluting of the substrate and subsequent creation of metallurgical bonding between the clad material and the substrate are the most common methods for obtaining the coating. Microwave cladding may be used on a diverse set of materials with less cost and time of production. Another feature of microwaves is that they produce no emissions, which is crucial for promoting green manufacturing technologies. This article highlights the existing state of research on the microwave cladding of different substrates by suitable clad materials. The article further discusses the various surface modification parameters i.e. microstructure, microhardness, and tribological properties used by past researchers. It also reports the past researchers' findings and points out the future research scope in this subject.
Keywords: Microwave, Cladding, Surface Modification, Substrate & Cladding powder.

INTRODUCTION

Low wear and corrosion resistance of the metal causes surface integrity to deteriorating and base materials to be damaged. While in operation, certain components of equipment used in mining, mineral processing, manufacturing, agriculture, and a variety of other sectors are subjected to significant wear and corrosion. There are two approaches to avoid damage to base materials caused by such a problem. The first method is to make the components out of a material that is resistant to wear and corrosion, and the second method is to modify the functional surfaces of the components. Surface modification is more cost-effective than the prior technique in practice [1]. Surface modification can be accomplished through a variety of methods. Some of them entail methods such as Tungsten Inert Gas Cladding (TIGC), Laser cladding (LC), and Plasma Transferred Arc (PTA) cladding, etc. These are the most suitable ways to enhance the major mechanical and tribological properties of materials. These methods have certain advantages, but they also have some limitations [2]. They carry significant initial and ongoing costs, as well as the creation of a hazardous radiation environment. To overcome the constraints of conventional technologies, it is necessary to develop a cost-effective alternative approach that makes use of some sort of energy source [5].

Microwaves are electromagnetic waves that have wavelengths ranging from one millimetre to one metre with remarkable uniform heating properties [1]. This remarkable heating property of microwaves has prompted academics to look for ways to use this type of energy in materials processing and industrial applications. Microwaves have been utilized as an efficient energy source for heating various metals in recent decades. Microwave cladding is a newly discovered approach for overcoming the limits of conventional cladding technologies by using microwave radiation as a heating source. It's a low-cost method with excellent metallurgical bonding with improved mechanical and tribological features. Microwaves also have the advantage of being emission-free. As a result, the advancement of microwave-based processing technology is critical since it reduces reliance on fossil fuels and other high-energy-based heating systems. Microwave cladding presents itself as a viable alternative to traditional cladding methods as there is a rising awareness of reduced emissions and initiatives in the industry to embrace greener technologies [8].

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The microwave cladding of metal-based powder (micron, nano, and composite) over metallic surfaces has been described by a number of researchers. This paper presents an overview of microwave cladding. The research papers written by several researchers till dates are reviewed in chronological sequence including the substrates and clad materials used are listed in Table 1. The papers introducing the different output parameters of cladding are reviewed and their research findings are reported under the domain of microstructure, hardness, and tribological properties.

TABLE 1. Summary of investigations on Microwave cladding.

Authors (year)	Substrate Material	Coating Powder	Coating thickness	Investigations	Frequency	Microwave power	Research findings
Gupta et al.2011 (Ref. 2)	SS-316	WC10Co2Ni	2 mm	Microstructure, wear resistance, microhardness	2.45 GHz	600–900 W	The homogeneous and crack-free excellent metallurgical bonded coating was obtained with better wear resistance better at lower sliding speeds.
Gupta et al.2011 (Ref. 3)	SS-316	Nickel-based (EWAC)	1 mm	Microstructure, microhardness	2.45 GHz	1 kW	The homogeneous and crack-free excellent metallurgical bonded coating was obtained with improved mechanical properties.
Gupta et al.2012 (Ref. 4)	SS-316	EWAC + 20% $Cr_{23}C_6$	500 µm	Microstructure, microhardness	2.45 GHz	900 W	Improved microhardness and value was observed as 425 ± 140 HV.
Gupta et al.2012 (Ref. 5)	SS-316	WC10Co2Ni	2 mm	Microstructure, microhardness	2.45 GHz	900 W	The homogeneous and crack-free excellent metallurgical bonded coating was obtained.
Sharma et al.2012 (Ref. 6)	Austenitic stainless steel	Tungsten-based	500 µm	Microstructure, flexural strength	2.45 GHz	900 W	The excellent metallurgical bonded coating was obtained by partial dilution of materials, but at the clad surface, there were multi-directional cracks.
Zafar et al.2013 (Ref. 7)	Austenitic stainless steel	Inconel 718	1 mm	Microstructure	2.45 GHz	900 W	The homogeneous and porosity-free excellent metallurgical bonded coating was obtained with no interfacial cracking.
Gupta et al.2014 (Ref. 8)	Austenitic stainless steel	WC10Co2Ni	2 mm	Microstructure, microhardness	2.45 GHz	900 W	The coating achieved a higher microhardness.
Zafar et al.2014 (Ref. 9)	AISI 304	WC–12Co	1 mm	Microstructure, microhardness	2.45 GHz	1.4 kW	The homogeneous and porosity-free excellent metallurgical bonded coating was obtained with no interfacial cracking. The average microhardness was found to be 1135 ± 88 HV on average.
Bansal et al.2015 (Ref. 10)	Mild steel	Ni-WC	1 mm	Microstructure, abrasive wear, microhardness	2.45 GHz	1.1 kW	Superior abrasive wear resistance was found.
Pathania et al.2015 (Ref. 11)	Mild steel	EWAC + 20% WC10Co2Ni	300 µm	Microstructure, mechanical characterizations	2.45 GHz	900 W	The homogeneous and crack-free excellent metallurgical bonded coating was obtained with improved mechanical properties.
Zafar et al.2015 (Ref. 12)	Austenitic stainless steel	WC–12Co	1 mm	Microstructure, microhardness	2.45 GHz	1.4 kW	Wear resistance and microhardness were considerably improved for both nanometric and the micrometric clad layers.

TABLE 1. Summary of investigations on Microwave cladding (continued).

Authors (year)	Substrate Material	Coating Powder	Coating thickness	Investigations	Frequency	Microwave power	Research findings
Zafar et al.2015 (Ref. 13)	AISI 304	WC-12Co	1 mm	Microstructure, microhardness, tribiological properties	2.45 GHz	1.4 kW	The homogeneous and crack-free excellent metallurgical bonded coating was obtained with improved mechanical properties. Wear rate and coefficient of friction were both lowered by 67% and 56%, respectively.
Hebbale et al.2016 (Ref. 14)	SS-304	Nickel-based	1 mm	Microstructure, microhardness	2.45 GHz	900 W	The homogeneous and crack-free excellent metallurgical bonded coating was obtained with improved mechanical properties.
Yadiyal et al.2016 (Ref. 15)	M2 high-speed steel tool	WC-Ni	20 µm	Microstructure, elemental composition	2.45 GHz	900 W	Successfully developed crack-free WC-Ni clads with good wear-resistant.
Zafar et al.2016 (Ref. 16)	SS-304	WC-12Co	1 mm	Microstructure, mechanical properties	2.45 GHz	1.1 kW	The homogeneous and porosity-free excellent metallurgical bonded coating was obtained with no interfacial cracking and better mechanical properties.
Zafar et al.2016 (Ref. 17)	SS-304	WC-12Co	1 mm	Microstructure, elemental composition, mechanical properties	2.45 GHz	1.1 kW	During heat treatment up to 400^{o}C, microstructural studies and phase analyses revealed the formation of eta phases, which increased the resistance to wear and hardness of the clads.
Zafar et al.2017 (Ref. 18)	SS-304	Ni-based	300µm	Microstructure, mechanical properties	2.45 GHz	1 kW	The findings revealed effective enhancement in the mechanical and tribological properties after post-processing.
Hebbale et al.2018 (Ref. 19)	AISI-420	Cobalt-based	1 mm	Microstructure, microhardness	2.45 GHz	900 W	Successfully developed a crack-free good metallurgical bonded coating with enhanced mechanical properties.
Kaushal et al.2018 (Ref. 20)	AISI 304	Ni-WC-based	1.8 mm	Microstructure	2.45 GHz	900 W	The homogeneous and porosity-free excellent metallurgical bonded coating was obtained with no interfacial cracking and better microhardness.
Kaushal et al.2018 (Ref. 21)	SS-304	Nickel–alumina	0.6 mm	Microstructure, microhardness	2.45 GHz	900 W	The homogeneous and porosity-free excellent metallurgical bonded coating was obtained with no interfacial cracking. Clad has a micro-hardness four times that of the substrate, making it excellent for anti-wear applications.
Kaushal et al.2018 (Ref. 22)	SS-304	Ni-based + 20% Cr_3C_2	600 µm	Microstructure, microhardness, wear resistance	2.45 GHz	900 W	The findings revealed effective enhancement in the tribological and mechanical properties after post-processing.
Babu et al.2019 (Ref. 23)	SS316L	Ni-SiC bimodal	500–600 µm	Hardness, fracture toughness, erosion resistance	2.45 GHz	900 W	The findings revealed effective improvement in the mechanical and tribological properties, which makes it suitable for work under erosion environments in fluid machinery.

TABLE 1. Summary of investigations on Microwave cladding (continued).

Authors (year)	Substrate Material	Coating Powder	Coating thickness	Investigations	Frequency	Microwave power	Research findings
Kaushal et al.2019 (Ref. 24)	SS-316 L	Ni–WC–Cr3C2	0.85 mm	Microstructure, microhardness	2.45 GHz	900 W	The findings revealed effective enhancement in the mechanical properties
Nair et al.2019 (Ref. 25)	SS316L	High entropy alloy (AlxCoCrFeNi)	550–600 µm	Microstructure, hardness, wear	2.45 GHz	900 W	The hardness and the wear resistance directly depended on Al-contents.
Prasad et al.2019 (Ref. 26)	Pure titanium grade-2	Co-Mo-Cr-Si	500 µm	Microstructure, phase analysis, microhardness, wear	2.45 GHz	900 W	Concerning the substrate, the cladding layers' frictional coefficient and microhardness increased
Singh et al.2019 (Ref. 27)	Low carbon martensitic steel	Ni + 20 wt% Cr_7C_3	1.2 mm	Microstructure, phase analysis, nanohardness, fracture toughness	2.45 GHz	1.5 kW	The results revealed enhanced erosion resistance thus, enhanced average nanohardness.
Mishra et al.2020 (Ref. 28)	Low carbon steel	Ni-WC	………	Microstructure, hardness, coefficient of friction, abrasive wear	2.45 GHz	900 W	Results showed that the addition of 12 wt percent WC enhanced the hardness, microstructure, and abrasive wear of the cladding.
Kumar et al.2020 (Ref. 29)	SS-321	Ni-based alloy	0.2 mm	Microstructural characterization, microhardness, sliding wear	2.45 GHz	900 W and 1300 W	Inter diffusion of the component elements indicated excellent metallurgical connection of the clad layer and substrate.
Singh et al.2020 (Ref. 30)	Mild steel	Inconel-625	1 mm	Microstructure, microhardness, corrosion	2.45 GHz	1.2 kW	The result exhibited dense microstructure with a porosity value of less than 1% and enhanced tribological and mechanical properties.
Mago et al.2021 (Ref. 31)	SS-316	Ni–40Cr3C2	1 mm	Microstructure, microhardness, flexural strength, fracture toughness	2.45 GHz	900 W	It observed dense microstructure and enhanced the toughness as compared to the substrate.
Singh et al.2021 (Ref. 32)	ASTM A743 (hydro turbine steel)	Ni + 10% Cr7C3	500 µm	Microstructural, mechanical aspects	2.45 GHz	1 kW	The findings revealed effective improvement in the mechanical and tribological properties, which makes it suitable for work under erosion environments in fluid machinery.

DEVELOPMENT OF CLADDING AND TESTING

The microwave cladding process and the testing after cladding is summarized in the flowchart shown in the Figure 1. The charcoal powder acts as a susceptor material, allowing for hybrid heating while also reducing the risk of clad cracking. To prevent clad powder particles from contaminating the susceptor, a 1 mm thick plate can be employed.

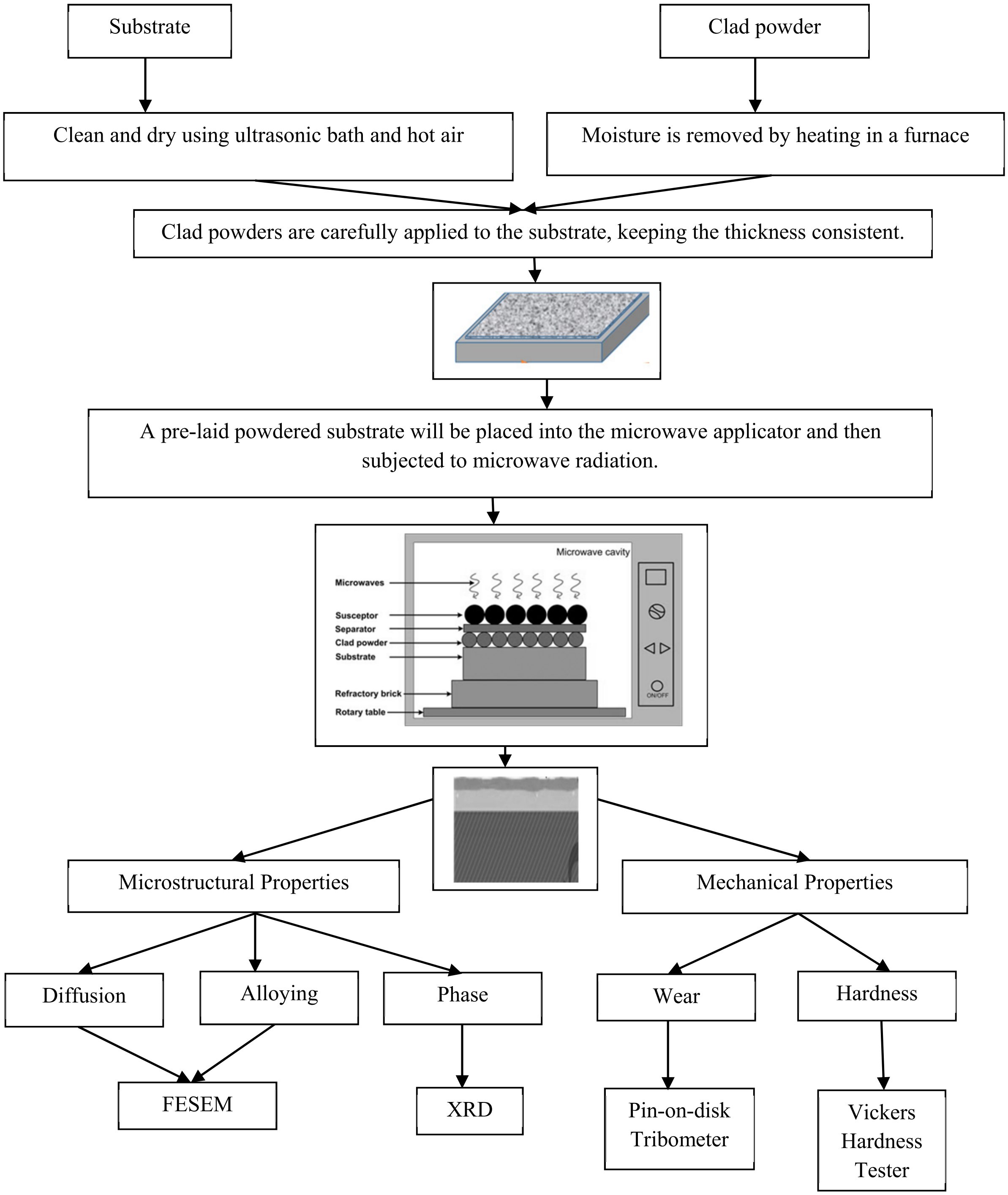

FIGURE 1. Flowchart showing the steps of microwave cladding and characterization

MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION

Materials of cladding and substrate greatly affect the microstructural pattern of the coating. It is also affected by the microwave parameters. The microstructure and composition of different observed phases of the developed coating can be evaluated by different tools such as EPMA (electron probe microanalyzer), FESEM (field emission scanning electron microscope) equipped with EDS (energy-dispersive X-ray spectroscopy), TEM (transmission electron microscope), etc. Mechanical characteristics of the modified surfaces were analyzed based on microhardness and tribological properties. Almost all the researchers [2-32] investigated the microstructure of the cladding and found improved microstructure as compared with the substrate. Resistance to plastic deformation by indentation, scratching or other frictional means is defined as hardness. Microhardness was measured with the help of a microhardness tester using a Vickers indenter. Microhardness was shown to be enhanced by many times when microwave cladding was used [21]. During sliding or rolling of two solid surfaces in solid-state contacts material removal takes place from one or both of two solid surfaces termed as wear. Such tribological characteristics of the surfaces are a common trouble in various industries. Pin-on-disk tribometer is the most effective tool to perform tribological properties tests. Effective improvement in the mechanical and tribological properties of microwave cladding has been found, which makes it suitable for work under erosion environments in fluid machinery [32]. The details of studies carried by researchers are presented in Table 1 in the investigations column for respective studies.

CHALLENGES AND OPPORTUNITIES

Microwave cladding is a new surface modification technology that has enhanced mechanical characteristics and better adhesion between the substrate and clads. However, we must overcome several challenges in order to make the method more effective and suited for industrial applications [33]. The challenges and opportunities in this field can be listed as follow:

- Due to non-uniformities in the composition of advanced material, non-uniform heating of materials takes place, which is responsible for thermal damage and the generation of internal stresses. We can solve these issues by inventing new microwave heating methods that allow advanced materials to be heated uniformly.
- During microwave processing, live experiment measurements of material properties are challenging; nevertheless, we have the opportunity to construct mathematical models and simulations of the process for a greater awareness of process physics and improvements in clad qualities.
- For greater energy distribution per unit area in materials, a focused microwaves system can be created.
- Due to the standard size of microwave applicators, industrial applications are limited. Applicator designs that are customized and cost-effective are an opportunity.
- Microwave leakage is dangerous to humans, thus safety and health measures must be strictly adhered to throughout processing.

CONCLUSION AND FUTURE DIRECTIONS

Following important remarks and suggestions for future research can be made from reviewing research papers on different investigations on microwave cladding:

- Microwave cladding is an energy-efficient and quicker cladding process than conventional methods.
- It can be applied to an extensive range of substrates to develop superior metallurgical bonding with the clad material to enhance the mechanical and metallurgical properties.
- It can be applied to produce a crack-free structure with lesser porosity.
- It can be remarked that more concentration was given to investigations based on microstructure, microhardness, and wear resistance, whereas the studies concentrated on the oxidation and erosion-corrosion behavior of coating were less attempted.
- Intensive research is required to elucidate the situation of the complex physical and chemical reactions between the substrate and the clad materials during microwave cladding.
- Very few researchers focused on the parametric optimization of microwave Cladding. So, researchers should put extra effort to optimize the parameters by applying AI-based modeling and optimization techniques.
- Microwave cladding can be used to enhance the surface properties of the cutting tools.

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