Laser cladding technique for erosive wear applications: a review

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Abstract

Slurry erosion is a serious menace in most of the hydro machine components all around the globe. Slurry erosion is accountable for heavy economic losses. However, some counter measures are being taken to mitigate the effect of sand particles passing through hydro-machine parts and research is also underway to improve the component surface by applying different surface coatings. Laser cladding is a surface deposition process that is used to achieve very good metallurgical bonding with minimum porosity as compared to other surface coating techniques. In this research paper, an attempt has been made to compile the literature related to laser cladding technology, its applications, process parameters, coating materials and their effectiveness to bestow solutions to various types of surface degradation with special emphasis on slurry erosion problems. This paper will serve as a reference for the researchers working in the area of slurry erosion prevention.

1. Introduction

The wear induced by strong particle erosion has been a subject of concern for more than 60 years due to the potential for damage to machinery and the related repair/replacement expenses in industrial machinery during the processing or transport of multi-phase slurries. Wear can be described as distortion to a solid surface caused by a mechanical action of contacting strong, liquid or gas by removing or displacing material [1]. According to Budinski [2] wear procedures can be divided into four categories namely erosion, abrasion, adhesion and fatigue. Slurry erosion happens when wear is caused by a solid-liquid blend, explicitly referred to as slurry [3]. This is a prevalent occurrence in submerged components of hydro turbines and numerous other associated industrial circumstances [4]. Slurry erosion is a complicated method that involves the interaction of three coexisting stages namely liquid carrier, solid particles and metal surface in many aspects [5]. Slurry erosion could be defined widely as the operation by which the material is degraded through mechanical interaction from a surface in contact with continuous moving solid particle slurry. Fluid machinery including pumps, valves, hydro-turbines and vessel propellers are typically exposed to slurry erosion, where the blend of solid particles with a fluid medium causes surface damage. The surface is presented to monotonous effects of hard erodent particles, which in the long run prompts extreme surface harm and material loss. Turbulent flow may exacerbate material loss rate further. It is a critical issue regarding the performance, dependability and service life of the slurry components used in numerous industrial applications such as mechanical equipment used in oil industries, solid-liquid hydro-transport systems, hydroelectric power plants, plants of coal liquefaction and boilers used in industries where coal is transported directly in water or oil [6–9]. In mines, mineral slurry transport is both an economical and environmentally friendly alternative, whereas pumping is usually the only option for moving concrete to its destination at big construction locations. Wear is the primary factor associated with the costs of such pumping projects and mostly the wear environment dictates the original capital expenses and precious pipeline life [6–10]. One of the significant elements influencing wear is the particle size inside the slurry. Particle size is in centimetres in heavy duty industry [10], whereas in case of light particle mineral operations the particle sizes typically range from 100 to 250 μm [11–15].
Erosion is described as wear induced by solid particles hitting a surface, transferred via a gas flow or entertained in a fluid streaming medium [16]. The impinging angle of the particles and relative velocity determines the abrasive wear on a surface [17]. Hydro abrasive erosion depends upon several parameters such as size of sand, hardness, concentration, shape, quantity, and velocity, in most cases minimizing the impact energy of the particles by monitoring the parameters mentioned or indirectly. Despite this, enormous surface destruction to hydroelectric devices and structures occurs at any stage at a sufficiently elevated velocity, causing scratching and removal of material [18]. It has been learned that because of their excellent corrosion characteristics and acceptable resistance to strong particle erosion, in hydroelectric power plants stainless steels are widely used [16]. Bitter [19] suggested two erosion wear theories: cutting and deformation, according to him, the cutting wear is triggered by the particle velocity element parallel to the target surface, whereas the deformation wear is accountable for the normal component of the velocity. Some researchers [20–24] indicated that hardness of the target material or hardness of the impacting solid particles was dominant for wear of target surface. Wang and Yang [25] noted that a dominant function in the erosion process is the surface hardening of metals. The worn surfaces were analysed by scanning electron microscope and different wear processes such as micro-ploughing, lip formation, platelet, tiny indentation craters, and micro-cracking were described. It was reported that the depletion of materials such as metals and alloys was produced by the micro-cutting and micro-ploughing of strong particles for ductile materials. The crack coalescence results in the removal of large-scale components for brittle materials.

Material degradation by the dint of slurry erosion relies on myriad variables that can be classified into three primary groups: the first one associated with fluid flow circumstances (flow speed, particle impingement angle, concentration of particles, density of liquid, liquid chemical activity, temperature of fluid), the second is linked to solid particles (their size, hardness, shape, strength) and the third is related to the target material (mechanical and endurance characteristics: toughness, fatigue, number and size of defects, yield and ultimate strength, topography of the surface and microstructure) [26–31]. Impact speed and large particle size affect a single particle’s kinetic impact energy. The erosion rate increases with increase in impact velocity, particle size and slurry concentration.

The next important factor that has an enormous effect on material degradation is material stiffness, which is severely linked to material hardness. With growing rigidity/the target material hardness, the critical impact angle rises, at which peak erosion rate happens [32–35]. The peak erosion rate for ductile materials happens at approximately 20°. The highest rate of erosion happens at ordinary impact angle in the case of brittle materials. The hardness of strong particles, despite the material hardness, affects the material erosion rate [32, 35].

Materials utilized in fluid machineries for instance turbines, propellers, pumps, and valves typically show surface deprivation in the form of erosion and result insignificant economic impact [30, 36]. The materials used in these applications have restricted wear, erosion, and corrosion resistance. Therefore, to counteract these types of degradation, sophisticated materials with superior surface characteristics are required.

Coatings can generally be considered as materials with protection from the process of huge degradation of the surface. Coatings provide a way to stretch the boundaries of use of metals at the top of their performance capacity by enabling maintenance of the mechanical features of the substrate parts while protecting them from wear and corrosion [37–40]. Coatings have a benefit that they are comparatively inexpensive and can be implemented in situ. Myriad coating deposition procedures are available and the selection of the best process depends on the functional requirements, the adaptability of the coating material to the intended technique, the level of bonds required (size, shape and substrate metallurgy), the availability and cost of the equipment.

A vast number of coating materials have been tested by different researchers against the slurry erosion. Tested materials can be segregated into: cobalt-based, titanium-based, ferrous, nickel-based materials and bulk metallic glass [32, 33, 41–44]. For ductile ferrous products, e.g. stainless steel SS304, the rate of erosion rises with increase in impact velocity, while it reduces to a critical value in testing time [42]. Multiple surface treatment techniques to boost surface hardness were implemented to alleviate the damaging impacts of slurry erosion. The primary technique is to place the coating on substrate. A number of deposition methods are used such as the detonation-gun spray process [45], oxy fuel powder process [46, 47], wire arc spraying process [46], high velocity oxy fuel process [47], physical vapor deposition [48], laser surface alloying [43], plasma and flame spray methods (thermal sprayed coatings) [49]. There are also other techniques that enhance the resistance of slurry wear, e.g. work hardening [50], nitriding [51], brush plating and next alloy surface [52], boronizing [53], boriding [53].

To resist erosive wear, coating of the appropriate material is required to modify the functional surface. Thermal spraying, high velocity oxy-fuel, carburizing, nitriding and coating/cladding [54, 55] are countless methods for improving surface characteristics. Advancement of the functional surfaces erosive wear resistance by cladding with appropriate overlaying material would be one of the simplest and most economical alternatives to the above problem [56] as it have a plethora of benefits such as high intensity, focused and regulated source of heat, excellent coating characteristics, low dilution (min 1%–5%), minimum material variations owing to low
heat load, controlled coating thickness. Laser cladding is one of the prominent surfacing techniques of providing anti-wear alternatives for industrial applications.

2. Laser cladding process

Laser cladding method is having extreme importance for various industrial purposes where different shapes of nozzles used which continuously emits the laser beam and different powder mixtures comes in contact with laser beam and melts and produce a layer of powder coating on surface. It is also known as hard facing or surfacing, that aimed at enhancing the substrate characteristics (base metal) and it is performed either using laser beam or arc as the source of heat for the process. The filler material used in the method is placed layer by layer before being machined to attain the final dimension until the necessary thickness is covered. Laser cladding has many benefits over the various conventional procedures of coating. The performance of laser cladding is much better than other techniques. It provides the potential for developing such a technology for repairing. Mechanical sections have been repaired using the method. There are many other methods that consume more time and energy, but laser cladding is an option to techniques of diffusion. The laser cladding system is made up of various parts shown in figure 1.

Different carbon steel, alloy metals, stainless steel and nonferrous alloy metals are the substrate materials. There are two types of clad materials shown in table 1. Placing of cladding material to the substrate followed by the creation of melt pools: wire feed, blown or injected powder and pre-placed power method.

The laser cladding has several process parameters. The main parameters are: laser energy, laser beam spot diameter, laser scanning velocity or comparative work-piece motion velocity, pre-powder layer thickness, powder feed rate, nozzle angle and stand-off, etc figure 2 represents the cause and effect diagram for laser cladding process which classified the process parameters into five major categories: machining parameters, characteristics of laser beam, characteristics of product, laser clad characteristics and characteristics of cladding powder. The process parameters should be legitimately controlled in order to optimize the process.

Laser cladding is applied not only for coating, but also for repair and rehabilitation as well as for rapid prototyping. The diverse applications are listed in table 2.

3. Laser cladding materials

Undoubtedly, there are diverse alloys used such as Ni, Fe, Co, Al, Ti, Cu, Nb based alloys and some other alloys like stainless steel, and tool steel. Different authors have done investigation on deposition, microstructure, characteristics and parameter dependency in order to produce a uniform and homogeneous clad layer with a
better metallurgical bond to the substrate, free of cracks or porosity. Laser coatings with commercial alloy products often exhibit superior characteristics as that of standard coatings.

3.1. Stellite 6
Stellite 6 is widely used alloy in which Co is major constitute and containing 1% C, 27% Cr, 4.7% W and 0.9% Si for resistance to high temperature, resistance to wear, corrosion resistance, oxidation resistance and high hardness. Many researchers have used the stellite 6 coating on various substrates by using different coating methods. Abbas and West \[87\] produced the layer of stellite 6 using the continuous wave CO2 laser on En 3b mild steel base material. To measure the impact of integrated SiC particles, a comparative study of structure, chemical composition, wear and hardness was conducted. It was discovered that the micro-hardness for the Stellite alloy 6 clad was increased from 540–580 HV to about 1390 HV for the composite matrix area by the incorporation of about 19 wt percent SiC in the cladding mixture. Gupta \[88\] et al studied the wear performance of stellite 6 by the laser cladding technique on EN19 steel. The clad layer microstructure was discovered to consist of three areas: a clad layer involving of Stellite 6 dendrites, an alloyed part comprising of a cellular microstructure that was a combination of Fe and Co, and the heat-affected area, which was a combination of pearlite and martensite. It was witnessed that Stellite 6 has significant improvement in the hardness that was 1200 HV as compared to the as-received EN19 steel substrate. Frenk et al \[89\] performed extensive experimental and theoretical research on laser cladding of mild steel with Stellite 6 using CO2 laser wave to comprehend the effect of powder feed rate and scanning velocity on clad height and mass effectiveness. It was concluded that with increase in the scanning velocity thickness of stellite 6 coating decreased whereas increase in the powder feed rate increase the coating thickness. Tiziani et al \[90\] made comparison of stellite coatings produced by different methods like TIG, oxyacetylene, CO2 and Nd:YAG laser on austenitic stainless steel, and concluded that the coating of Stellite 6 produced by laser cladding has improved significant properties as that of others method. Stellite 6 stainless steel by laser cladding of 13Cr–4Ni was conducted to study the efficiency of strong particle erosion cladding and cavitation erosion at varying power densities (from 32 to 52 J mm \(^{-2}\)) studied by Singh et al \[91\] and comparison of results with the AISI 304 stainless steel. The clad’s peak hardness (705 HV) was achieved at 32 J mm \(^{-2}\) and further decreased as the laser energy density increased Stellite 6 cladding considerably increased the resistance of stainless steel to strong particle erosion.

3.2. Ni-based hard facing alloy
Ni-based hard facing alloys like NiSiB, NiCrSiB etc have better weld ability and low melting points. These alloys possess the excellent toughness, thermal and corrosion resistance properties. Be et al \[92\] investigated the performance of laser cladded layer of Inconel 625 (NiCrSiBFeC) on SS316 substrate and concluded that coating thus produced was of superior quality to substrate with higher corrosion resistance. Alexandru et al \[93\] used Ni based powders to produce the coating on AISI 5140 steel substrate by various methods and one of which was laser cladding. It was noted that Ni based coating was not only free from cracks and pores, but had very good adherence to the substrate. Researchers concluded that Ni based cladding samples had an increased micro-
| S. No. | Coating material | Applications | Authors | Concluding remarks |
|--------|------------------|--------------|---------|-------------------|
| 1.     | Ni-base super alloys | Turbine blades, mining machine parts, air folds | Damborea et al [58], Wang et al [59], Xue and Islam [60], Mazumder et al [61], Xue et al [62], Bohrer et al [63], Gaumann et al [64] | Researchers observed improvement in the fatigue endurance and service performance of cladding of nickel based super alloys in comparison with conventionally processed parts. |
| 2.     | Ni-Cr3C2 | Well drilling and oil extraction equipment | Katipelli et al [65] | Authors found that coating provides better erosion resistance in the components as compared to substrate. |
| 3.     | Inconel 625-CrC | Gas turbine airfoil thermal barrier | Gaumann et al [64] | It was found that substrate and coating materials had good adhesion of bonding. |
| 4.     | Stellite, Stellites | Seal runner, gate valve, torsion shafts, injection molds and extruder parts | Bruck [66], Mazumder et al [61] | Stellite coatings were found to be suitable in providing resistance against the slurry erosion in different parts of valve, runner and turbine. |
| 5.     | 316L | Blade integrated disks, injection molding tools, turbine blades | Fessler et al [67], Mazumder et al [61] | Researchers found the problem of thermal stresses in the components due to laser cladding technique. |
| 6.     | 316L-Stellite12 | Functionally graded materials (3D objects) | Yakovlev et al [68] | Authors successfully developed the FGM structures using laser cladding technology. |
| 7.     | 316L-Stellite12-FeCu-WC/Co-CuSn-bronze | Components of cooling systems in International Thermonuclear Experimental Reactor | Yadroitsev et al [69] | It was observed that addition of FeCu-WC/Co-CuSn-bronze to 316L enhanced the smoothness of coatings. |
| 8.     | Al-Ti | Cutting tools, inserts, diffusion barriers in semiconductor technology | Katipelli et al [70] | Coatings found to be highly successful for wear resistance by laser cladding method. |
| 9.     | Al-Cu alloy | Automotive industry | Dubourg et al [71] | Researchers were successful in developing highly dense coatings by laser cladding of Al-Cu alloy suitable for automobile industry. |
| 10.    | Al-Si | Cylinder heads and blocks | Mazumder et al [61] | Authors observed that addition of Si content in Al leads to increase the hardness. |
| 11.    | Al/Si-TiC | Automotive industry | Dubourg et al [72] | It was observed that adhesive wear resistance improved significantly with addition of Si and TiC contents in Al. |
| 12.    | Cu-Ni | Engine components, ceramic turbine components, direct metal tools, drug delivery devices, armor and armament components, building block for temperature-insensitive structures | Shin et al [73], Mazumder et al [74] | Researchers found the structure of component had an overall negative coefficient of thermal expansion. |
| 13.    | Ti6Al4V | Large aerospace components, hollow motorcycle engine stems | Arcella et al [75], Capshaw [76] | 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 [77] | Authors observed that the laser cladding coating of TiC-Ti effectively prevents the formation of cracks. |
| S. No. | Coating material           | Applications                        | Authors       | Concluding remarks                                                                 |
|-------|---------------------------|-------------------------------------|---------------|-----------------------------------------------------------------------------------|
| 15.   | TiC-90MnCrV8              | Tools and molds                     | Axen et al [78]| Researchers observed that coefficient of friction decreases with increasing carbide content. |
| 16.   | WC-20Ni4Mo                | Teeth of rock bids, cutting tools   | Beidi et al [79]| It was found that hardness of rock bids and cutting tools increased significantly by laser cladding of WC-20Ni4Mo coatings. |
| 17.   | WC-NiCrB                  | Oilfield and forestry industries    | Marchione et al [80]| Researchers observed that erosive wear resistance increased by alloys coatings. |
| 18.   | H13-Ni/Cr alloy-TiC       | Mold inserts                        | Jiang et al [81]| Authors found that heating produced during laser cladding process resulted in formation of coarse grains. |
| 19.   | H13 tool steel            | Molds and dies                      | Hu et al [82]| It was observed that coating enhanced the hardness of the surface. |
| 20.   | CPM 9V tool steel, CPM 15V tool steel | Rotary cutting dies | Mazumder et al [61], Xue and Islam [83]| Abrasive wear resistance improved due to coating achieved by laser cladding technique. |
| 21.   | Rene 80, Inc625           | Turbine parts                       | Mazumder et al [61]| Authors found that remelting of substrate was necessary to obtain a good bonding of deposited layer. |
| 22.   | Cr-CrB2, Mo-MoB           | Automotive, aerospace, paper and plastic industries | Rajput et al [84]| Researchers observed that both sliding-wear resistance and erosion resistance of the steel substrate increased by chromium based coatings. |
| 23.   | Zn-Al                     | Propeller and drive shafts, engine components | Carvalho et al [85]| Coatings produced by laser cladding had good metallurgical bonding with substrate. |
| 24.   | YPSZ, YPSZ-Al2O3          | Gas turbine engines                 | Jasim et al [86]| Researchers concluded that there was a possibility to produce a clad layer of thermal barrier coating with different topography on gas turbine engines. |
| 25.   | AISI 410                  | Valve seat                          | Bruck [66]| Authors found that coatings obtained by laser cladding on valve seats were sound with minimum dilution and distortion. |
hardness and homogenous microstructure than the substrate. Feng et al [94] studied the hardness and wear resistance of Inconel 625 coatings on polycrystalline advanced martensitic steel by laser cladding method. The microstructure, hardness and wear resistance were investigated at elevated and both room temperatures. By the results of XRD, SEM and EDS techniques it is concluded that laser cladded coating of Inconel 625 produced finer microstructure and lower wear rate because of lower dilution of iron and higher hardness. Yang et al [95] analyzed the microstructure of Ni-Cr alloy on steel. Results showed that laser cladding coating has superior creep properties, high temperature oxidation, and corrosion resistance.

3.3. Fe-based alloys

Fe-based alloys are less costly and extensively used alloys. Weerasinghe et al [96] used laser cladding method to produce coating of 316 stainless steel powders on an En3 mild steel substrate and investigated clad geometry and distribution of homogeneous element within the cladded layers. The clad layers of stainless steel were observed to be free of porosity and of sound coating. Yang et al [97] carried out research work to investigate the microstructure, micro-hardness, abrasive wear resistance, and corrosion resistance of Fe-Cr-Si-B alloy powder coating using laser cladding method on low carbon steel base material. It was observed that coating obtained by laser cladding had enhanced the abrasive wear resistance, corrosion resistance and significantly increased the micro-hardness as compared to the substrate. Manna et al [98] produced a coated surface of different composition of Fe-B-Si, Fe-B-C and Fe-B-C-Si-Al-C on an AISI 1010 steel substrate. From the results, it was found that wear resistance was enhanced by the different coatings of iron based alloys. Jiang and Kovacevic [99] carried their research work to study slurry erosion behaviour of Fe-Cr-B-Si coatings at different impact angles on AISI 4140 steel substrate and compared Fe-Cr-B-Si coatings with slurry erosion behaviour of laser cladded chromium carbide and tungsten carbide coatings. The coatings of Fe-Cr-B-Si had shown less wear as compared to chromium carbide and tungsten carbide coatings.

3.4. Metal matrix composite coatings

Metal matrix composite (MMC) coatings use alloy powders and various carbides that gained the popularity due to their higher hardness and better corrosion resistance. MMC is metal based composite material having properties more than the individual materials. MMC is usually composed of a metal matrix and various hard phases. Myriad papers on multiple carbides have been published in this area (WC, TiC, ZrC, SiC, B4C, Cr2C3, and Cr3C2), borides (TiB, TiB2 and Ti2B), and oxides (Al2O3, ZrO2, and TiO2). Nowotny and Techel [100] evaluated the wear properties and microstructure of carbide coatings produced by utilizing the laser cladding method. They inferred that maximum wear resistance obtained was a result of non-dissolved WC particles. Zhong et al [101] used laser cladding technique to produce the layer of composite coatings of Ni-Al+TiC. The coating had good geometry, no cracks or porosity, with micro hardness of 1538HV. Apart from this, good metallurgical bonds with base material were obtained. Wang et al [102] investigated the abrasive wear performance and microstructure of WC-Ni Particulate reinforced metal matrix composite (PR-MMC) coatings using laser cladding technique to produce a coating of WC-Ni PR-MMC on H13 hot work tool steel substrate. It was found that the shape of the WC particle influences the microstructure and wear resistance. The crushed WC particles resulted in higher wear resistant surfaces. Anandkumar et al [103] evaluated the performance of composite materials coatings comprising of an Al−Si matrix reinforced with silicon carbide (SiC) particles (Al-12 wt% Si alloy) using the technique of laser cladding on UNS A03560 cast Al alloy substrates. In this research work, effect of process parameters on microstructure and abrasive wear performance were studied. On the basis of specific energy used, it was concluded that SiC particles either continued to remain undissolved or react with molten Al or form a partially dissolved microstructure in Al-Si-SiC composite coatings. Vilar [104, 105] analyzed the abrasive wear behavior of Fe-Cr-C coating which includes varying volumes of Nb2C reinforced particles, generated by laser cladding technique. The findings indicate that material’s wear strength reduced continually with increase in volume fraction of Nb2C reinforcement particles. Pei and Zuo [106] produced TiC–Ni alloy composite coating by laser cladding on 1045 steel substrate. It was found that clad layers consisted of TiC particles, γ-Ni primary dendrites, and inter dendritic eutectics. The morphology altered from tiny spherical to coarse flower-like cluster. Laser processing parameters like laser power and scanning speed had a significant effect on the gradient distribution of TiC particles in the coating.

4. Slurry erosion parameters

The parameters such as slurry concentration, particle size, particle shape, the impact velocity of erodent, impingement angle, substrate material properties and environmental conditions, etc are responsible for erosion wear rate. The effects of these erosion parameters on wear rate as investigated by various researchers have been discussed in following paragraphs.
Desale et al. [107] carried their research work on ductile materials to analyze the effect of slurry erosion under normal impact conditions using the slurry pot tester. In this research work, various erodent materials were used such as alumina, quartz and silicon carbide, whereas mild steel, copper, etc. were used as substrate material on which erodent material strikes with the velocity of $3 \text{ m s}^{-1}$, particle size as 550 micron and concentration as 10% by weight. From the test results, the researchers found that hardness of substrate and hardness of particles were dominant factors for erosive wear.

Clark [108] investigated the effect of particle velocity and particle size on erosive wear. He suggested that for erosive wear of cylindrical specimen, analyzing surface profile process was much better than that of mass loss method. Other crucial parameters such as slurry concentration, the angle of impact, particle density, hardness, nature of slurry liquid, type of flow, properties of the target material were also found to have significant effect on the erosive wear rate.

Desale et al. [109] examined the effect of striking erodent particles on erosive wear. In the experimentation, aluminum alloy and stainless steel were used as substrate material, while alumina, quartz and silicon carbide were used for making the slurry. At low impingement angles, shape and density of erodent particles were more dominant factors for erosion as compared to high impingement angle. It was concluded that the effect of hardness of target ductile materials lesser significant as compared to erodent properties such as shape and size.

Gandhi et al. [110] studied the effect of narrow sized and multi-size particulate slurries for erosive wear by utilizing the slurry pot tester. For experimentation, sand-water mixture and cast-iron was used as target material. For wear, median and weight diameter were dominant in case of multi-sized particulate slurries, whereas, mean particle size was considered as prominent for narrow sized particle slurry. It was concluded that increase in particle size leads to commensurate erosion. Gupta et al. [111] used pot tester to evaluate the wear performance for brass and mild steel. The effects of slurry concentration, particle size and velocity were studied for wear rate. The effect of velocity and particle size was less as compared to slurry concentration. It was also identified that the weighted mean diameter is the best representative diameter for evaluating the wear in the case of multi-sized particulate slurries.

Patel et al. [112] investigated the effect of silt erosion on pelton turbine buckets made of brass material. Different parameters were considered for instance size of silt, silt hardness and concentration, velocity of impact and hardness of material. The output value of weight loss verified with analytical values. Rajesh et al. [113] studied the impact of silica sand particles for erosion wear of polyamides at various velocities and impact angle. It was concluded that at oblique impact angle effect of velocity was dominant than at normal impact angle. At normal impact, the brittle fracture was witnessed using SEM analysis, while in the case oblique impact, there was micro cutting and plastic deformation observed. Mass loss from the turbine surface is directly affected by the silt size, silt-hardness, flow velocity, silt concentration and inversely proportional to the hardness of turbine material.

Bhandari et al. [114] carried the research work on the erosion resistance of two different hydro-turbine steels (CA6NM and CF8M). The effect of various parameters like slurry concentration, striking velocity and particle size of erodent were considered for erosive wear. They concluded that impact of solid concentration and striking velocity was higher as compared to particle size. It was also found that CA6NM was having less resistance than CF8M steel. Mansouri et al. [115] analysed the effect of sand particle size as well as viscosity of liquid on the erosion behaviour of SS316 steel. From the results, effect of particle size was found to be prominent, while the viscosity had minimal effect on erosive wear.

Chattopadhyay [116] carried their research work to study the silt erosion behavior of turbine runners and made comparison for erosive wear performance of various steels such as CA6NM, stainless steel, 316L, Stellite 6. He found that slurry concentration was dominant for erosive wear and erosion performance of stellite 6 was least as compared to AISI 316L steel and CA6NM steel. In potash handling machinery pipelines, slurry erosion and corrosion performance were investigated for AISI 1018 steel substrate. The effect of slurry concentration and rotational velocity was considered and inferred that rotational velocity and concentration of slurry had a significant effect on the erosion rate. The amount of synergy between erosion and corrosion reduced as rotational speed increased [117].

From the exhaustive literature review as presented in this paper, it may be concluded that erodent particle size, slurry concentration, impact velocity, impact angle and target surface properties such as micro-hardness, toughness and ductility are the main parameters responsible for slurry erosion phenomena.

5. Studies related to slurry erosion prevention using laser cladding technique

Research work done by various researchers on slurry erosion prevention using laser cladding technique has been discussed in the subsequent paragraphs. Further, work has also been summarized in the table 3 as a ready reference for readers.
Table 3. Work carried out by different researchers.

| Author name       | Substrate     | Coating material          | Hardness | Wear test method | Variations of parameters in slurry erosion testing | Minimum erosion occurs at | Wear mechanism                                      |
|-------------------|---------------|---------------------------|----------|------------------|---------------------------------------------------|----------------------------|--------------------------------------------------|
| Desale et al [118] | AISI 316L     | Colomonoy-6               | 746 HV   | Average mass loss | Impact angle                                      | 90°                        | Micro-cutting or plastic deformation and Brittle fracture |
| Satish et al [119]| AISI 304L     | Inconel-625               | 352 HV   | Average mass loss | Impact angle                                      | 15° and 90°                | Micro-cutting or plastic deformation and Brittle fracture |
|                   | AISI SS304L   | METCO-41                  | 294 HV   |                  |                                                   |                            |                                                  |
| Paul et al [120]  | SS 316 L      | PAC 718                   | 321 HV   | Average mass loss | Impact angle                                      | 90°                        | Micro-cutting and Brittle fracture                |
|                   |               | Triboloy T-700            | 534 HV   |                  |                                                   |                            |                                                  |
| Basha et al [121] | 16Cr-3Ni steel| Colomonoy-5               | 475-500 HV| Average mass loss| Impact angle                                      | 12 m s⁻¹ and 90°           | Repetitive plastic, deformation and cutting       |
|                   |               | METCO-41C                 | 825-950 HV| Cumulative mass  | Impact velocity, Impact angle                     |                            |                                                  |
|                   |               | Walllex-50                | 850 HV   |                  |                                                   |                            |                                                  |
|                   |               | Tribaloy-700              | 800 HV   | Cumulative mass  |                                                   |                            |                                                  |
| Jiang and Kova-   | AISI 4140 Steel| Fe-Cr-B-Si               | 1000-1200 HV| Average mass loss| Impact angle                                      | Less dependent on angle    | Ploughing and micro-cutting                      |
| cevic [99]        |               |                          |          |                  |                                                   |                            |                                                  |
| Balu et al [122]  | AISI 4140 Steel| WC-Ni matrix (NT-20)      | 500 HV   | Average mass loss | Impact angle                                      | 45° and 30°                | Micro-cutting                                    |
|                   |               | (NT-60) (NT-80)           |          |                  |                                                   |                            |                                                  |
| Farahmand et al [123]| Abrasive water jet      | Ni-60% WC                | 950-1150 HV| Cumulative volume loss | Impinging angle                                 | 30°                        | Ploughing scars and plastic deformation,Brittle fractioning and cracking |
| Jia et al [124]   | AISI 631 Carbon steel | NiCoFeCrAl₃ | 710-765 HV | Cumulative volume loss | Impinging angle                                 | 90°                        | Micro ploughing and Micro-cutting                |
| Singh et al [125] | AISI 304 13Cr-4Ni | WC                      | 815 HV   | Cumulative volume loss | Erosion duration                           | Minimum time               | Ploughing and Micro-cutting                      |
|                  | 13Cr-4Ni      |                         | 725 HV   |                  |                                                   |                            |                                                  |
| Singh et al [126] | 13Cr-4Ni      | Stellite 6               | 705 HV   | Cumulative volume loss | Exposure time                             | Minimum time               | Micro-cutting and Brittle fracture              |
| Zhao et al [127]  | Q345 Steel    | Al₆CoCrFeNiTi₁₀₀₅        | 801.1 HV | Average mass loss | Impinging angle                                 | 90°                        | Micro-cutting, blended cutting and ploughing     |
Slurry erosion wear performance of Colmonoy-6 and Inconel-625 powders deposited on AISI 316L steel and AISI 304L steel using laser cladding technique was investigated by Desale et al [118]. The authors used slurry pot tester to evaluate the wear performance of above mentioned materials. Further, authors observed the increase in the erosion rate with increase in orientation angle up to 22.5°, followed by decrease in the erosion rate with increase in orientation angle up to 90°. The highest micro-hardness value acquired on AISI 316L for Colmonoy-6 clad was 746 HV, whereas in the case of Inconel-625 clad on AISI 304L steel, the micro-hardness was 352 HV for Inconel-625 clad. The Colmonoy-6 coated surface demonstrated better erosion resistance in comparison with AISI 316 steel, whereas Inconel-625 clad surface showed only marginal increase in erosion resistance at shallow impact angles and less erosion resistance when compared to the AISI 316 steel at normal impact condition.

The slurry erosion performance of AISI SS304L steel and Tribaloy T-700, PAC 718 and METCO 41 C clad surfaces was studied by Satish et al [119]. The authors observed two different mechanism namely micro-cutting/plastic deformation and brittle fracture at different impact angles on the cladded surfaces. At low impact angle, ploughing was observed as main wear mechanism. AISI SS304L material showed maximum erosion rate at 37.5° impact angle, while it was minimum at normal impact angle. It has also observed that METCO 41 C clad exhibited the higher erosion rate in comparison with substrate at normal impact angle. The reason for this behavior might be the greater dilution of the layer and grain structure. Except for the size and shape of the craters, the material removal mechanism was same for the base material and clad surface. Further, at normal impact angle indentation with rim were observed instead of platelet craters. Paul et al [120] also investigated the cavitation and slurry erosion behavior of METCO 41 C (Fe based alloy), Stellite-6 and Colmonoy-5 (Ni based alloy) laser cladding on AISI 316L steel. The micro-hardness of Colmonoy-5 clad layer was found to be maximum among the three above mention claddings deposited on AISI 316L steel. The metallographic examination of the specimens showed that the coated layers of Stellite-6, Colmonoy-5, and METCO 41 C mainly contain very good dendritic column structure, while the clad-substrate interface showed a planar and non-epitaxial structure. X-ray diffraction tests of Stellite-6, Colmonoy-5, and METCO 41 C laser clad samples showed different metal matrix carbides, borides, and silicides. The authors observed that at an impingement angle of 30°, METCO 41 C exhibited the highest slurry erosion resistance, followed by Stellite-6 and Colmonoy-5.

Strong particle erosion of Wallex-50 and Tribaloy-700 clad layer deposited on 16Cr-5Ni steel was studied by Basha et al [121] using slurry jet erosion tester. The micro-hardness of the clad layer was found to be 2.2 times the micro-hardness of the unclad surface. At an impingement angle of 30° and a concentration of 10 kg m⁻³ from erosion tests, researchers found that the erosion rate for 16Cr-5Ni steel was higher as compared to laser cladded steel surfaces. 16Cr-5Ni steel showed mixed and only ductile mode of slurry erosion at impact velocities of 12 m s⁻¹ and 10 m s⁻¹ respectively, whereas Tribaloy-700 shown only ductile mode of slurry erosion at different impact velocities.

The slurry erosion performance of Fe–Cr–B–Si, chromium carbide and tungsten carbide coatings deposited by laser cladding technique on AISI 4140 steel at different impact angles varying from 30° to 90° was investigated by Jiang and Kovacevic [99]. The researchers observed that the performance of Fe–Cr–B–Si coating under slurry erosion conditions was best among above mentioned three coating materials. Further, the researcher observed the delamination as the dominant erosion mechanism for material loss at normal impact angle, whereas ploughing and microcutting were observed as main mechanism for material loss under shallow impact angles conditions.

Bala et al [122] investigated the effects of single and multi-layered WC-Ni based deposits using a laser cladding deposition technique. The research showed that the surface roughness (Rₐ) improves with an increment in the impingement angle. The eroded surface reveals tiny grooves along the slurry route at a reduced angle of impingement, while a greater angle of impingement generates crater, lips, and big grooves. Further, the researchers observed that the matrix hardness improved more evenly with the increase in the nano size WC mass fraction. The maximum hardness was observed at the top layers of the multilayer deposition. In addition to this, rise in the nano-sized WC mass fraction (up to 10 percent mass fraction), the erosion resistance in single and multi-layered was enriched more efficiently at greater impingement angles. The slurry erosion behavior of laser cladded Ni-WC layer was also studied by Farahmand et al [123]. The researchers studied the erosion behavior of laser cladded WC-Ni layer using an abrasive water jet set up. Further the researchers studied the impact of addition of 1% La₂O₃ to Ni-WC powder. From the experimental results, it was observed that laser energy density has a significant effect on the quality of the laser clad deposited for slurry erosion applications. The laser clad deposited using 315 J mm⁻² showed the higher erosion resistance in comparison with the laser clad deposited using 400 J mm⁻² and 700 J mm⁻² for Ni-60% WC coating powders. In addition, due to the ductile material characteristics at small impact angles, the erodent particles slipped on the surface and produced grooves on the smooth Ni matrix. Meanwhile, there was a brittle fracture in the reinforcing stage, which led to the propagation
of the fracture across the carbide grains. Further, 1% by weight addition of La$_2$O$_3$ powder to Ni 60%-WC coating powder enhanced the mechanical properties of the clad.

Jia et al [124] studied the slurry erosion resistance of NiCoFeCrAl$_3$ high entropy alloy (HEA) clad using a jet erosion testing machine. Authors observed that laser clad NiCoFeCrAl$_3$ HEA coatings have excellent erosion resistance at a relatively small impingement angle. From the results of volume loss at different impact angles it was observed that the NiCoFeCrAl$_3$ showed the slurry erosion behavior similar to that of quenched tool steel. From the SEM images, it found that the HEA coating erosion process was micro-ploughing, micro-cutting and removal of lips or flakes were the main mechanism of HEA coatings. Hence, the researchers concluded that plastic deformation and abrasive wear were the predominant causes of slurry erosion in case of HEA coating.

The erosion and corrosion behavior of tungsten carbide laser cladded stainless steels was investigated by Singh et al [125]. Laser cladded specimens’ performance under slurry erosion conditions was compared with that of HVOF sprayed tungsten carbide coating and uncoated AISI 304 & 13Cr-4Ni steels. The hardness and erosion behavior of substrate materials improved with laser coating. The highest erosion resistance was observed at a laser power density of 114 W mm$^{-2}$ for cladded materials. Researcher found that the erosion of laser cladded stainless steel occurred due to removal of WC particles.

The effect of variation of laser power densities with in a range of 32 J mm$^{-2}$ to 52 J mm$^{-2}$, on wear resistance of Stellite-6 coating material deposited on 13Cr–4Ni steel under solid particle erosion and cavitation erosion conditions was studied by Singh et al [126]. Further, the wear test results of above mention cladding were compared with that of uncoated AISI 304 steel. Maximum micro-hardness of 705 HV for the clad material was achieved at laser power density of 32 J mm$^{-2}$ and it decreased with increase in the laser power density up to 52 J mm$^{-2}$. Stellite-6 cladding exhibited significantly higher wear resistance in comparison with uncoated 13Cr–4Ni and AISI 304 steel under solid particle erosion conditions. Among the claddings deposited at different laser power densities, the cladding deposited at laser power density at 32 J mm$^{-2}$ showed highest resistance against the solid particle erosion. It was observed that laser cladding increased the cavitation erosion prevention of stainless steel in a solution of 3.5 percent sodium chloride to more than 90 percent.

Zhao et al [127] conducted their research work on the slurry erosion behavior of laser cladding-made high-entropy alloy (HEA) coatings. AlCoCrFeNiTi$_{0.5}$ HEA coating exhibited excellent slurry erosion prevention at different impingement angles due to its elevated hardness, excellent plasticity and low stacking fault energy. The Al$_{1.0}$ HEA surface erosion rate was found to be 1.78 times smaller at an impingement angle of 45° and 1.68 times lower at an impingement angle of 90° than the Cr16 alloy. With the rise in sand concentration at 45° and 90° impingement angles, the erosion rates of the test materials increased in a nonlinear manner. SEM observation verified that for all HEA coatings, the dominant erosion mechanisms at low impinging angle were micro cutting, blended cutting and ploughing. For Al$_{1.0}$ and Al$_{1.5}$ HEA coatings, platelets were noted as the foremost erosion mechanisms at normal impingement angle as compared to fatigue fracture and repetitive plastic deformation as the predominant phenomenon of material removal for Al$_{2.0}$ and Al$_{2.5}$ HEA coatings.

6. Conclusion

From the critical review of the literature presented in this paper, it may be concluded that deposition of layer of hard material on the surface of relatively soft substrate material using laser cladding technique can prevent the substrate material from various surface degradation phenomenon such as slurry erosion, solid particle erosion, corrosion and wear etc. Further, it has been observed that Ni-based, Fe-based, Co-based self-flux alloys and other alloys like Al-based, Ti-based, Cu-based etc cladding materials can be successfully deposited by laser cladding technique. Based on the research of various researchers mentioned in the paper, it can be concluded that MMC/ Hybrid coatings among the mentioned coating powders were most successfully in providing resistance against slurry erosion. Also, it has been observed that most of the research studies were focused towards evaluating the performance of various coating materials on distinct substrates to enhance the surface characteristics of the substrates. Very little or no work has been done to study the effect of powder particle size and laser cladding parameters such as clad position, preheating, laser spot size, injection angle nozzle range and proportion of clad overlap on the coating microstructure for a given combination of coating and substrate material. Hence, it can be concluded that research can be done to optimize cladding powder particle size and laser cladding parameters for a given combination of coating and substrate material to obtain better coating microstructural and mechanical properties such as porosity, hardness, toughness etc and to mitigate the slurry erosion problems in mechanical components.

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References

[1] Davis J R 2011 Surface Engineering for Corrosion and Wear Resistance (Materials Park OH: ASM International) p 54
[2] Budinski K G 1988 Surface Engineering for wear Resistance (New York: Prentice Hall) p 15–43
[3] Miller J E 1992 Slurry Erosion Friction Lubrication and Wear Technology 18 (Materials Park OH: ASM International) p 233–35 ASM handbook
[4] Chauhan A K, Goel D B and Prakash S 2009 Solid particle erosion behaviour of 13Cr 4Ni and 21Cr–4Ni–N steels J Alloys Compd 467 459–64
[5] Jha A K, Batham R and Ahmed M 2011 Effect of impinging angle and rotating speed on erosion behavior of aluminum Trans Nonferr Met Soc China 21 52–8
[6] Taijan I and Debreceni E 1972 Theoretical and experimental investigation on the wear of pipeline caused by hydraulic transport 2nd International conference on Hydraulic Transport of Solids in Pipes (BHRA)
[7] Bain A G and Bonnington S T 1970 Interviews—slurry pipelines:exciting technology entering period of renaissance accepted The Hydraulic Transport of Solids by Pipeline (Pergamon: Oxford)
[8] Charles M E 1979 Transport of solid by pipelines Proc. of Hydrotransport-1 BHRAProc.of Hydrotransport-1 BHRAProc.of Hydrotransport-1 BHRAProc.of Hydrotransport-1 BHRAProc.of Hydrotransport-1 BHRAProc.of
[9] Tan Y, Zhang H, Yang D, Jiang S, Song J and Sheng Y 2011 Numerical simulation of concrete pumping process and investigation of wear mechanism of the piping wall Tribol. Int. 46 137–44
[10] Gupta R, Singh S N, Seshadri V and Basics in Minerals Processing 1992 Accelerated wear rate test rig for the predicting of erosion in slurry pipelines 196th NCEMPP, IIT Bombay CL 1 - CL 4
[11] Osa A 2013 Interview on Multiaceros 12.12.2013 (Chile: Begrisstain M 2014 Interview on AMPO) 11.4.2014 (Spain: Wood R J K and Jones T F 2003 Investigations of sand-water induced erosive wear of AISI 304L stainless steel pipes by pilot-scale and laboratory scale testing Wear 255 206–18
[12] Gupta R, Singh S N and Seshadri V 1995 Prediction of uneven wear in a slurry pipeline on the basic measurements in a pot tester Wear 184 169–78
[13] Roco M C, Nair P and Addie G R 1987 Test approach for dense slurry erosion ASTM Spec. Tech. Publ. 964 185–210
[14] Hutchings J M 1992 Tribology—Friction and wear of Engineering Materials (165-279: Edward Arnold)
[15] Mack R, Dritta P and Lang E 1999 Numerical prediction of erosion on guide vanes and in labyrinth seals in hydraulic turbines Wear 233–235 685–91
[16] Mann B S 1999 An experimental study to determine the effects of low and high-energy particle impact on the erosion of hydraulic turbine material and protective hard coating Proceedings of WCPC/Green Power—the 2nd International Conference on Accelerated development of hydropower resources in the 21st Century Three Gorges Project Site Yichang Hubei China p 28–30
[17] Bitter J 1962 A study of erosion phenomena Parts I Wear 6 5–21
[18] Zia J, Hutchings J M and Bursting T G 1990 Design of slurry erosion test rig Wear 140 331–44
[19] Feng Z and Ball A 1999 The erosion of four materials using seven erodents towards an understanding Wear 233–235 684–74
[20] Singh P, Bansal A and Goyal D K 2019 Erosion wear evaluation of HVOF sprayed WC-12Co coating on some pipeline materials using Taguchi approach Kovove Materialy–Metallic Materials 57 113–20
[21] Bansal A, Singh J and Singh H 2019 Slurry erosion behavior of HVOF-sprayed WC-10Co-4Cr coated SS 316 steel with and without PTFE modification Journal of Thermal Spray Technology 28 1448–65
[22] Liebhard M and Levy A V 1991 The effect of erodent particle characteristics on the erosion of metals Wear 151 381–90
[23] Wang J F and Yang D 2008 Finite element model of erosive wear on ductile and brittle materials Wear 265 871–8
[24] Grewal H S, Agrawal A and Singh H 2013 Design and development of high velocity slurry erosion testing using CFD Journal of Materials Engineering and Performance 22 152–61
[25] Finnie L 1995 Some reflections on the past and future of erosion Wear 186–187 1–10
[26] Finnie L 1960 Erosion of surfaces by solid particles Wear 3 87–103
[27] Grewal H S, Agrawal A and Singh H 2013 Slurry erosion mechanism of hydroturbine steel: effect ofoperating parameters Tribology Letters 52 287–303
[28] Lathabai S and Pender D C 1995 Microstructural influence in slurry erosion of ceramics Wear 189 122–35
[29] Arora M, Ohl C D and Morch K A 2004 Cavitation inception on microparticles: a self-propelledparticle accelerator Physical Review Letters 92 174501–4
[30] Oka Y I and Yoshida T 2005 Practical estimation of erosion damage caused by solid particle impact: II. Mechanical properties of materials directly associated with erosion damage Wear 259 102–9
[31] Singh G, Virdi R L and Goyal K 2015 Experimental investigation of slurry erosion behaviour of hardfaced AISI 316L stainless steel universal Journal of Mechanical Engineering in the 3rd–52
[32] Grewal H S, Agrawal A and Singh H and Shollock B 2014 Slurry erosion performance of Ni-Al2O3 based thermal-sprayed coatings: Effect of angle of impingement Journal of Thermal Spray Technology 23 389–401
[33] Shitole P P, Gwande H, Desale G R and Nandre B D 2015 Effect of impacting particle kinetic energy on slurry erosion wear Journal of Bio- and Tribo Corrosion 11 1–9
[34] Sugiyama K, Harada K and Hattori S 2008 Influence of impact angle of solid particles on erosion by slurry jet Wear 265 713–20
[35] Obulela B A, Lepule M L, Andrews A and Olubambi P A 2014 Tribo corrosion characteristics of laser deposited Ti–Ni–ZrO2 composite coatings on AISI316 stainless steel Tribol. Int. 78 160–7
[36] Fu Y, Wei J and Batchelor A W 2000 Some considerations on the mitigation offretting damage by the application of surface-modification technologies J. Mater. Process. Technol. 99 231–45
[37] Dutta I and Manna I 2003 Laser processing of materials Sadhana 28 495–562
[38] Siddiq P S and Hocking M G 1999 Review of inorganic coatings and coating processes for reducing wear and corrosion Brit. Corros. J. 34 171–83
[39] Arora H S, Grewal H S, Singh H and Mukherjee S 2013 Zirconium based bulk metallic glass—Better resistance to slurry erosion compared to hydroturbine steel Wear 307 28–34
Mater. Res. Express 7 (2020) 012007

13

[42] Nguyen Q B, Lim C Y H, Nguyen V B, Wan Y M, Nai B, Zhang Y W and Gupta M 2014 Slurry erosion characteristics and erosion mechanisms of stainless steel Tribology International 79 1–7

[43] Basha S S, Periasamy V M and Kamaraj M 2014 Slurry erosion resistance of laser-modified 16Cr–5Ni stainless steel International Journal of ChemTech Research 6 691–704

[44] Pugsley V A and Allen C 1999 Microstructure/property relationships in the cavitation erosion of tungsten carbide–cobalt Wear 225–229 1017–24

[45] Grewal H S, Bhandari S and Singh H 2012 Parametric study of slurry–erosion of hydroturbine steelwelds and without detonation gun spray coatings using taguchi technique Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 43 3367–401

[46] Santa J F, Raema J C and Toro A 2007 Slurry erosion of thermal spray coatings and stainless steels for hydraulic machinery Wear 263 258–64

[47] Santa J F, Espitia L A, Blanco J A, Romo S A and Toro A 2009 Slurry and cavitation erosion resistance of thermal spray coatings Wear 267 160–7

[48] Mann B S, Arya V, Maiti A K, Rao M U B and Joshi P 2006 Corrosion and erosion performance of HVOF/TiAlN PVD coatings and candidate materials for high pressure gate valve application Wear 260 75–82

[49] Kumar A, Sayra P K and Bhandari S 2011 A review paper on slurry erosion of plasma and flame thersalsprayed coatings National Conference on Advancements and Futuristic Trends in Mechanical and Material Engineering

[50] Mohammadi L 2011 Effect of cold work on erosion-corrosion of 304 stainless steel Corros. Sci. 53 549–56

[51] Recco A A C, López D, Bevilacqua A F and Tschiptchins A 2007 Improvement of the slurry erosion resistance of an austenitic stainless steel with combinations of surface treatments: Nitrizing and TiN coating Surf. Coatings Technol. 202 993–7

[52] Zhuo C, Han D, Tao J, Linlin L and Jiang X 2009 Erosion-corrosion behavior of nano-particle in forced Ni matrix composite alloying layer by duplex surface treatment in aqueous slurry environment Corros. Sci. 51 1053–68

[53] Mann B S 2000 High-energy particle impact wear resistance of hard coatings and their application in hydroturbines Wear 237 140–6

[54] Mann B S 2000 High-energy impact wear resistance of hard coatings and their application in hydro turbines Wear 237 140

[55] Sharma A K, Aravindhan D and Narayanswamy P 2001 Microwave glazing of alumina–titania ceramic composite coatings Materials Letter 50 295

[56] Tucker T R, Clauser A H, Wright I G and Stropki J T 1984 Laser processed composite metal cladding for slurry erosion resistance Thin Solid Films 110 703

[57] More S R, Bhart D V and Menghani J V 2017 Resent Research Status on Laser Cladding as Erosion Resistance Technique: An Overview Materials Today: Proceedings 4 9902–8

[58] Damboleona D and Vazquez A J 1993 Laser cladding of high-temperature coatings Journal of Materials Science 28 4775–80

[59] Wang P Z, Yang Y S, Ding G, Qu J X and Shao H S 2007 Laser cladding coating against erosion-corrosion wear and its application to mining machine parts Wear 209 96–109

[60] Xue L and Islam M 1998 Free-form laser consolidation for producing functional metallic components Proceedings of ICALEO

[61] Mazumder J, Choi J, Nagarathnam K, Koch J and Hetzner D 1997 The direct metal deposition of H13 tool steel for 3-D components JOM 49 55–60

[62] Xue L, Chen J Y, Islam M, Pritchard J, Manente D and Rush S 2000 Laser consolidation of Ni-base IN-738 superalloy for repairing gas turbine blades Proc. of ICALEO

[63] Bohrer M, Basalka H, Birner W, Emiljanow K, Goede M and Czerner S 2002 Turbine blade repair with laser powder fusion welding and shape recognition Proc. of the Int. Conf. on Metal Powder Deposition for Rapid Fabrication

[64] Gaumann M, Henry S, Cleton F, Wagner J D and Kurz W 1999 Epitaxial metal laser forming: analysis of microstructure formation Materials Science and Engineering 271 232–41

[65] Zhang D W and Lei T C 2003 The laser process and microstructure and erosion–corrosive wear performance of laser–clad Ni–Cr7C3 composite coating Wear 255 129–33

[66] Bruck G J 1988 Fundamentals and industrial applications of high power laser beam cladding Proc. of SPIE

[67] Fessler J R, Merz R, Nickel A H and Prinz F B 1996 Laser deposition of metals for shape deposition manufacturing Proc. of the Solid Freeform Fabrication Symp.

[68] Yakovlev A, Trunova E, Greevy E, Pilloz M and Smurov I 2005 Laser-assisted direct manufacturing of functionally graded 3D objects Surface & Coatings Technology 190 15–24

[69] Yadroits I, Bertrand P, Laget B and Smurov I 2007 Application of laser assisted technologies for fabrication of functionally graded coatings and objects for the International Thermonuclear Experimental Reactor components Journal of Nuclear Materials 362 189–96

[70] Katipelli L R, Agarwal A and Dahotre N B 2000 Laser surface engineered TiC coating on 6061 Al alloy: microstructure and wear Applied Surface Science 153 65–78

[71] Dubourg L, Pelletier H, Vaisiere D, Hlavka F and Cornet A 2002 Mechanical characterisation of laser surface alloyed aluminium–copper systems Wear 253 1077–85

[72] Dubourg L, Ursescu D and Hlavka F 2005 Laser cladding of MMC coatings on aluminium substrate: influence of composition and microstructure on mechanical properties Wear 258 1745–54

[73] Shin K H, Natu H, Dutta D and Mazumder J 2003 A method for the design and fabrication of heterogeneous objects Materials and Design 24 339–53

[74] Mazumder J and Stiles E 2000 Fabrication of designed materials using direct metal deposition Proc. of ICALEO

[75] Arcella F G and Froes F H 2000 Producing titanium aerospace components from powder using laser forming JOM 52 28–30

[76] Capshaw B 2002 Improved performance for motorsports applications through laser powder deposition technology Proc. of Int. Conf. on Metal Powder Deposition for Rapid Manufacturing

[77] Liu W and DuPont J N 2003 Fabrication of functionally graded TiC/Ti composites by laser engineered Net Shaping Scripta Materialia 48 1337–42

[78] Axen N and Zhumg G H 1992 Abrasive wear of TiC–steel composite clad layers on tool steel Wear 157 189–201

[79] Beidi Z, Xiaoyan Z, Zengyi T, Shuguo Y and Kun C 1993 Coarse cemented WC particle ceramic–metal composite coatings produced by laser cladding Wear 170 161–6

[80] Marchione R 2002 Industrial applications of laser cladding Proceedings of the on Metal Powder Deposition for Rapid Manufacturing

[81] Jiang W, Nair R and Molan P 2005 Functionally graded mold inserts by laser-based flexible fabrication: processing modeling structural analysis and performance evaluation Journal of Materials Processing Technology 166 86–293.

[82] Hu Y F, Chen C W and Mukherjee K 1998 Development of a new laser cladding process for manufacturing cutting and stamping dies Journal of Materials Science 33 1287–92
Balu P, Hamid S and Kovacevic R 2013 An Experimental Study on Slurry Erosion Resistance of Single and Multi-layered Deposits of

Anandkumar R, Almeida A, Colaço R, Vilar R, Ocelík V and Hosson 2007 Microstructure and wear studies of laser clad Al-Si

Wang S H, Chen J Y and Xue L 2006 A study of the abrasive wear behavior of laser-clad tool steel coatings

Pei Y T, Ouyang J H, Lei T C and Zhou Y 1995 Microstructure of laser-clad SiC-

Gupta R, Singh S N and Sehadri V 1995 Prediction of uneven wear in a slurry pipeline on the basis of measurements in a pot tester

Rajesh J J, Bijwe J, Venkataraman B and Tewari U S 2004 Effect of impinging velocity on the erosive wear behavior of polyamides

Bhandari S, Singh H, Kansal H K and Rastogi V 2012 Slurry erosion studies of hydroturbine steels under hydro accelerated conditions

Gandhi B K and Borse S V 2002 Effects of Particle Size and Size Distribution on Estimating Erosion Wear of Cast Iron in Sand-Water

Chattopadhyay R 1993 High silt wear of hydro turbine runner

Elemuren R, Evits R, Ogoucua I, Kennell G, Gerspacher R and Odedhi A 2018 Slurry erosion-corrosion of 90◦ AISI 1018 steel elbow in saturated potash brine containing abrasive silica particles

Desale G R, Gandhi K and Jain S C 2008 Slurry erosion of ductile materials under normal impact condition

Clark H M I 2009 Particle velocity and size effects in laboratory slurry erosion

Singh R, Kumar D, Mishra S and Tiwari S K 2014 Laser cladding of stellite 6 on stainless steel to enhance solid particle erosion and
cavitation resistance

Jiang W H and Kovacevic R 2004 Slurry erosion resistance of laser clad Fe

Manna I, Majumdar J D, Ramesh C B, Nayak S and Dahotre N B 2006 Laser surface cladding of Fe

Jasim K M, Rawlings R D and West D R F 1990 Thermal barrier coatings produced by laser cladding

Yang,, Yan C J and Wang 1987 Laser cladding of FeCrSiB alloy

Frenk A, Vandyoussef M, Wagnière J D, Kuru Z and Zeydi 1997 A Analysis of the laser cladding process for Stellite on steel

Carvalho P A, Deus R, Colaco and Vilar R 1998 Laser alloying of zinc with aluminum: solidification behavior

Vasconcelos A M, Santos J M, Desale G R and Gandhi K 2016 Slurry erosion of laser clad FeNiCrSiB alloy

Basha S, Periasamy V M, Kamaraj M and Shariff S M 2013 Improvement of slurry erosion wear resistance of 16Cr

Paul C P, Gandhi B K, Bhargava P, Dwiwedhi D K and Kukreja L M 2014 Cobalt-free laser cladding on AISI Type 316L stainless steel for

Mansouri A, Shirazi S A and Mclaury B S 2014 Experimental and numerical investigation of the effect of viscosity and particle size on

Mater. Sci. Technol. A: Solid State Phenomena

Proc. of the ICALEO’93 (Orlando FL USA)

Surfaces and Coatings Technology

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Mater. Sci. Technol. A:

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Mater. Sci. Technol. A:

Mater. Sci. Technol. A:

Mater. Sci. Technol. A:

Mater. Sci. Technol. A:

Mater. Sci. Technol. A:
[124] Ji X, Duana H, Zhang H and Ma J 2015 Slurry erosion resistance of laser clad NiCoCrFeAl high entropy alloy coatings Tribology Transactions. Accepted (https://doi.org/10.1080/10402004.2015.1044148)

[125] Singh R, Kumar M, Kumar D and Mishra S 2012 Erosion and corrosion behavior of laser cladded stainless steels with tungsten carbide Journal of Materials Engineering Performance 21 2274–82

[126] Singh R, Kumar D, Mishra S and Tiwari S K 2014 Laser cladding of stellite 6 on stainless steel to enhance solid particle erosion and cavitation resistance Surface & Coatings Technology. Accepted (https://doi.org/10.1016/j.surfcoat.2014.04.008)

[127] Zhao J, Ma A, Ji X, Jiang J and Bao Y 2018 Slurry Erosion Behavior of AlxCoCrFeNiTi0.5 High Entropy Alloy Coatings Fabricated by Laser Cladding Metals 8 126