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Identifying defects and problems in laser cladding and suggestions of some remedies for the same

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Abstract

The cladding method is a technology of bulk coating deposition. It finds wide applications for providing laser coating of resistance to abrasion, erosion, corrosion, sliding wear, and heat barrier for improved performance and prolonging service life of the end products. Coating development by laser cladding is quite challenging due to the involvement of a large number of process controlling parameters. About thirty sets of process parameters involve in material deposition and quality control of the laser coatings. Ample research and investigations were already carried out and are still going on for the improvement of surface properties of several engineering components using laser cladding method. As per review, identifying the causes of defects-and-problems in laser cladding and suggesting their remedies are rarely found to be presented in the open literature.
In this present investigations, firstly, measures to mitigate the defects and problems in laser cladding are presented with a comprehensive review aiming to be useful for applying cladding in the coating industries. Secondly, troubleshooting in laser cladding was undertaken for the ease of material deposition as well as improvement of coating quality. Problems like material deposition, surface cracks and porosity were identified and reduced experimentally and presented.

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Keywords: Laser clading problems, coating defects, resurface cracks, porosity, remedies

1. Introduction

Cladding, close to hard facing, embedding, plating [1], are the techniques of bulk deposition coating that strongly bond with the substrate. The bond layer tends to become thicker when alloying occurs at the junction. Dimensional

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accuracy and surface quality of the clad product are provided by proper post-finishing operations like hard machining, grinding, ball peening and so on.

The laser is extensively used as energy source for cladding process in industries. The process is popularly known as 'laser cladding' where the coating materials are melted and fused over the substrate, resulting in strong metallurgical bonding. This method is used to restore worn out costly machine components to impart heat resistance coating and to improve tribological properties of mating surfaces of the components. A wide range of materials, alloys, intermetallic and metal matrix composites (MMCs) are used as coating materials. The various aspects of laser cladding are presented here.

1.1. Favorable characteristics of laser cladding

Laser cladding is important and becoming popular in hard facing, restoration, repairing and coating of engineering components due to their several advantages which include:

- Small, pinpointed or selective area cladding is possible by controlling the thermal inputs precisely. The power density 10^4 to 10^7 kW/cm^2 is possible even in a short pulse of 10^{-3} to 10^{-12} s or in the continuous wave [2]. It may reach a temperature up to 10^5K[3].
- Intense laser power concentration enables faster processing ability. Total heat input for material deposition is far less in laser irradiation related to other conventional material deposition (welding) methods[4]. Even laser weld deposition creates a yield strength and ultimate tensile strength greater than that of the base metal[5].
- High heat input produces excessive dilution and wider HAZ in the substrate that causes distortion of the product [6] due to excessive residual thermal stress. The dilution, as well as HAZ of the substrate, may be controlled in laser cladding by using intense laser source with high irradiation speed, and it may restore the product without distortion.
- High dense coating with little dilution of the substrate, homogeneous distribution of elements and strong fusion bonding between the coating and substrate material are the unique features of laser cladding. Fast heating-cooling rates (10^4 to 10^{11} K/s), high thermal gradient (10^6 to10^8 K/m), and rapid re-solidification velocity (1 to 30 m/s) may yield fine microstructure and formation of metastable even amorphous phases[2]. Thus favourable improvements in properties are possible in the coating.
- A wider range of materials like metals, ceramics, MMCs, etc. can be processed by laser cladding method.
- Powder materials of different types, shapes, sizes, densities, etc. can be easily mixed, preplaced, and used.
- Faster process than nitriding, boriding, carburizing etc. and can be automated or robotized for enhancing process capability.
- The process is relatively less expensive[7].
- Laser cladding is less hazardous than plasma spray coatings.
- Automation or robotization of the process may make the processes eco-friendly.
- Bulk coatings like cladding may enhance strength in the coating-substrate system.

Laser cladding becomes more effective and useful when hard layer are bonded on relatively much softer substrates.

1.2. Engineering applications of laser cladding

Laser cladding is also familiar in industries as one of the "additive manufacturing" technology and finding increasing commercial applications [8]. Laser cladding provides longer service life by hard facing and restoration of wear parts.

The various industrial components or parts that are subjected to cladding for improving performance and service life are listed below:

Aerospace:
- turbines
  - blades (rails, seal fins, notches, root fins, squealer tips)
  - vanes (buttresses, platform)
  - nozzles (rotary seals)
- liners,
- stator rings,

Power Generation:
- steam turbines
  - blades (tips, leading edge, aerofoil tips)
  - centrifugal compressor rotors
  - gas turbines
- piston rods,
- combustion baskets,
- transition liners,
- burners flanges and valves,

Automobiles:
- camshaft,
- rocker lobes,
- engine block seals,
- cylinder liners,
- valve seats,
- crankshaft,

Injection molding:
- multi-cavity inserts,
- tooling,
- edge repair,
- screw and grooves,

Mining:
- earth mover tools and blades,
- pusher shoes,
- hydraulic supports (cylinder seals),
- bearing surfaces,
- drilling components (bits, cylinder housings, pistons),
- axels (drive splines, differential assemblies)
- rotary cutters,

Marine:
- ship (propeller, hall, nose, power transmission shaft),
- dredger (pump impellers and bucket),

Agri-parts:
- ploughs,
- harvesting blades,

Oil and gas industries:
- offshore drill rig,
- centrifugal compressor and steam turbine shafts and centrifugal compressor impellers which are damaged by erosion and/or wear,[9]

Tea processing industries:
- cutter,
- buckets,

Construction and others:
- slurry pump blades (deliverables),
- concrete mixer blades,
- sintering plant equipment,
- hammer mill impellers, forging dies, caster rolls,
- tamper tools,
- crusher jaws and roll shells,mixer rotors

1.3. Technical challenges in laser cladding

Some problems and challenges creep in during laser cladding such as
- The clad top surface needs post processing for desired dimensional accuracy and surface integrity.
- A large number of process controlling parameters are involved.
- Laser cladding of complex shaped job is difficult.
- Cladding ability depends upon work material properties like laser reflectivity, thermal conductivity, heat capacity etc.
- It is difficult to control particle size, shape, and distribution in particulate reinforced laser coatings.
- Turbulence in the molten pool causes unevenness on the surface and may cause agglomeration in the dispersion.
- The in-situ synthesis process may afford homogeneity even nano-structured coating. But, self-propagatinghigh-temperature synthesis (SHS) in-situ reactions may cause violent combustion like uncontrollable situations.
- Concentrated internal stress may cause microcracks in the coating and control of internal stress, and their distribution is a tedious job.

- High dilution of substrate material leads to a rapid change in coating properties and leads to alloying of coating materials to the substrate material.
- Working zone needs to protect from severe environmental oxidation.
- Processing of highly laser reflective materials like aluminium, silver etc. may cause damage to the machine components (lenses, windows) due to intense back reflection of the laser beam.
- The rectangular shape, large area, and uniformly distributed laser energy throughout the cross-section of the beam are the ideal conditions of laser beam quality for the cladding purpose.
- The waviness of coating surface increases with short track distance.
- Intense heating of material may cause during laser cladding undesirable phenomena like uncontrollable melting, surface vaporization, plasma formation, photo chemical ablation[10] etc.
- Evaporation of chemical binder[11] and larger overlapping gap between the two successive tracks may result in porosity and holes respectively in a coating.

1.4 On laser cladding quality improvement

Laser cladding quality is reasonably based on several potential characteristics mainly;

- geometrical properties: dilution, clad dimensions, roughness, etc.
- mechanical properties: hardness distribution, wear resistance, frictional resistance, residual stress, fracture toughness, young modulus, etc.
- thermal properties: heat resistance, thermal expansion, etc.
- metallurgical properties: bonding ability, cohesion, microstructure, grain size, homogeneity, dispersion, corrosion resistance, etc.
- qualitative properties: porosity, cracking.
- post processing ability

Successful development of the good quality laser cladding has huge potential in the different coating and restoration industries.Coating development by laser cladding is quite challenging due to the involvement of a large number of process controlling parameters. About thirty sets of process parameters involve in material deposition and quality control of the laser coatings. The process parameters are related[12] to laser optical systems, coating and substrate materials properties, and environmental conditions.

1.5 Effects of process parameters on laser cladding process

1.5.1 Laser and optical system:

power (energy):

- responsible for material melting (power density about 100 W mm^{-2}; beam interaction time of about 1 second, normal minimum laser beam power about 2 kW, are the needed for cladding in practice)
- high power concentration may cause evaporation of material and low power may cause holes and porosity at the coating-substrate interface.

beam mode energy (uniformly or non-uniformly) distribution:

- uniformly distributed beam energy is essential for surface engineering.
- the non-uniform beam may cause inhomogeneity in the coating constitution.

beam wave type [continuous, pulsed and mixed wave]:

- CW is generally used in laser cladding.
- pulsed and mixed wave have effects on microstructure, Marangoni flow, internal stress etc.

wavelength:

- wavelength has a great role on energy absorption (shorter wavelength gets better absorption to the substrate materials and increases the process efficiency)

beam cross-section (spot) (square, rectangular, circular, elliptical, etc.):
- a rectangular beam is preferred for laser surfacing.

beam spot size (dimension):
- beam dimension is important in productivity and overlapping.

beam operation (beam velocity, inclination angle, overlapping etc.):
- melting of material, dispersion of reinforcement in the coating, bending or deformation of the work materials depend upon energy density which is the combined effect of beam power, velocity, and spot area.

1.5.2 Materials properties:

Substrate material properties:

physical properties (reflectivity, roughness, wetting property, viscosity at molten state, etc.):
- physical properties of work material effect on the process like coupling efficiency, the surface topography of coatings, etc.

chemical properties (reactivity):
- chemical reactivity of metal increases when it is melted, and proper shielding is essential to avoid unwanted phase formation.

thermal properties (conductivity, heat capacity, melting point temperature, thermal expansion coefficient, etc.):
- compatibility of thermal properties of substrate and coating are important for coating sustainability at various temperature.
- temperaturerise, evaporation of material, conduction loss, etc. depend upon material thermal properties of works material

mechanical properties (strength, modulus of elasticity, etc.):
- sustainability of the coating in mechanical loading condition depends upon mechanical properties

initial temperature and heat evacuation conditions:
- the pre-heated substrate may provide a compressive stress in the coating and may reduce cracking.

Coating materials (powder) properties:

physical properties (particle size, shape, wetting property, etc.):
- melting, mixing of the coating materials may have effect on some coating properties

chemical properties (chemical affinity):
- highly reactive SHS reactions between the coating compounds may cause powder flying off from irradiated zone

thermal properties (conductivity, heat capacity, melting point, thermal expansion coefficient, etc.):
- important for coating sustainability and performance in thermal loading conditions.

mechanical properties (hardness, strength, modulus of elasticity, etc.):
- effects on sustainability in mechanical loading conditions, frictional and wear performance of the coatings

deposition methods:

pre-deposition (deposition thickness, adhesion):
- pre-deposition thickness provides clad thickness.
- burning of high concentrated adhesive or sticking agent may cause blowing off of powders and may leave pores in the coatings.
- powder loss is generally less (may high depending upon the degree of in-situ reactions) in two step method.

blown powder method (powder feed rate, feeding angle, etc.):
- the material deposition rate and powder catchment efficiency are important for clad bead deposition.
- high powder loss

wear feeding method:
- no material loss

rapid manufacturing (prototyping) techniques, etc.:
- one of the best-suited methods of laser cladding
- thickness, material combination, etc. are controllable
- the finemicrostructure may not be generated, and bonding problem may persist

in-situ and ex-situ process:
- the in-situ method is advantageous for homogeneous, fine dispersion of reinforcement without a wetting problem
- the highly exothermic in-situ reaction may cause powder flying off
- ex-situ material deposition is easier in metallic compounds
- improper wetting of ceramic powder may cause separation and blow of powder, cracks, segregation and agglomeration of reinforcements in case of ex-situ material deposition

1.5.3 Environment:

vacuum:
- cladding in a vacuum may provide a pore-free material deposition

gaseous (inert gas, reactive gas, gas pressure, etc.):
- Ar, He, etc. inert gasses are used as shielding environment to avoid environmental contamination
- cladding may perform in N_2, O_2, CO_2 environment to form hard ceramic nitride, oxides, carbides in the coating matrix

open environment condition:
- using self-fluxing reagent

2. Some cladding defects, problems and their remedies

2.1 Thermo-capillary (Marangoni) flow

Marangoni flow is the dominant convection mechanism in a laser melted pool [8]. The coefficient of the surface tension of a molten pool varies with a temperature gradient. As the temperature increases, the surface tension decreases. The surface tension gradients or chemical concentration gradients[12] drive fluid flow by means of capillary forces generally acting from the center of the melt towards the edges.

The molten material also experiences a force due to thermal expansion of material while transforms from solid to liquid. As the laser beam moves forward, that force greatly acts on the molten pool opposite to the laser movement. The schematic view of possible Marangoni flow in laser molten pool is given in fig.1.

Marangoni flow causes mixing of materials, waviness on the top surface and widening of the melt pool. Sometimes it may cause inhomogeneous mixing of substrate materials to the coating materials. So, reduction and elimination of Marangoni flow may reduce those problems. Pulsating power source may reduce Marangoni flow to a large extent but may produce a rough surface

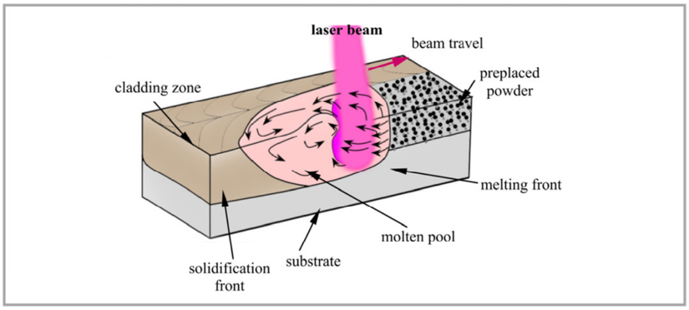

Fig.1. Possible Marangoni flow in molten pool during laser irradiation of preplaced powder[13-15]

2.2 Unfavourable uniformity in coating materials (layers)

The reinforcement particles in the composite coating may not be uniformly distributed throughout the coating matrix. Proper mixing of powder (coating) materials is important. Uneven distribution of coating materials may observe due to wide differences in densities of multiphase/multicomponent coating materials. Laser assisted in-situ synthesis of coating compounds may reduce this problem[16]. The scan speed and power combination also may play a great role in the distribution of reinforcement particles.

2.3 Cracks and spalling

Cracks and spalling[17] are usually the major problems in laser cladding. These problems are created by thermal stress due to rapid solidification[18] of the clad. The residual stress may be tensile and compressive in nature. Tensile residual stress is always detrimental and may cause cracking[19]. A crack in the coating layer parallel to the surface may cause spalling of the clad. Vertical hair cracks are often beneficial to accommodate the strain that occurs during thermal cycling. Segmented cracks are also found to accommodate strain and thermal cyclic lifetime extension.

The cracks may be controlled by reducing internal tensile residual stress. Proper laser power distribution may reduce this problem[20] and even may favourably generate compressive residual stress[21,22] in the coating.

Preheating the substrate and also selection of proper metallurgical combination [23] may reduce even eliminate cracks. Zhang et al. 2010[24] reported that the cracks were absent at 450°C pre-heating temperature of AISI316L austenitic stainless steel for laser cladding using Colmonoy 6 powders. Pre-heating of the substrate and the metallurgical combination of nano-WC (up to 10%) and La_2O_3 (up to 2%) to the Ni-60 % WC decrease the crack susceptibility on SS06. Ghosh and Saha, 2011[25] showed that the crack density increases with the increase of the amount of ceramic reinforcement the formation of laser sintered SiC_p reinforced Al-Cu-Mg matrix composite. Small amounts of grain refining agents[26,27] such as Sc, Ti, and Zr can be used to minimize solidification cracking. The minor alloying element like Fe-Si ratio is also found to affect significantly the solidification cracking susceptibility in Al alloy. The Fe- and Ni- based materials are also used as crack resistant materials[28].

Crevices[8] may cause due to lack of fusion at the toes of adjacent overlapping cladding tracks in the case of higher aspect ratio (thickness/ width) of the clad section. A reduction in laser scan speed and powder feed rate (in blown powder method) may enable molten clad material to flow into discontinuities to form a rigid overlap region.

2.5 Holes and porosity[18]

The holes and porosity are the common problems in clad deposition. They have adverse effects on strength, ductility and fatigue property of the coating. Holes and pores formed due to entrapping of gas into the clad layer that is caused due to,

- moisture content in the oxide layer or shielding gas,
- grease on the surface of the workpiece,
- burning of the sticking agent[29] (in the case of preplaced method),
- working with low power laser is prone to leave holes and porosity in the clad substrate interface.

The gas pores are one of the common problems in Al melting and processing. Hydrogen has significant solubility in liquid Al[8,30]. As the molten Al solidifies and with growing dendrites, the hydrogen is rejected and causes porosity[31]. The different process to reduce hydrogen pores are[27]

- thermal vacuum degassing process,
- the addition of Freon (CCl_2F_2) to the shielding gas to reduce hydrogen in melt Al deposition,
- the addition of Li in the Al promotes the formation of lithium hydride and may absorb hydrogen even in heat treatment.
- proper power combination may reduce holes and porosity.

Since the effect of vibration[32] on work, during laser irradiation, may reduce holes, internal stresses, cracking, and agglomeration may also reduce.

2.6 Blowing away of powders

Low capture (about 10 to 30 wt. %) of the feed powder[33] is a major problem in blown powder (one step) laser cladding. Powder loss cannot be avoided even in preplaced powder method. The premature burning of the sticking agent may loosen the powder material and continuous flow of the shielding gas may blow away the powders. A faster cladding speed with larger beam area may reduce this problem significantly.

The self-propagatinghigh-temperature synthesis (SHS) reaction in case of in-situ material deposition method may cause powder loss by causing violent reactions [34]. SHS reactions may also cause flying off of powder particles and may hit and damage the laser optics. The change in powder composition ratio and use of diluent of the reactants may reduce reaction rate and improve material deposition ability. To avoid powder loss, feeding wire method is suitable.

2.7 Poor wetting[35]

The ceramics show poor wetting behaviour [36] and ex-situ laser material deposition may prevent strong metallurgical bonding between reinforcements and the matrix materials. As wt. % of reinforcement is increased, bonding problem increases[35]. Some metals like Ni, Co, etc. and their alloys are compatible with most of the ceramics.

Boron and silicon improve wetting characteristics of molten material resulting in good bonding between the coating materials and develop smooth surface of the coating top layer by reducing surface tension in the molten material pool. Use of metal coated ceramic powder may eliminate this problem also. In-situ synthesis of ceramics in the coating matrix[38,39] eliminate the wetting problem.

2.8 Thin interface

The too thin interface between the coating and the substrate may weaken the bonding. Coating materials with different thermal expansion coefficient to the substrate may cause severe stress concentration in coating substrate interface and may result in horizontal cracks and spalling of the coating.

Proper laser power and scan speed combination may melt and fuse coating materials to the substrate for developing strong metallurgical bonding. Substrate dilution of about 5 vol. % is sought in laser cladding[8]. Surface roughening of the substrate before clad deposition by grit blasting, grinding, etc. may also develop good bonding between the substrate and the coating.

2.9 Irregular top surface topography of the clad layer

The laser cladding surface quality is generally not found smooth. The topography is even full of unevenness and waviness. The laser beam may be oscillated with a frequency in the order of 1 kHz, perpendicular or parallel to the direction of traverse, to produce a smoother clad surface[8].

Laser glazing process may also smoothen the surface. Post-processing like grinding, polishing, electro-discharge machining, etc. may be essential to meet dimensional tolerances, and to satisfy requirements for precision applications.

2.10 Over dilution[18] and distortion of substrate or product[5]

Excessive dilute on causes deterioration of desired coating characteristics and wider HAZ which may result in distortion of the product. The distorted product may become unfit with its functional pair after repairing, restoration or hard facing.

In the case of dimensional accuracy, hard facing is avoided by TIG/PAW clad bead deposition. Proper combination of laser power and scan speed is important to melt a very thin layer of the substrate with less HAZ to maintain coating quality as well as to avoid distortion related problems.

3. Some recent investigations on remedies of some laser cladding problems

Laser cladding on steels is a common in coating industries. Cladding like thick coating can share themechanical loading partially which may be effective for Al and Al-alloys, Ti, Ti-alloys like materials for further essential engineering applications. The current authors worked on development of bulk coatings on Al and Ti-alloy(Ti-6Al-4V) which are difficult to laser-clad-materials.

3.1. Challenges in cladding of Al and Al alloys and present remedial

Al and Al-alloys are the next common engineering metals after steel. Laser cladding of Al-based alloys are highly difficult [11] due to typical material characteristics like:

- Very high thermal conductivity (about 337 W/m-K) and high laser reflectivity (about 60%) of Al or Al-alloys restrict localized heating and melting.
- Laser absorptivity gets increased at the molten phase which leads to a sudden increase in temperature, and low melting point of Al (660^{o}C) yields uncontrollable melting.
- Highly viscous property of Al at molten phase reduces alloying affinity and wetting ability.
- Intense back reflection of the laser from Al surface may damage the laser spares.
- High heat conduction loss of Al reduces process efficiency.
- Rapid formation of Al_2O_3 passive layer further reduces wetting ability between a substrate and coating materials.
- Al highly absorbs hydrogen in the molten state and releases hydrogen on solidification in the form of fine porosity which falls coating quality.

To eliminate the above problems, the current authors[40] introduced intermediate coat layer between Al substrate and pre-placed coating materials. The most of the problems related to cladding on Al could be reduced and it became easier to develop the clad layer. As an example, the clad layer developed without using intermediateNi coat layer and with intermediate Ni coat layer are given in fig.2 and 3 respectively.

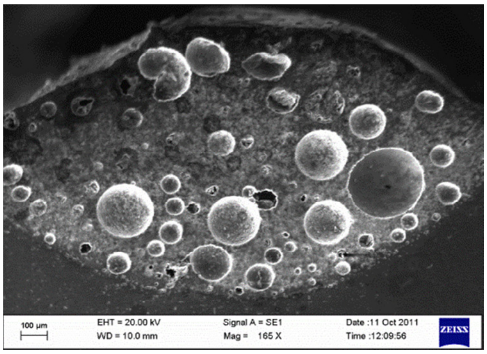

Fig. 2. Clad layer on Al sample without intermediate coat layer layer(at 165 X magnification)

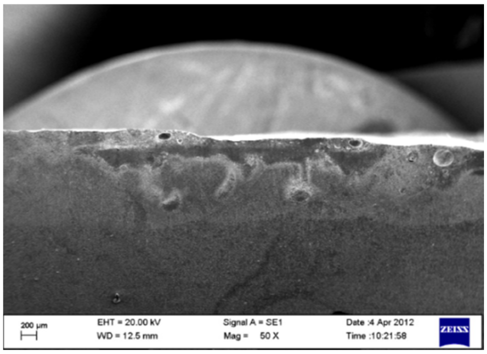

Fig.3. Clad layer developed on Al sample using intermediate Ni-coat (at 50X magnification)

The Ni-coating can be done on Al substrate using plasma spray or Ni-electroplating efficiently. The intermediate Ni-coating layer used in the present work, was developed using Ni-electroplating method. It was evident from the experimental investigations that the coating deposition was easier using intermediate Ni-coat layer aslaser power requirement was reduced. It might be due to relatively less thermal conductivity of Ni than Al. The Ni may act as heat barrier which may efficiently raise the temperature and melt the pre-placed powder coating materials easily.

High concentration of heat in the coating zone may reduce porosity like problems and also increase the process speed.

3.2. Challenges in cladding of Ti and Ti alloys and remedial measures

Ti and Ti alloys are important in 'light weight high strength' applications. They are highly demanding materials in aerospace, automotive, power generation industries. Ti and Ti-alloys are difficult-to-clad due to the following reasons.

- A very low thermal conductivity of Ti-alloys (for Ti-6Al-4V it is about 6.7 W/m-K) leads to a large increase in local temperature during laser interaction that results in uncontrollable melting and vaporization of the substrate material.
- Higher chemical affinity of Ti towards elements like oxygen, nitrogen, carbon, boron, etc. may decompose ex-situ B_4C, SiC, *h*BN, graphite, carbon nanotubes like coating compounds.

Technical challenges and difficulties provide further scope for research and development which are continuously pursued in the fields of surface engineering, especially surface coating including laser cladding.

Introduction of intermediate coat layer on Ti and Ti-alloyscan also reduce problems like metal evoporation which is a common problem of processing Ti-alloy(Ti-6Al-4V). The effect of intermediate coat layer is evident from the following figs. 5 and 6.

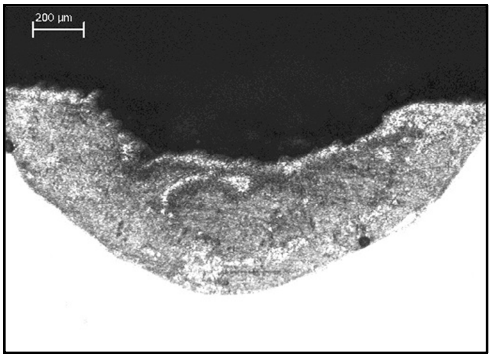

Fig. 5. Laser irradiated track without Ni-coat layer

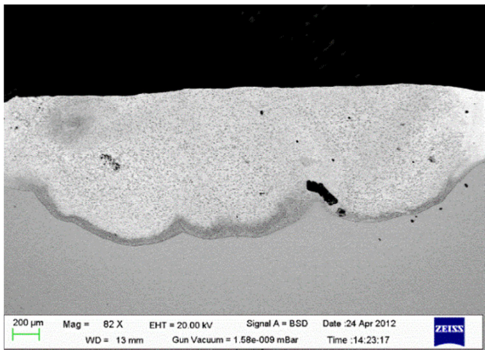

Fig.6. Laser irradiated coating with Ni-intermetiate coat layer

Cracks and porosity could be significantly reduced using Diamalloy in place of Ni as a coating composition. The efects of metallurgical combination on cracks and porosity are presented in fig. 7 and 8 below.

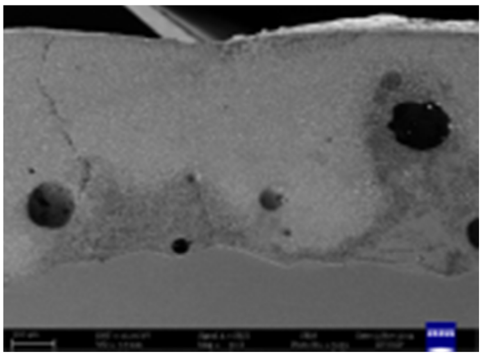

Fig. 7. Laser clad layer using 75%WC+25%Ni r

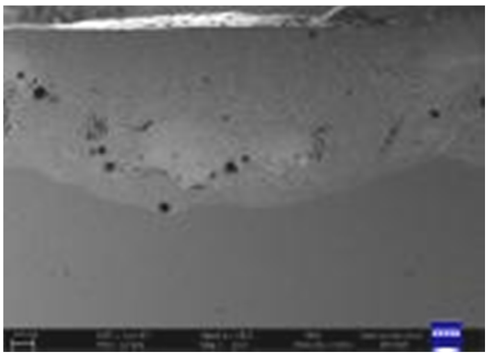

Fig.8. Laser clad layer using 75%WC + 25% Diamalloy

The top layer of the bulk laser coating (of about 1mm thickness) is not smooth (as shown in fig.9) . It is essential to finish the rough top surface for its subsequent uses in precision engineering applications. The present authors studied on finishing of clad layer in grinding(as shown in fig.10) and electro-discharge machining (EDM).

Fig. 9. Pictiorial view of laser clad surface before grinding

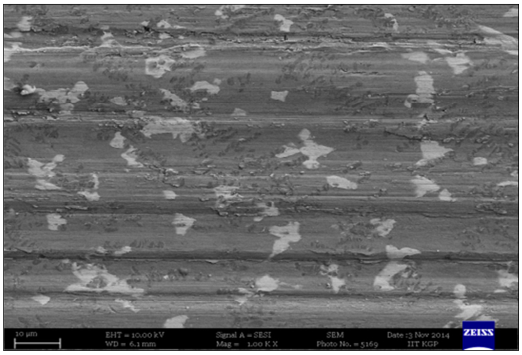

Fig.10. SEM view of clad layer suface topography after finishing by grinding(at 1000 X magnification)

In grinding process, the samples sufficiently experience thermal and mechanical loading. Both grinding and EDM process are suitable to prove bonding effciencyof the coating with the substrate. Neither any seperation of the coatings nor any horizontal crack in the coating interface is observed after grinding or EDM process,which indicates good metallurgica bonding of the coating with the substrate.

Conclusions

The various problems and defects of laser cladding are identified and remedial measures for the same are presented on based on review of existing literature. Some new techniques are introducedas well to eleminate the cladding problems. It is evident that,

- Theintermediate (Ni-coat) layer may efficiently reduce laser cladding problems and may also reduce porosity like defects in the coatings on Al substrates.
- Compared to Ni, Diamally performs better to eleminate coating cracks and porosity.
- The laser clad layer is not smooth and essential to finish for precision engineering applications. Proper grinding is important for testing the coating stability as well as for various end uses.

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