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Review Article

Review study of laser cladding processes on Ferrous substrates

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Abstract

The development of cladding (also called as hardfacing coatings) as a surface treatment is technologically significant in many industries like aeronautical, automotive, agricultural, Power Plants etc. The conventional surface coating techniques such as Physical Vapor Deposition (PVD), Chemical Vapour Deposition (CVD), Thermal Plasma Spraying, Electro deposition, Carburizing, Nitriding, Flame Induction Hardening, Galvanizing Diffusion coating offer many limitations like High processing time, high heat input energy, high material consumption, lack of flexibility, poor precision and lack in scope for automation. But surface engineering techniques using laser as source energy are free from these limitations. Also they have advantages over conventional welding metal deposition Gas Metal arc welding (GMAW) Gas Tungsten Arc Welding (GTAW) is the smaller dilution zone which in turn produces a smaller Heat Affected Zone (HAZ). Further laser cladding provides with more dense coatings, metallurgical bonding with substrates and minimal thermal distortion in the processed parts as compared to other more standard deposition methods. In addition to these advantages, the laser cladding process, as a method of hardfacing, is used to increase the wear, abrasion, corrosion and oxidation resistance and or at higher operating temperatures and impact performance of metallic components. One of the major benefits associated with laser cladding is the ability to finely control the heat input. With the continuous developments, the present technology on this process is employed to produce Laser Cladding with Metal Matrix to deposit hard facing coatings on metallic surface subjected to high abrasive wear and corrosive atmosphere. The hardfacing material consists of a mixture of hard, reinforcing phases immersed in a ductile metal/alloy matrix. The reinforcement constituent is normally a ceramic or a compound of a refractory metal as titanium, tungsten or chromium carbides or Nitrides and Borides. The matrix is usually a Nickel or Cobalt or alloy based on these elements which further enhances the layer resistance to corrosion, particularly at elevated temperatures. The mechanism of producing hard and wear resistant microstructure is that uniform distribution of hard and fine particles in a ductile matrix results in considerable improvement in wear resistance. Such a composite microstructure combines advantages of both the hard but brittle ceramic particles and the soft but ductile metallic matrix. This microstructure if produced into a surface layer of a component enhances wear life of that component. This review work focusing on this modern laser cladding techniques, studies the deposition of ductile material like Nickel (Ni) and Chromium (Cr) based composite layers on Carbon Steel/Martensitic steel (substrate). Nickel/Chromium alloy matrix, comparatively ductile provides toughness, ductility, corrosion and impact resistance whilst being wear resistance at elevated temperatures. More commonly Tungsten Carbide ceramic material is used as hard substance since it has outstanding physical and chemical properties compared to other commonly used ceramic materials. Tungsten Carbide (WC) has high melting point (3410º C), high hardness, low thermal expansion and good wettability by molten metals and alloys. The fine control of the heat input allows the matrix to be completely melted and alloyed to the substrate surface (Base Metal), whilst at the same time, the ceramic particles are distributed evenly throughout the matrix giving an extremely hard, wear and corrosion and impact resistant coating. Also, optimum conditions to obtain dense, uniform carbide distribution and hardness close to nominal values will be defined.

Following objectives are generally achieved through optimization of the laser cladding processes.

- Effect of heat input on the Heat Affected Zone (HAZ)
- Characterization of Microstructure
- Micro Hardness
- Bead Geometry parameters
- Correlation between the various influencing parameters
- The effect of Nickel/Chromium content with respect to microstructure, susceptibility for cracking and the wear rate of the resulting coating.

Keywords

Laser Cladding,
Dilution,
Macrostructure,
microstructure,
erosive wear,
abrasive wear,
Tungsten Carbide,
composite laser clad,
HAZ.

Introduction

Ordinarily cladding in the context of manufacturing meant the bonding together of dissimilar metals, is different from fusion welding or gluing as a method to fasten the metals together and used to be achieved by extruding two metals through a die as well as pressing or rolling sheets together under high pressure and this was followed as a mean of obtaining high wear resistance surface required in many industrial applications to extend the life of parts during production. This had been a cost effective solution to coat the surface of an exposed region with a material having superior wear resistance. Over the years the cladding technique has undergone tremendous developments.

Present day cladding, also called as hardfacing or surfacing, is a deposition process with a purpose of improving the properties of the substrate (base metal) and are accomplished either using laser beam or arc as the heat source for the process. Filler material used in the process is deposited layer-by-layer until covering required thickness before being machined to achieve the final dimension. There are many cladding processes as shown in the table 1.1.

The aim of most cladding operations is to overlay one metal with another to form a sound interfacial bond or weld without diluting the cladding metal with substrate material. In this situation dilution is generally considered to be contamination of the cladding which degrades its mechanical or corrosion resistant properties. Thick section cladding (>0.25mm) is frequently carried out by welding methods, substantial melting of the substrate is produced and there can be high dilution which is not generally the preferred result in the cladding operation although welding provides good bond strength between the coating and the substrate, relatively thick and pore free deposits.

Table 1.1 Cladding Techniques

Sl No	**Methods**	**Types and characteristics**
1	LASER	(i) Preplacement or In-situ (ii) Blown or Injection powder (iii) Wire feed Low heat input, thin layers, low dilution and porosity, high hardness, excellent bonding, small HAZ, high initial equipment investment and slow processing rates.
2	Chemical (Electrolysis)	Thin layer of coating
3	Welding	(i) Oxyacetylene flame-liquid-solid bond, high heat input (ii) TIG- reasonable bonding, medium heat input (iii) Open arc- low heat input (iv) SMAW (v) MIG (vi) SAW (vii) Electroslag (vii) Paste fusion (viii) Plasma arc
4	Spraying	(i) Flame- (a) Powder (b) Wire - All of fusion bond, no dilution (ii) Electric arc metalizing (iii) Plasma-liquid-solid bond, low heat input, no dilution (iv) Detonation (D-) gun-Forge bond, very low heat input
5	PTA	Thick layers produced, high deposition rates, low equipment cost, covers large areas, high heat input and part distortion.
6	CVD	Very thin layers of the order of micrometer
7	PVD	(i) Vacuum coating (thermal evaporation) (ii) Sputtering (iii) Ion Plating (iv) Ion implantation
8	Mechanical Plating	(i) Peening(ii) Fillet rolling
9	Electrochemical	(i) Acqueous(ii) Fused salts

Table 1.2 Comparison between laser cladding and other coating techniques.

Feature	Laser Cladding	Welding	Thermal Spray	CVD	PVD
Bonding Strength	High	High	Moderate	Low	Low
Dilution	High	High	Nil	Nil	Nil
Coating materials	Metal, Ceramics	Metals	Metal, Ceramics	Metal, Ceramics	Metal, Ceramics
Coating thickness	50 µm to 2 mm	1 to Several mm	50 µm to Several mm	0.05 µm to 20 µm	0.05 µm to 10 µm
Repeatability	Moderate To High	Moderate	Moderate	High	High
HAZ	Low	High	High	Very low	Very low
Controllability	Moderate To High	Low	Moderate	Moderate To High	Moderate To High
Cost	High	Moderate	Moderate	High	High

Laser Cladding technology and process

When the cladding is carried out using laser as a heat source then the process is called as "Laser Cladding". Laser cladding has been defined as "A process which is used to fuse with a laser beam another material (called clad material) which has different metallurgical properties on a substrate (base metal) where by only a very thin layer of the substrate" has to be melted in order to achieve metallurgical bonding with minimal dilution of added material and substrate in order to maintain the original properties of the coating material". Laser cladding offers many advantages over conventional coating processes such as arc welding and plasma spraying. The laser cladding technique can produce a much better coating, with minimal dilution, minimal distortion, and better surface quality. The various components of the laser cladding system is shown in the figure 1.1

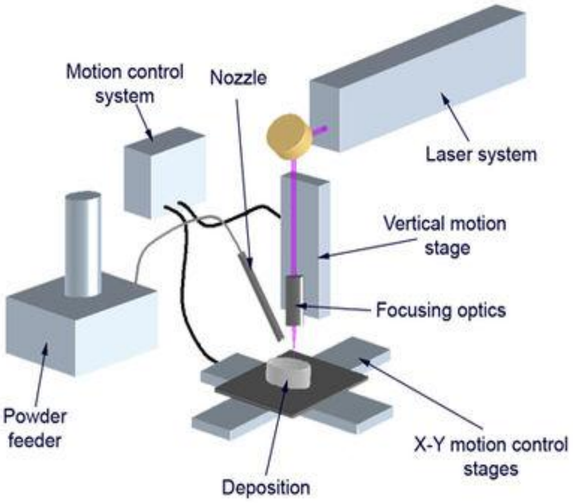

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Figure. 1.1 Schematic of the equipments of laser cladding system

(i) The substrate materials are various carbon steel, alloy metals, stainless steel and non-ferrous alloy metals.

(ii) The clad materials are of two kinds.

   (a) Metal Powders such as Chrome, Nickel and Cobalt base, Nickel base and Fe - base alloy powder.

   (b) Ceramic Powder such as WC, SiC, TiC, $Al_2O_3$and ZrO_2

The Laser cladding process essential steps.

(i) Supply of cladding material to the substrate followed by melt pool formation:
  (a) By wire feed
  (b) By blown or injection powder
  (c) By pre-placed power method

(ii) Fusion by a moving laser beam.

The figure 1.2 shows the physical phenomena during different laser material processing techniques. The Heating, Heating and re-heating and heating and powder addition are shown in the figure.

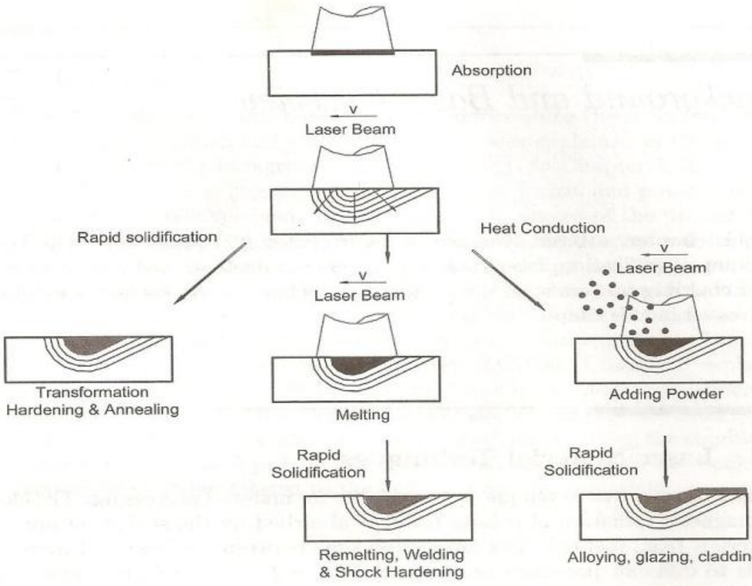

Figure 1.2 Schematic of physical phenomena during different laser material processing techniques.

Pre-placed powder method Vs Powder injection method

The pre-placed powder method is the most straightforward one to use the powder is applied as a paste (mixture of binder and powder) on the substrate. So no special equipment is required. It is very easy to achieve. But the pre-placed powder method is not suitable for the cladding of larger areas or for large work-pieces where several adjacent partly overlapping tracks are required. The powder injection method requires the use of a dedicated powder delivery system and a powder nozzle to direct the powder to the desired position. The literature research showed that laser cladding is predominantly performed by powder injection, because that method is more flexible and easier to control.

Further laser cladding with powder injection results in some good quality clad areas. The powder injection process starts with the formation of a melt pool in the substrate. Simultaneously, powder particles of the coating material, are injected as a powder stream into the laser generated melt pool and melts straightway; a strong fusion bond between the coating material and substrate is achieved immediately. A preheating phenomenon exists in the process: The particles are preheated during their flight through the laser beam, melting of the particles starts after they enter the melt pool. In the melt pool, they exchange heat and mix with the elements already present. The powder particles might also affect the laser power density. After laser beam scanning, it rapidly solidifies. Thus a clad layer is formed almost instantaneously.

Laser cladding by powder injection has received significant attention in recent years due to its unique features and capabilities in various industries involved in metallic coating, high-value components repair, prototyping and low – volume manufacturing. This emerging laser material processing technique is an interdisciplinary technology utilizing laser technology, computer-aided design and manufacturing (CAD/CAM), robotics, sensors and control and powder metallurgy and rapid solidification. Further development of this technique depends on enhancement of the technologies and the process quality. The figure 1.3 shows the different process techniques of the laser cladding technology.

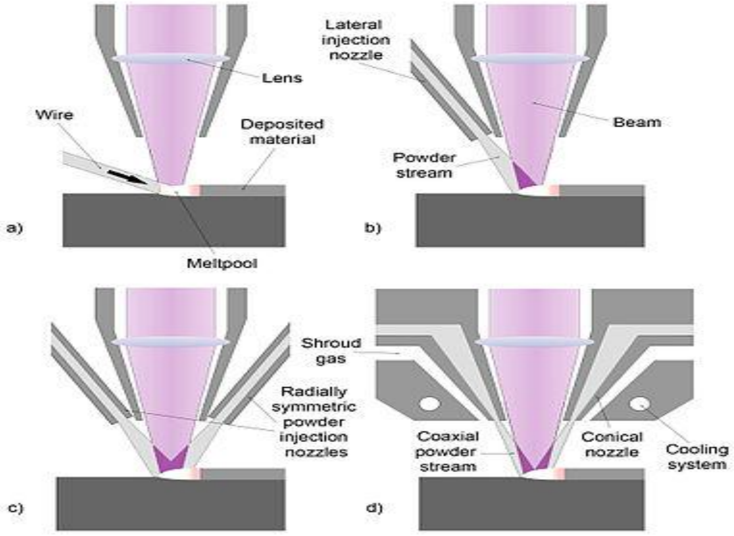

Figure 1.3 Schematic of the different types of laser cladding system

The powder injection laser cladding process has several other advantages over the pre-placed powder laser cladding process: (1) For larger areas, which require the application of several adjacent tracks, the clad can be produced with less dilution. Contraction of the clad layers on cooling down still occurs, but because material is fed to the substrate next to the previous track no part of the substrate is irradiated unnecessarily; (2) the coating thickness can be varied by controlling the material feed rate; (3) products with a complex geometry can be treated, because material is fed continuously to the interaction zone, The flowing out of the molten material by gravitation is not a problem because of this.

Over the years the laser cladding technology has developed coupled with the advancements in the allied engineering fields, materials technology and the demand from the critical application fields involving especially high to extremely high temperature environments like Nuclear, spacecrafts, aeronautical, automotive and thermal power plant industries. This can be understood from the following figure 1.4

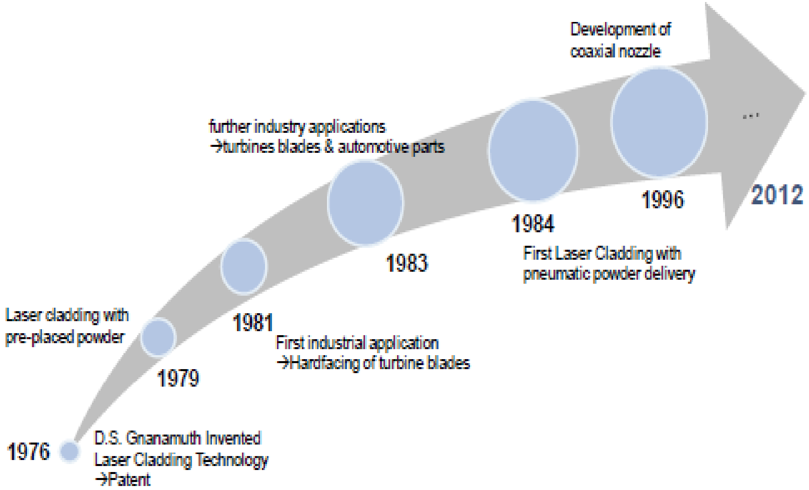

Figure 1.4 Some Mile stones in the history of laser cladding

A good comprehension of the underlying physics of the laser cladding process is key in the development of the process as a reliable coating and manufacturing technology.

Different regions of a typical laser cladding

The different regions of a typical laser cladded tungsten carbide on a substrate material are shown in the figure. The interpretation and main characteristic of each of the zone are as also given hereunder.

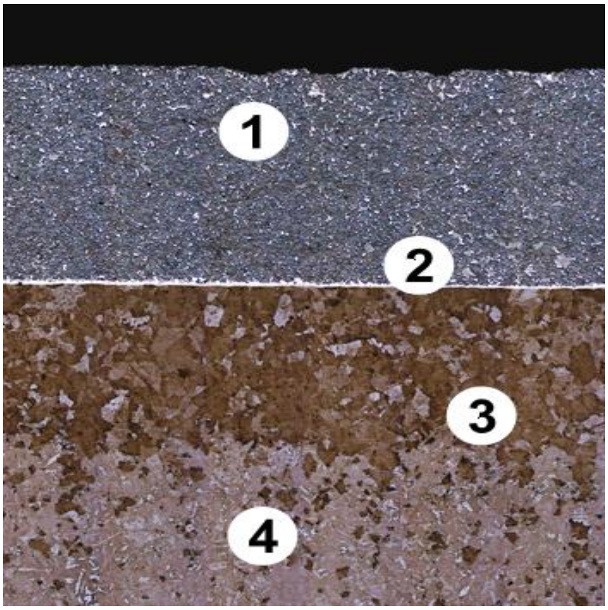

Figure 1.5 Different regions of a cladding

Region 1 indicates Cladding

Dense tungsten carbide loading with uniform carbide distribution - high wear resistance with predictable wear rates and continuous operation up to 1900°F.
No interconnected porosity- superior corrosion and impact resistance

Region 2 indicates Bond Line

True metallurgical bond (>70,000 psi (483MPa)) with high interparticle bond strength - provides unsurpassed strength and prevents chipping, flaking and check cracking

Region 3 indicates Diffusion Zone

Minimal dilution - substrate retains uniform properties in diffusion zone

Region 4 indicates Substrate

Heat treatable - can be heat treated after cladding process to restore substrate’s mechanical properties
1.6 Clad Dimensional Characteristics
The figure 1.6 shows the important characteristics of a clad layer

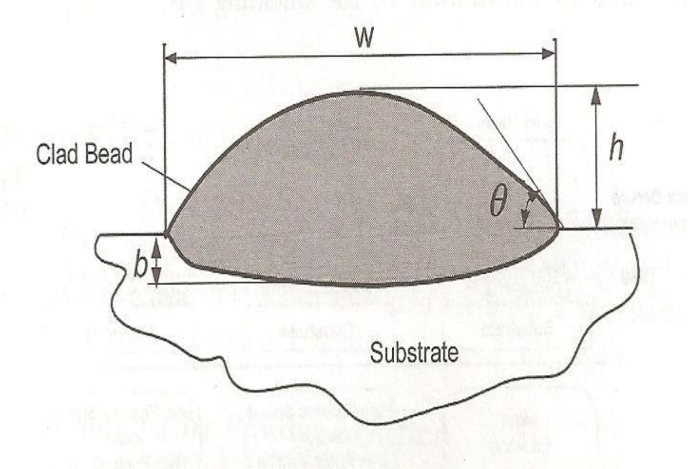

Figure 1.6 Clad Dimensional Characteristics

The different characteristics of the clad layer are,
b-clad depth h- Clad Height w- clad width

Pre-placed powder method Vs Powder injection method.

The figure 1.7 depicts different stages during the process of cladding indicating the heat transfer phenomena.

The different stages are,

(i) Heat absorption by the substrate material,

(ii) Heat conduction through the substrate material,

(iii) Melting and coating. In this stage the substrate material and cladding material are melted they make coalescence and forms coating of pure cladding material layer on the substrate and mix of the two materials at the interface, which is referred to as dilution.

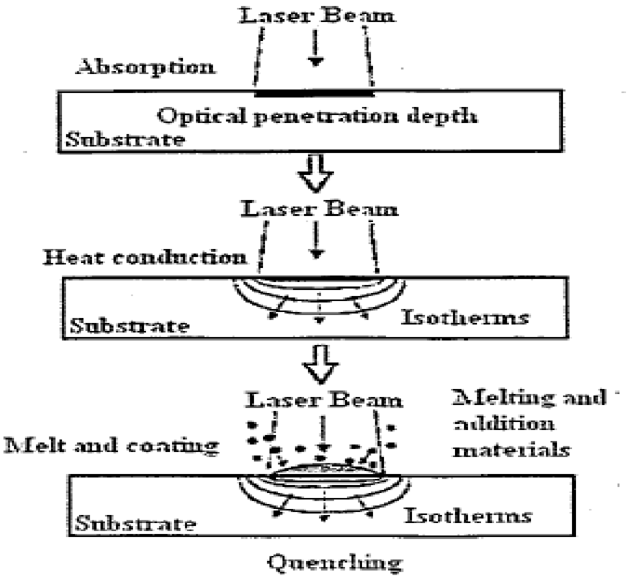

Figure 1.7 Heat Transfer Process of powder injection laser cladding

Necessity of Laser Cladding

(i) High dilution is an associated characteristics in cladding by welding methods like TIG, Oxy –acetylene flame and plasma surface welding processes in which the melt pool is well stirred by electromagnetic, Marangoni and convective forces. Also dilution necessitates laying down thicker clad layers to achieve required clad property though having the advantage of good interfacial bond. But comparatively very thin dilution and in particular the ability to heat and clad in specified areas alone lead to use of laser cladding compared to that of the welding methods.

(ii) The advanced technology products demand a very accurate, clean and well controlled and homogeneous microstructure with the required mechanical properties.

(iii) Since energy and natural are limited the application of laser cladding is becoming inevitable which enables the use of low-price materials while retaining outstanding service performance.

(iv) To fetch in cost effectiveness and to obtain good economy benefits on the premise of guaranteed service performance the consumption of the high-level alloy materials should be greatly decreased.

(v) Use of laser cladding becomes mandatory to applications where only a part of the work piece needs to be resistant to corrosion, wear and oxidation.

Advantages of Laser cladding

(a) The energy supply can be well controlled.
(b) A very local treatment is possible.
(c) Most suited technique for graded material application.
(d) The total heat input is low hence low deformation of the substrate and small HAZ.
(e) Low dilution between track and substrate
(f) Strong metallurgical bond.
(g) The heating and cooling rates are high resulting in fine microstructure and metastable phases.
(h) Porosity can be completely eliminated.
(j) The treatment is non contact process hence no wearing of tools nor any mechanical forces acting on the workpiece.
(k) The process depth is well defined.
(l) Well adapted for near-net-shape manufacturing.
(m) Built part is free of crack and porosity.

(n) Particular dispositions for repairing parts (ideal if the mould of the part no longer
exist or too long time needed for a new fabrication).
(p) Compact technology.
(q) Best technique for coating any shape and increase life-time of wearing parts.
(r) A lot of material flexibility (metal, ceramic, even polymer).

Industrial Uses of Laser Cladding

(i) Failure of engineering components or materials due to chemical (corrosion and oxidation) or mechanical (Wear, erosion and abrasion)is most likely to initiate from the surface because both external and internal surfaces/interfaces are more prone to environmental degradation, and intensity of externally applied load is usually at the surface.

(ii) Conventional surface engineering techniques possess several limitations like high time/energy/material consumption, poor precision and flexibility, lack in scope of automation/improvisation and requirement of complex heat treatment schedule.

(iii) Thermodynamic constraint of restricted solid solubility and kinetic limitation of thermally activated solute transport to solid-state diffusion impose further limits to the level of improvement possible through the conventional or near-equilibrium processes.

(iv) Sometimes the conventional coating methods use poisonous chemical electro plating materials that cause detrimental effects to the humans and on the environment.

(v) The replacement of more expensive metal alloys in service with the same quality alloy materials throught greatly increases the manufacturing cost in terms of formability and cost of the material while this problem could be addressed by the use of low-price metals with localized changes in only those areas subject to wear, corrosion and oxidation.

(vi) Repair of the surfaces in service with welding technology leads to high dilution rate and the microstructure that is coarser and more prone to hot cracking. Sometimes, the repair-welding layer of the repaired work pieces could very easily detach from the substrate greatly decreasing the operating life of the coating.

Technological parameters of laser cladding

The most important technology parameters of laser cladding are as: laser power, laser beam spot diameter, laser scanning speed or the speed of relative movement of the work-piece, pre-placed powder layer thickness, powder feeding rate, nozzle angle and stand-off etc. In addition, the specific energy and dilution are two important parameters, which have to be controlled.

Specific energy:

Laser cladding results is related to the specific energy E:

$$E = P/(D \times V)\ \mathrm{J/m^2}$$

Where P is the laser power, V is the feed rate of the work piece, and D is the diameter of the laser beam spot.

Dilution rate:

It is known that laser cladding requires the achievement of a strong fusion bond between the cladding material and the substrate, which requires the formation of a melt pool in the substrate. So that the depth of this melt must be as small as possible in order to obtain a pure surface layer, which is not diluted by the base material. The dilution of the produced clad layer by elements of the substrate is used to characterize the clad quality.

In order to reduce the influence of the substrate on the cladding alloy components, and in order to achieve the metallurgical bonding between cladding layer and substrate, dilution rate should be preferably small. When a laser beam irradiates both the cladding layer and substrate, elements of the substrate infuse the cladding layer, and cause cladding component change. The degree of the change is the dilution rate.

Also the shape of the clad profile depends on the wetting angle and interfacial free angles. The different clad shapes (cross sections) are shown in the figure 1.8.

The different shapes of the bead represented by the figure are for

(a) High dilution, well wetting
(b) ideal bead
(c) No dilution, Non-wetting

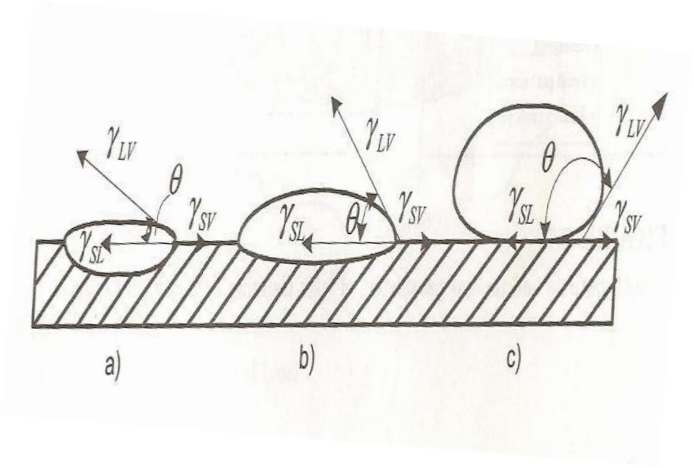

Figure 1.8 Laser cladding cross sections

Dilution rate can be approximately calculated by two ways.

One method is based on the clad layer geometry, namely, measuring the cross sectional area of cladding layer. The dilution is then defined as the ratio of the cross section area of substrate over the cross section area of clad layer. The formula is as below:
Dilution rate (η) = Ss / (Se + Ss)

Ss - is cross section area of substrate,

Se- is cross section area of clad layer.

The geometrical dilution is then defined as the ratio of the clad depth (D_c) in the substrate over the total clad height (T_c) as shown in Figure. This geometrical approach assumes a homogeneous distribution of elements over the clad cross-section.

Geometrical dilution rate (η) $=\frac{Dc}{Tc}$

This method is quite easy to use and the absolute error is within 5%.

Dilution rate, on the one hand controlled by laser treatment parameters, and on the other by cladding materials, such as the alloy powder's granularity, melting point, chemical composition and the substrate's wettability, etc. Laser cladding technology, is practicable when the dilution rate is between 5% and 10% or so. By this, the expected designed cladding layer properties can be realized, as well as the production of fine metallurgical compounds between the cladding layer and substrate. Optimisation is based on producing both fine metallurgical compounds and the appropriate dilution degree as far as possible. The figure 1.9 shows the correlation between laser parameters

Figure 1.9 Correlation between laser parameters

Generic Scope of Laser cladding

The scope of laser cladding generally includes the examination of the following.

(a) Macrostructure
(b) Bead geometry parameters
(c) Microstructure
(d) Micro hardness of the clad surface
(e) Wear resistance (abrasive and erosive wear)

LITERATURE REVIEW

The literatures throw light on the overview of the processes and procedures, properties of the materials, different phenomena related to the cladding, cladding materials, cladding processes, morphology and characterization of laser clad compounds, influence and distribution of hard particles in the clad composition and its influence on the micro-hardness and wear resistance properties (Tribological behaviour), interaction of the hard particles with the matrix elements, behaviour and interaction of substrates with clad composition at the interface, distribution of temperature etc. Also a comprehensive study of the is essential to know the interrelationships between various process parameters and their influence on the material properties both macroscopical and microscopical, and changes in the properties. A lot of researches are being carried out to find out an effective way of producing hard, wear and abrasion resistant, corrosion resistant, chemical resistant and heat resistant materials for high temperature and high corrosion environment applications. These literatures are useful for complete understanding of the laser cladding process.

LITERATURES

[i] William M. Steen, “Laser Material Processing” Third Edition, 2005 Springer-Verlag London Limited.

(a) Various laser surface treatments including Different cladding techniques are dealt in this book.

(b) Laser cladding processes, arrangement of laser cladding method, process of cladding by blown powder technique (Figure 2.1) and co-axial powder feed method (Figure 2.2), the variation of typical laser cladding rates with power (Figure 2.3), relationship between clad thickness and powder particle size using the blown powder process (Figure 2.4), cladding thickness versus the distortion of a standard size for coatings produced by various techniques (Figure 2.5), the operation window (Figure 2.6) for blown powder laser cladding, The three basic cross section profiles for single track clad beads (Figure 2.7) and effect of preheating observed on a sample have been covered.

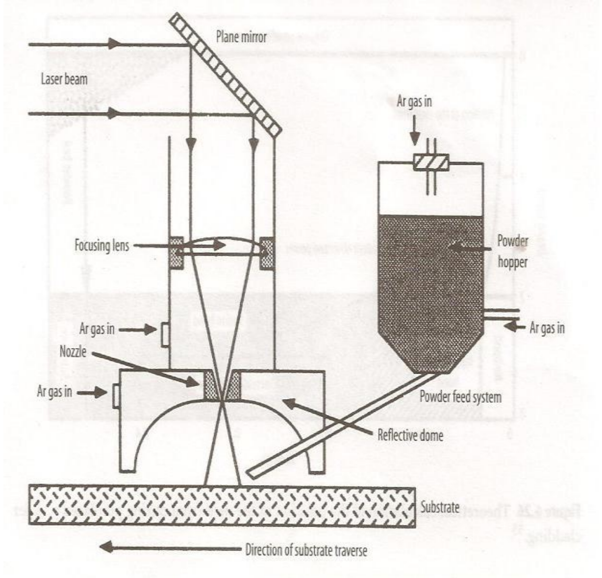

Figure 2.1 Arrangement for laser cladding by the blown powder technique

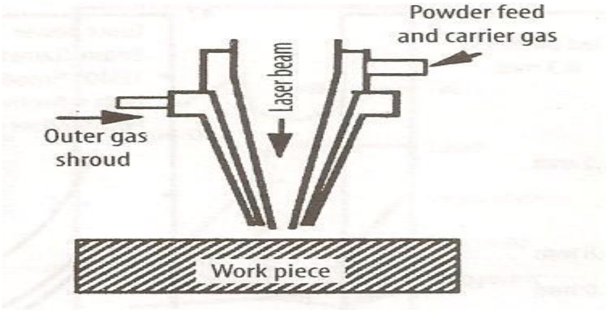

Figure 2.2 Diagram of a coaxial powder feed nozzle.

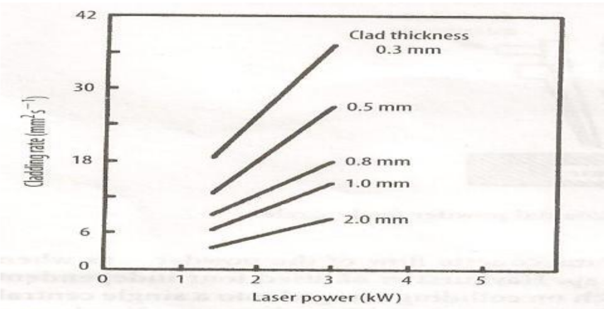

Figure 2.3 The variation typical laser cladding rates with power and clad thickness using blown powder process with reflective dome.

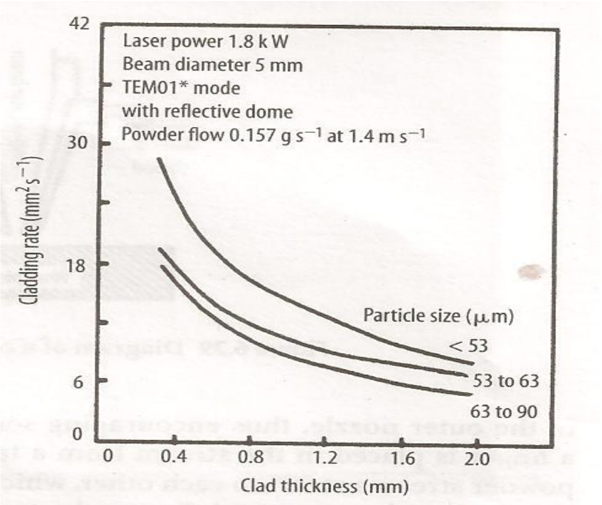

Figure 2.4 The variation typical laser cladding rates with clad thickness and powder particle size using blown powder process with reflective dome.

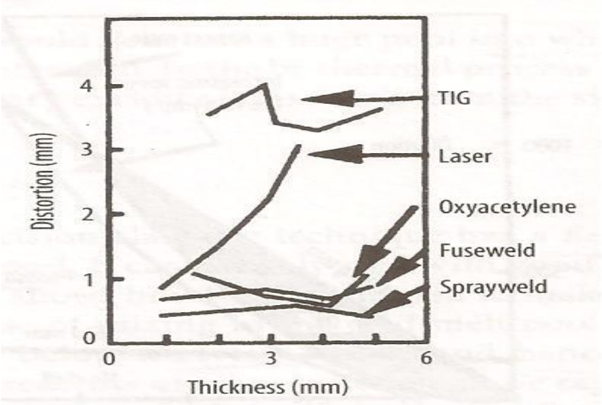

Figure 2.5 Hardfacing thickness versus the distortion of a standard size sample for coatings produced by various techniques.

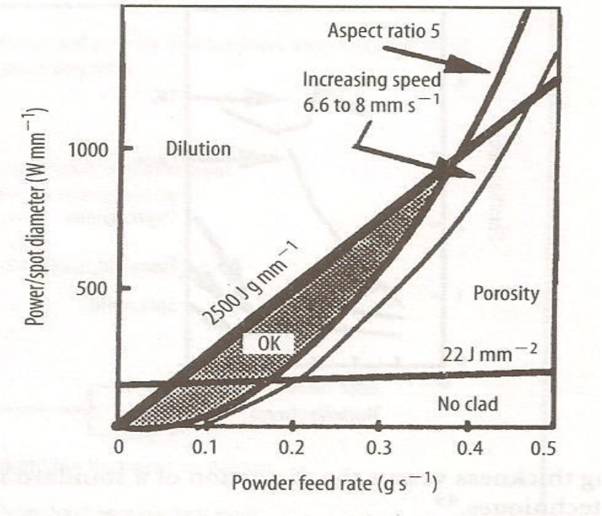

Figure 2.6 The operating window for blown powder laser cladding.

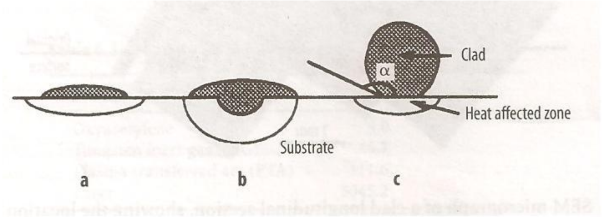

Figure 2.7 The three basic cross section profiles for single track clad beads.

(c) Further, the relationship between laser absorption intensity, powder intensity and laser interaction time as shown in the figure 2.8. explained by the author. The relationship has been constructed for base material Iron.

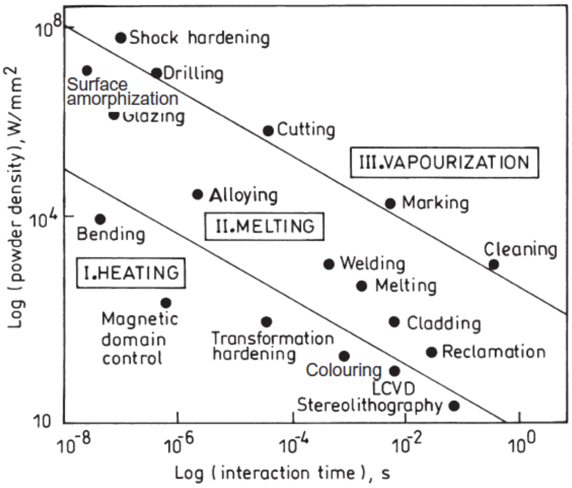

Figure 2.8 Range of laser processes

This figure shows the regions of different operations that can be performed by the application of laser based on the intensity of the laser and its interaction time. In the diagonal lines represent lines of constant temperature for the boiling and melting point of Iron. The domain for different laser material processing techniques as a function of laser power and interaction time is illustrated in the figure. The processes are divided into three major classes, namely involving only heating (without melting/vapourizing), melting (no vapourizing) and vapourizing. Obviously, the laser power density and interaction/pulse time are so selected in each process that the material concerned undergoes the desired degree of heating and phase transition. It is evident that transformation hardening, bending and magnetic domain control which rely on surface heating without surface melting require low power density. On the other hand, surface melting, glazing, cladding, welding and cutting that involve melting require high power density. Similarly, cutting, drilling and similar machining operations remove material as vapour, hence need delivery of a substantially high power density within a very short interaction/pulse time. For convenience, a single scalar parameter like energy density (power density multiplied by time, J/mm2) is more useful for quantifying different laser assisted processes. However, the practice is not advisable as the specific combination of power and time (rather than their product) can only achieve the desired thermal and material effect.

[ii] Jyotsna Dutta Majumdar Indranil Manna, “Laser-Assisted Fabrication of Materials” , Springer Series in Material Science, Volume 161, Edition 2013. The characteristics of laser beam wavelength, pulse duration, beam format, various parameters of Laser-Matter Interaction for Material Processing like Lattice Heating, mathematical model for Spatial Distribution of Deposited Energy, Heat Transfer by Laser Irradiation, Plasma Formation during Laser irradiation and Effect of Ultra High Power Laser Irradiation are set out. Mathematical models are, for

(i) Spatial Distribution of Deposited Energy

$$I(z,t) = I_0(t)(1-R)\exp(-\alpha z)$$

where I – Laser Beam Intensity,
I_0 – Incident Intensity,
Z – depth,
t – time,
R – reflectivity coefficient and,
α – absorption coefficient,

(i) Heat Transfer by Laser Irradiation

Thermal Diffusivity $D = k/(\rho c_p)$

where k – thermal conductivity W/m^2 K
ρ – density kg/m^3
c_p – specific heat capacity W/kg

The vertical distance (z) over which heat diffuses during the pulse duration (tp) is given by, z = (2Dto)1/2. Here, z in comparison to laser absorption depth (α-1) determines the temperature profile. For laser irradiation of metal, the typical value of α-1 is much less than z.

(iii) Under the one-dimensional heat flow condition, the heat balance is given by

$$\rho c_p \frac{\partial T(z,t)}{\partial T} = Q(z,t) + \frac{\partial}{\partial z} k \frac{\partial T(z,t)}{\partial z}$$

where T – Temperature
Q – power density
t – time
z – depth

Depending on the temperature profile, the irradiated material may undergo only heating, melting or vaporization.

[iii] LASER Cladding With Powder effect of some machining parameters on clad properties, author: M.F. Schneider, Proefschrift, Ph.D. Thesis University of Twente, Enschede, The Netherlands, March 1998.

This literature covers Laser cladding and other laser surface treatments, Applicability of laser cladding, Laser cladding methods, Clad layer properties, Material properties, Effect of process parameters, Experimental methods, Temperature profile on a clad surface, Determination of the absorption of laser energy. This literature is based on the experiments carried out on the cladding process. Following are the inferences from this experiment. The purpose of the experiments on laser cladding was to study the effect of the machining parameters on the clad results and to determine the kind of application (or geometry) which the methods are most suited for.

The existence of a working region can be explained easily, as will be shown with the following example. For a typical clad experiment the following experimental parameters can be used:

- laser power: 1300 W
- feed rate: 5 mm/s
- clad thickness: 0.5 mm
- laser spot size: 3.0 mm

This implies that less than 10 % of the absorbed laser power is required for the melting of the preplaced powder. The major part contributes to the heating of the substrate. This fact can be noticed during the experiments. When cladding with 800 W instead of 1300 W, the laser power is sufficient for melting of the powder. However, this molten powder only forms droplets on the surface of thesubstrate and does not flow out. The surface temperature remains below the critical temperature that is necessary to allow wetting by the molten powder.

The hardness in the clad layers (cobalt base Metco 18C) depended strongly on the dilution. The produced good quality clad layers had a hardness of about 800 Hv, which is much higher than the hardness of the applied powder. This is an effect of the high cooling rates and the small degree of dilution that must be accepted in order to achieve a strong fusion bond between the two materials. The hardness could be increased further by allowing more dilution. However, this does not agree with the basic principle of laser cladding. The experimental conclusions might suggest that laser cladding depends on the applied specific energy, because that parameter relates the clad properties tothe laser power and the inverse of the feed rate.

[iv] Technology Assessment of Laser-Assisted Materials Processing in Space Karthik Nagarathnam and Karen M. B. Taminger Applied Research Center, Old Dominion University, 12050 Jefferson Ave. Suite 717, Newport News, VA 23606, 757- 269-5641, 1knagarat@odu.edu NASA Langley Research Center, MS 188A, Hampton, VA 23681, 757-864-3131, k.m.taminger@larc.nasa.gov

As per this literature, based on several experimental findings, typical laser processing maps were developed for surface engineering applications, laser surface cladding, laser beam welding and laser surface melt quenching (Nagarathnam and Mazumder, 1996). Further this study concludes that Diode-pumped solid-state lasers are inherently well suited to be used as a multifunctional tool because they have characteristic wavelengths and power outputs suitable for numerous materials including reflective alloys and for most laser processing techniques. These lasers are also capable of fiber optic delivery, which greatly increases laser manufacturing flexibility by expanding the ability to treat complex geometries and inaccessible areas with less difficulty. In addition, diode-pumped solid-state lasers are well suited for adapting to space applications due to their compact size, robustness, and minimal cooling requirements. Establishing an in-space laser manufacturing capability will require significant improvements over state-of-the-art laser technology in power efficiency, maximized life with minimal maintenance, and ability to operate using DC input power. Ongoing development of these types of lasers addressing manufacturing issues on earth will contribute to increasing versatility and feasibility of lasers for supportability of short- and long-term missions on-orbit, the moon, Mars, and beyond.

[v] Processing and Characterization of Lase-Cladded Coating Materials, K.Komvopoulos and K Nagarathnam. Jounal of Engineering Materials Technology, 112(2), 131-143 (Apr4 01, 1990) (13 Pages doi:10.1115.1.2903299 Received July 03, 1989; Revised August 21, 1989; Copyright © 1990 by The American Society of Mechanical Engineers

In this study the following have been carried out by the author.

(a) The feasibility of laser cladding as a surface modification process was experimentally investigated.

(b) Emphasis was placed on identification of the effects of independent critical process parameters such as laser power, process speed (interaction time), and feed rate of cladding powder mixture on the microstructure, compositional homogeneity, geometry (e.g., thickness and width), and mechanical properties of the developed coatings.

(c) Rapidly solidified coatings metallurgically bonded to AISI 1018 steel substrates were formed in situ by using a 10 kW continuous wave CO2 laser to melt a thin layer of the substrate as well as a powder mixture consisting of Fe, Cr, C, and W with a weight ratio of 10:5:1:1 delivered to the substrate by means of blown shielding gas and a pneumatic screw feed system.

(d) Various diagnostic methods, indentation hardness measurements, and scratch-resistance testing of the laser-cladded coating materials revealed a high degree of grain refinement, increased solid solubility and uniform distribution of alloying elements, high hardness, and appreciable resistance against plastic shear deformation when the important process parameters were optimized.

(e) Microstructure studies demonstrated that coatings with very fine or relatively coarse dendritic, feathery, and particulate type microstructures were obtained, depending on the processing conditions.

(f) This investigation verified that due to the inherent rapid solidification and high concentration of key elements in the surface, hard coating materials of novel microstructures and physical properties which can be tailored to the surface requirements of the application can be produced with minimum dilution and thermal distortion. Implications of the laser cladding process in tribological applications are also interpreted qualitatively in light of the obtained results.

[vi] Microstructural and microhardness characteristics of laser-synthesized Fe-Cr-W-C Coatings Metallurgical and Materials Transactions August 1995, Volume 26, Issue 8, pp 2131-2139K. Nagarathnam, K. Komvopoulos.

In this literature the effects of laser-processing parameters on the microstructure and microhardness of Fe-Cr-W-C quaternary alloy coatings were investigated experimentally. The coatings were developed by laser processing a powder mixture of Fe, Cr, W, and C at a weight ratio of 10:5:1:1 on a low-carbon steel substrate using a 10 kW continuous wave CO2 laser. Depending on the processing parameters, either hypoeutectic or hypereutectic microstructures were produced. The hypoeutectic microstructures comprised primary dendrites of nonequilibrium face-centered cubic (FCC) austenite γ phase and eutectic consisting of pseudohexagonal close-packed (HCP) M7C3 (M = Cr, Fe, W) carbides and FCC γ phase. The hypereutectic microstructures consisted of HCP M7C3 primary carbides and eutectic similar to that in the hypoeutectic microstructures. The formation of hypoeutectic or hypereutectic microstructures was influenced by the alloy composition, particularly the C concentration, which depends on the amount of powder delivered into the melt pool and the extent of substrate melting. The enhancement of the lattice parameter of the γ phase is associated with the significant dissolution of alloying elements and lattice strains resulting from rapid quenching. The higher hardness of the hypereutectic microstructures is principally attributed to the formation of HCP M7C3 primary carbides. The relatively lower hardness of the hypoeutectic microstructures is related to the presence of y phase in the primary dendrites, excessive dilution from the base material, and relatively low concentrations of Cr and C. The results provide insight into the significance of laser-processing conditions on the composition and hardness of Fe-Cr-W-C alloy coatings and associated solidification characteristics.

[vii] Chen Zhenda et al carried out an investigation on laser cladding of WC-Ni composite to wear resistance. The WC particles were reinforced in the matrix of Ni-Cr-B-Si alloy. The results of the laser cladded surface coating had a high hardness of 2400 DPH. Dry sliding wear test has been conducted on the normalized mild steel, D2 steel and the clad layer and they observed high wear resistance of the clad layer and it was a combined result of tough Ni-based alloy matrix, uniform distribution of hard WC particles and the good bonding between the WC particles and the Ni based alloy matrix.

[viii] Laser cladding for wear-resistant cobalt base alloy and tungsten carbide composite coatings Journal: Journal Of The Chinese Institute Of Engineers - J Chin Inst Engineers , vol. 29, No. 3, pp. 423-431,2006DOI: 10.1080/02533839.2006.967113

According to this journal Stellite12 cobalt base alloys with different WC contents were deposited on SK3-carbon tool steel by laser cladding. The behavior of WC particulates, including dissolution and distribution, and the microstructure of WC-Co-Cr-C composite coatings with rapid solidification were investigated. Several significantly different solidified microstructures were characterized by dendrites, eutectics, faceted dendrites and the retained WC particles in the laser cladding WC + Stellite12 coatings, under different laser energy densities. When WC was melted and dissolved into the Stellite12 melt pool, the basic structure of solidification, characterized by the matrix and faceted dendrites in various shapes, and the contents of the faceted dendrites remained nearly identical. The faceted dendrites contained the majority of W as well as some Cr, Co while more Cr and Co were located in the matrix. The X-ray diffraction analyses indicated the existence of σ-Co, M23C6, M6C and M7C3 (M = W, Cr, Co) in the Stellite12 with different WC contents when deposited on substrates by laser cladding. The faceted dendrites provided the coatings with excellent resistance during dry sliding wear test. A higher content of WC gave higher volume fractions of faceted dendrites that imparted excellent wear resistance to the coating.

[ix] G. L. Goswami and Santosh Kumar, Laser Processing & Advanced Welding Section, Bhabha Atomic Research Centre,and R. Galun and B. L. Mordike, Institut fur Wekstoffkunde and Werkstofftechnik, Technical University of Clausthal, Germany‘Laser cladding of nickel based hardfacing materials as an alternative of stellite, BARC Newsletter, Issue No. 249.

The conclusions from this study are the following.

(a) Laser cladding of nickel based hardfacing materials has been done to produce defect free claddings, by optimising the process parameters.

(b) Ni-15Cr-32Mo claddings have better hardness & wear resistance compared to stellite-6 claddings. (Ni-20Cr)-40Cr2C3 claddings show comparable hardness and much higher wear resistance than that of stellite-6 clad layer.

(c) (Ni-20Cr)-40WC clad layers show lower hardness and much higher wear resistance than that of stellite-6 clad layer.

(d) Nickel based hardfacing materials emerge as potential alternative of stellite-6.

[x] J. M. Amadoa, M. J. Tobara, A. Yáñeza*, V. Amigób, J. J. Candelb a Universidade da Coruña, Campus de Esteiro s/n, 15403, Ferro, , ‘Crack Free Tungsten Carbide reinforced Ni(Cr) Layers obtained by Laser Cladding’ LiM 2011 bITM-UPV, c/ Vera s/n, 46022 Valencia Physics Procedia 12 (2011) 338–344.

Following are the features of this study.

NiCr-WC MMC layers using commercial premixed alloy powder were deposited on a low carbon steel by laser cladding. Reinforcement tungsten particles consisted in spheroidal fused tungsten carbides. Three NiCr alloys acting as metallic matrices were tested which differed in their Cr content. Through careful parameter selection pore free layers with minimal dilution and good metallurgical bonding with the substrate where obtained. EDX analysis inspection and microhardness measurements yielded a reduced presence of tungsten on the matrix with compositions and hardness close to the nominal values. Cracking of the deposited coatings was related to the chromium content of the NiCr matrix. For composition with Cr(wt%) roughly below 8% no cracks were observed in any of the deposited samples. Wear studies, indicate that the loss in matrix hardness by reducing the Cr content does not imply a loss in the wear rate of the resulting coating.

Conclusion

A great deal of research is now being carried out on the laser cladding, cladding machines, processes, its versatility of its applications with the use of different combination of alloying elements along with the matrix elements for improved degrees of bonding strength and its homogeneity with different substrate materials with low and controllable heat input in the workpiece, a high cooling rate, great processing flexibility, low distortion, minimum distortion, low thermal load and minimum post treatment. As the laser cladding process involves many parameters, such as laser power, laser energy density, beam diameter, laser focal point, scanning speed, powder feed/infection rate, substrate velocity etc. Also the laser cladding is a multi disciplinary subject since it involves control of mechanical properties, metallurgical properties, qualitative properties and geometrical properties. Hence many groups are focusing their attention on developing sensors to measure the process on line. This together with the developments in the research will take forward processing system parameters so that it can be developed around specific metallurgical properties for user defined applications such as microstructure, internal stresses, dilution zone gradients and clad bead geometry parameters.

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