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Review on Laser Deposition Welding: From Micro to Macro

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- Invited Paper -

Abstract

Laser cladding has become an established technology for parts repair and surface modification for cost-intensive components. Due to ongoing improvements of laser sources, process technology and strategy, the range of applications for laser deposition processes is continuously increasing. Critical issues as well as performance and economic efficiency problems have been solved in recent years. Consequently big advances have been done in laser cladding, from micro to macro, from low- to high power as well as in hybrid processes.

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1. Introduction

The prior use of laser cladding has been the repair and surface modification of high-value parts [1,2] but continuous developments of the process and the process technology enable new possibilities for micro applications, surface modification and rapid manufacturing. Currently various names can be found for laser cladding processes in the literature, caused by the number of institutes and companies which have worked on their own kind of process. “Laser Engineered Net Shaping” (LENS®), and “Direct Metal Deposition” (DMD) are examples of the divers names given to the process. Principally the basic procedure is similar but technical details and application scales differ. Independent of process variant and scale, laser cladding is based on a metallurgically-bonding of additive and base material. Therefore the base material is melted superficially, though the bulk energy input is going into the additive aiming in low

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dilution. The significant advantage of laser cladding is the broad range of additive materials: Metals, Ceramics, Polymers and Compounds, nearly all weldable materials can be used. For instance Steel, Aluminum and Titanium, have been used for laser cladding as well as Stellite, non-weldable rated nickel-based superalloys, shape memory alloys and nano composites. Reasoned by the high thermal gradient during processing, generally a small-grained structure is achieved after solidification. Due to this, laser cladded materials can exceed the tensile strength of conventionally produced parts without losses in the breaking strain [3].

The direct method of laser cladding can be used in various ways to apply material on parts, tools or substrates. With its additive way of production this process helps to close the gap of existing technologies and leads to a number of advantages. Major benefits are listed below:

- **Rapid Prototyping/Manufacturing:** Conventional manufacturing procedures of complex high value parts (prototypes) can be very time intensive and slow down the development process. At this point a rapid manufacturing technique (e. g. for production of Blisks) can lead to accelerated progress and reduced steps in the process chain. This can improve the final position of the product in the market significantly.
- **Enhanced Thermal Control:** Due to its local and defined input of energy the process offers a good controllability of the heat-affected zone. This limits the penetration depth in the base material and allows using heat sensitive materials with minor loss of their mechanical and specific properties. Beyond that, the controllable energy input facilitates the monitoring of solidification rate, which has a major effect on the formation of microstructure and consequently on the mechanical properties of the generated volumes.
- **Parts Repair:** Using laser cladding as parts repair method can increase product life cycles and avoid high investments for replacement tools. Cost intensive parts made of difficult-weldable materials like turbine blades and vanes or complex die casts made of special heat treated tool steel can be repaired with the aid of this method. For huge, work-intensive or expensive products the additive procedure can be used for the discrete rebuilding of over machined areas as well and offers in this way a reasonable alternative regarding a reproduction of the complete part.
- **Graded Parts:** In comparison to conventional fabrication methods of metallic parts, the possibility of creating graded functional parts, with a metallurgical-bond, is a significant advantage of the direct laser cladding process. This can be achieved using multiple powder-feeding systems and varying their feed rate ratio.

Generally laser processes benefit from the excellent focusability and controllability of the laser radiation. These lead to the possibility to deposit exact amounts of energy in well-defined spaces. Ease of automation is another advantage which led to a wide use in the automotive and other industries. On the contrary, there are the high investment and maintenance costs.

Even though there are a number of advantages of using laser cladding in the range of repair and prototyping applications, it is mainly used for parts and tool repair. While parts repair is often done manually and the process conditions are quite constant in the damaged area, the automatic generation of a complete 3D-prototype presupposes a closed-loop process control. Without monitoring, the process will have drawbacks due to instabilities at critical spots during part production and slightly changed environmental conditions. To reach a steady quality regarding grain structure, mechanical properties and surface consistence a real time control of the process is recommended.

There are several ways to bring in the cladding material. In most cases powder is used, which is fused to the workpiece or substrate in a melting pool and therefore forms a strong metallurgical bond.

The advantage of using powder materials is the increased number of substances that can be produced in powdery form. Due to the controllability of the laser energy, these welding processes can be performed with low heat input into the work pieces. Not in all cases this is an advantage and therefore needs to be compensated by additional processes. Since the beginning of powder injected laser cladding in the early 1980ies [4], big advances have been made and new process-combinations have been introduced.

2. Laser cladding

Most commonly used technologies for laser deposition procedures are based on wire or powder feeding systems. Generally lateral nozzles are used for wire systems, but a coaxial wire nozzle has been developed as well [5,6]. For powder based laser cladding the nozzles are arranged either laterally [7–9] or coaxially [10–12] to the laser beam. Though a laterally feeding offers easy adjusting and high process stabilities, the use of coaxial nozzles is established for additive manufacturing applications due to the directional independency.

A combined approach using simultaneous powder and wire feeding to build up material has also been investigated [13]. For all these cladding methods, the laser must be positioned directly over the clad bead, and the complete head has to be moved from one position to another for each bead of a wall or area. To overcome this problem, one approach used a rectangular-shaped diode laser beam and a nozzle with two powder line streams coming from both sides [14]. This method uses a wider “stripe” for cladding large surface areas instead of using multiple rows of clad beads side by side. A new approach for laser cladding based surface structuring has been presented in [15]. Here the desired geometry is built up using a laser scanner in combination with a fixed powder curtain. Special nozzle designs have been developed and investigated to enable processing of inner diameters and restricted accessible areas. ID-cladding heads with immersion depth up to 1 m at a bore diameter of 10 cm have been realized [16].

As laser sources CO_2-, Nd:YAG-lasers have been used in the beginnings, now Disk-, Diode- or Fiber lasers (single-mode, multi-mode) are established as well, due to their high electro-optical efficiency and the extended range of possible applications.

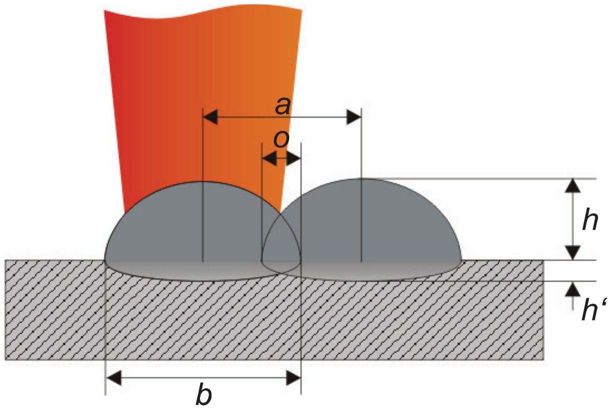
The additive manufacturing of volume parts is mainly done using spiral or meander deposited single tracks [17]. Extending the track wise deposition of material with a layer wise growth in z-direction enables the procedure to generate thicker functional layers on work pieces or to rebuild the original contour of damaged parts. Additionally it enables the direct additive manufacturing of volume parts. Although it is often called 3D-manufacturing it is mainly a 2 ½D-procedure due to certain geometrical limitations during processing.

Significant Parameters

The quality of the single track takes a major effect on the result of the finished part in the process of laser cladding. Beside the impact of substrate and powder material and the restrictions given by the installed equipment, the controllable parameters play a dominant role. In Fig. 1 the major parameters of deposition process are pictured [18,19]:

$$I = \frac{P_L}{A_L} \quad (2.1) \qquad E_{St} = \frac{P_L}{v} \quad (2.2)$$

$$t_E = \frac{\pi d_L}{4v} \quad (2.3) \qquad O_{Sp} = \frac{b-a}{b} \quad (2.4)$$



a	hatching distance
A_L	laser beam profile
b	track width
d_L	beam diameter
I	beam intensity
E_{St}	energy input per unit length
h	track height
h'	depth of melting pool
P_L	laser power
t_E	laser exposure duration
o	overlap
O_{Sp}	overlap ratio
v	feed rate

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Fig. 1. Mmajor parameters of laser cladding process

High accuracy of every single track is essential for adequate mechanical properties, and spatial resolution. Especially parts with structure details smaller than 100 µm can be debilitated in toughness by cracks and pores. Beyond that defects in the grain structure take effect on the temperature gradient during cladding and due to that they have influence on grain growth, microstructure and precision.

From Macro to Micro

The minimum producible track width is depending on the laser spot size, the beam caustic and the additive material characteristics (particle size, wire diameter, material properties). Currently the minimum thickness of cladded tracks is in the range of 30 µm. Therefore a consequent adaption of the process equipment regarding the needs of a laser micro cladding process is necessary. Admittedly, down scaling the possible spatial resolution of the direct sintering process is accompanied by increased cost and time efforts for parts production per volume. Nevertheless the plus of accuracy and precision can be conducive to enlarge the range of laser cladding applications and close the gap to conventional technologies. Table 1 gives an overview of four major process parameters to point out the ratio of a micro process towards a common cladding process.

Table 1. Comparison of micro process with common values for a macro process

Parameter		Micro-Process	Macro-Process
focusing spot diameter	[µm]	30 – 50	up to 22 mm
powder particle size	[µm]	5 – 30	45 – 150
resolution / repeatability of x-y-stage	[µm]	0.015 / ± 0.1	n.a.
powder mass flow	[g/h]	2.5 – 10	up to 8 kg/h

A linear downscaling of the process parameters from macro to micro is hardly feasible, due to the changed ratio of the process parameters and environmental conditions towards each other, e.g. powder grain size and spot size, or impact of external gas flow towards built rate and spatial resolution. Using a micro setup goes along with increased difficulties regarding powder handling and feeding, process stability as well as parts quality.

A new approach using a hollow micro laser beam is investigated to overcome existing problems [20]. The project is aiming on improved process efficiency and spatial resolution in the range of 5 µm.

2.1. Laser cladding with powder

Laser beam caustic, powder feeding and –focusing are significant parameters in the laser cladding process, especially in the range of micro applications they need to be considered in relation to each other. Being focused through the coaxial nozzle, the powder particles get in contact with the laser beam on their way towards the surface of the substrate. During this time the laser radiation can be absorbed, reflected or transmitted by the powder particles fed in to the process area. Altogether the fractions of absorption, reflection and transmission result in the total laser power emitted towards the substrate [18]. Since the transmission of metallic powder particles is negligible at the wavelength of 1070 nm the interactions of laser radiation and powder particles are predominantly affected by absorption and reflection. Here are a number of possible cases which are illustrated in Fig. 2 [18,21–23]:

Case 1) One part of the emitted laser radiation encounters directly a powder particle and is partially absorbed and reflected:

a) The reflected fraction is lost for the process
b) The reflected fraction encounters again a particle -> Case 1
c) The reflected fraction is nearly absorbed completely by multiple reflections
d) The reflected fraction encounters the substrate -> Case 2

Case 2) The other part of the emitted laser radiation encounters directly (unimpeded by particles) on the substrate surface and is partially absorbed and reflected:

a) The reflected fraction is lost for the process
b) The reflected fraction encounters a particle -> Case 1

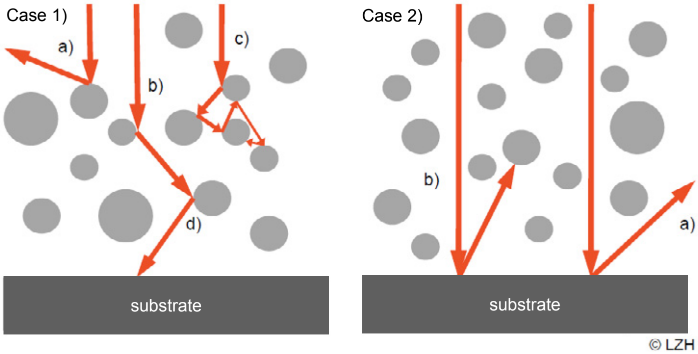

Fig. 2. Distinction of cases for the interaction of laser radiation and metallic powder particles

In consequence of the interactions between laser radiation and powder particles the intensity of the emitted laser beam is decreasing in dependence of cross sectional area of extinction, particle density and the vertical position. This correlation can be described using the formula of Lambert-Beer; whereby the absorbed fraction of laser radiation, effected by material density and heat capacity, leads to a rapid heating of the inserted powder material [24].

Especially the shape of powder particles, e. g. spherical and non-spherical particles (change in volume to surface ratio) has a significant impact towards the process.

Without changing a process parameter, the use of milled non spherical particles, in comparison to gas atomized spherical powders, can lead to higher particle temperatures after their contact with laser radiation. Before the particles have reached the substrate surface, they shall be heated up above their solidus temperature, but not being vaporized. In any case it has to be considered, that the heating curve is very different due to the various possible particle sizes, flight paths and interaction times with the laser.

2.2. Laser cladding with wire

In laser cladding, the coating material can also be delivered as a wire. The advantage of this approach is material use efficiency of nearly 100% and less health dangers which can arise with the use of metal powders [25]. Also, the wire feed process has a better process efficiency at high intensities, where a plasma is formed on the substrate [26]. At low intensities, wires absorb the laser radiation poorly and the process is difficult to control due to variations in the wire absorption coefficient [25]. Also, the thickness of the cladding has a limited range, the volume of machining after cladding is higher and the application of robots is not recommendable. Another drawback of the wire feed process is the rather high dilution of <20% compared to the <5% the powder process exhibits [26]. Today, laser cladding with hand fed wire is used in pulsed laser processes especially when working on filigree structures [27].

3. Laser cladding with additional energy sources

The advantages of laser cladding, low dilution, spatial well defined and low energy input into the work piece as well as excellent control- and repeatability come together with setbacks of this technology. These setbacks have metallurgic and economic reasons.

The metallurgical problems are hardening or ductility reduction in the heat affected zone and the formation of cracks. Cracks in the coating will arise if the ultimate tensile strength or the fracture strain of the material are exceeded [28]. To reduce the danger of cracking, temperature gradients should be minimized. Also the martensitic ϒ -> α phase transformations, which are characterized by large density changes should be suppressed when welding on steel [28,29]. This can be done by preheating. Heating the entire work piece in a furnace is most beneficial due to the uniform temperature distribution, but can hardly be integrated into a technological process [28,30].

Economically, laser cladding suffers from relatively low productivity combined with high investment and maintenance costs. Since only a few percent of the laser radiation are used for the process, laser cladding has low energy efficiency. A study by IWS Dresden shows that about 88 % of the electric power is lost [31]. Therefore supporting additional energy source are a good possibility to raise the efficiency and productivity of the laser cladding process.

In the last twenty years different additional energy sources for material heating in laser cladding have been investigated. These combinations are referred to as hybrid processes:

- Hot wire laser cladding – uses electric current for preheating of the deposition material [32,33]
- Two laser beams – utilizes a second, independently controllable laser source [34]
- Plasma heating – an electric induced plasma is used for heating of workpiece and powder [35]
- Laser induction cladding (LIC) – where an inductor pre- and/or post heats the work piece [30,36,37]

Brenner et al. [37] see LIC as the most promising technology since it provides
- one – to two orders higher productivity,
- low cost of energy and
- a localized temperature field which can be adapted to custom work piece geometries.

The investigation of this technology started in the 1990ies. Dekumbis [38] showed the advantages of the inductive pre-heating in 1993 with a comparison to laser only and plasma-transferred-arc processes. One year later, a patent application was filed by Goodmann [39] regarding induction based pre-heating in cladding.

Today’s hybrid processes increased the deposition rates compared to high-power laser cladding by a factor of 2 – 2.5. With the use of a high power laser source of 8 kW and 12 kW induction power a deposition rate of 14-16 kg/h is achieved. Fast feed rates of up to 3 m/min and dilutions of under 5% were realized by Brenner et al. [37]. Also the laser cladding technology is now open to new materials, due to tailored heat management. Heat treatable steels, case hardening steels, tool steels etc. can now function as substrates. Materials like Deloro 60 can now be cladded crack-free [16,29].

Brückner et al. [30] performed simulations to show that inductive pre-weld or post-weld heating yields a stress reduction. Also an optimum inductor size of 20 mm could be determined for 2 mm wide bead of Stellite 21 on steel Ck45 with a feed rate of 600 mm/min and a maximum preheating temperature of 700° C.

Another process combination is called plasma-enhanced-laser-cladding (PALC). This is a laser cladding process which utilizes a plasma-transferred-arc (PTA) for pre-heating the workpiece surface and the cladding material. Wilden et al. [35] show that this process is able to produce coatings with minimal porosity and dilutions of only 2%. The reduced energy consumption per length of about 50% results in a reduced heat affected zone. A comparison of the PTA, laser and hybrid process showed that deposition rates are an almost linear function of the energy and that expensive laser energy can be substituted by cheaper energy from the plasma process. Also, the study shows, that the cladding speed can be increased with laser/plasma combination process.

At the present time, Fraunhofer Laser Centre (Plymouth, MI, USA) and IWS Dresden (Germany) are carrying out investigations into hybrid technologies in which laser cladding is combined with induction preheating or plasma welding methods to increase the productivity and quality of cladding. [40]

4. Laser guided and stabilized GMA-cladding

A new technology is the laser guided and stabilized GMA-cladding (LGS-GMA). This technique is a combination process, utilizing the cheap electric plasma of a gas metal arc for the required melting energy for the work piece surface and the cladding material. The laser contributes energy for the stabilization of the arc plasma and also preheats the work piece surface [41,42].

To achieve a low dilution of the substrate and the coating material a cold GMA process with approx. 1.6 kW is applied. The stabilization realized by a 500 W fiber coupled diode laser which radiation is inciding into the plasma perpendicular to the work piece surface.

This technology is yet applied to few materials only. For example, a cladding material 1.4718 was used to coat a mild steel substrate (Fig. 3). The experiments have shown that with this technique a dilution of only 3 % can be achieved. Due to the resulting high purity of the coating an average hardness of 63 HRC was reached.

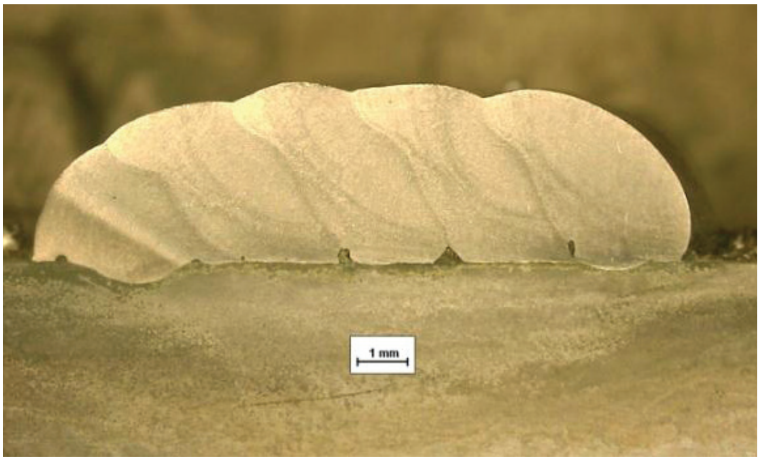

Fig. 3. Cross section of clad showing low dilution

5. Summary

With its specific advantages: local treatment, favorable mechanical properties of deposited material, extended range of materials and low dilution, laser cladding has become a well-known and established technology. Using its potential it was possible to close the gap of conventional techniques of parts repair and surface modification. Continuous improvements of laser sources, process strategy and technology have shift existing limits regarding weldability of materials, process speed, deposition rates and enabled new dimensions for laser micro cladding. Increased efficiency and cheaper prices for multi-kW Diode lasers have led to high power laser cladding processes (e.g. deposition rates of 8-9 kg/h for Inconel at 10 kW). Due to improved process strategies and increased feed rates (Ultra High Speed LMD – 100 m/min) laser cladding technologies are now getting interesting for rapid manufacturing, e. g. for production of Blisks (integrated and complex aero engine parts). Here reduced production cycles can be achieved. Adapted powder nozzles and optical heads allow the use of laser cladding processes for the treatment of inner diameters and areas with restricted access or critical environmental conditions.

Using single-mode Fiber lasers enabled new dimensions for micro processing, with track width down to 30 µm. Though working within the micro-scale is still a challenging task that requires special applications to justify increased efforts. Nevertheless laser micro cladding offers new chances for production and repair of micro tools, or surface modification of medical implants. Currently the feasibility of higher resolution and increased efficiency is under investigation as well.

Metallurgical and economic drawbacks can be impaired by application of an additional energy source for preheating. The most promising are Plasma-Augmented-Laser-Cladding (PALC) and Laser-Induction-Cladding (LIC). PALC has the advantage to offer the cheaper preheating energy. It also reaches low dilutions of <2 % and less than 10 % overspray. So far, this technology reaches less deposition rates of 1.8 kg/h and feed rates of 0.6 m/min with 1.8 kW laser power and 1.4 kW plasma power. The better investigation of the LIC process leads to high deposition rates of 14-16 kg/h with 8 kW laser power and 12 kW induction power. These powers have not yet been applied in the PALC process.

In laser guided and stabilized GMA-cladding (LGS-GMA) only 500 W of laser power have been used together with 1.6 kW arc power. Not only this 1:3 laser to arc ratio makes this technology the most economic. A GMA source also bears lower investment and operating cost than plasma or an induction source. The dilution of <5 % leads to high quality coatings.

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