Chapter 6 – Direct laser cladding, current status and future scope of application

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Abstract

During the last decades Direct Laser Cladding (DLC, also known as Laser Metal Deposition LMD) has become an established technique in many industrial fields for applying wear and corrosion protection layers on metallic surfaces as well as for the repair of high value added components. The most important application fields are die and tool making, turbine components for aero engines and power generation, machine components such as axes and gears and oil drilling components. Continuous wave lasers with a power up to 18 kW are used on automated machines with 3 or more axes, enabling 3D cladding. Mainly powder additive materials are used which implies a high diversity of available materials and offers the possibility to clad customized materials such as graded or nano-phased materials. In this respect powder feeding is a key factor for the quality of the layers as well as for the efficiency. The outstanding feature of DLC compared to other cladding techniques is the high precision which leads to a minimum heat input into the work piece and a very low distortion. Due to the high cooling rates a fine grained microstructure is achieved during solidification. A new development in laser cladding is micro cladding in a size range below 50 µm especially for electronic and medical applications. Furthermore, additive manufacturing is coming again into focus as a clean and resource-efficient method to manufacture and modify functional prototypes as well as unique and small lot parts.

Key words: Laser cladding, rapid solidification, repair, wear resistance, corrosion resistance, additive manufacturing

6.1 Introduction

In the early eighties of the last century with the advent of industrial high power lasers DLC was identified as an interesting field for researchers as a new technology for surface applications. Accompanied by the development of new laser sources (e.g. diode laser), improved beam quality and increased power efficiency laser cladding has become an established industrial technique during the last two decades for applying wear and corrosion protection layers on metallic surfaces as well as for the repair of high added value components. The most important application fields are die and tool making, turbine components for aero engines and power generation, machine components such as axes and gears and oil drilling components [1-8]. Furthermore, new applications are on the horizon such as micro cladding for electronic components [9-10] or the additive manufacturing of prototypes and even serial parts [11-12].

This chapter will highlight the fundamentals of laser cladding, give examples for the effect on microstructure and properties, show current applications and finally will give an outlook of the future.

6.2 Fundamentals of direct laser cladding

6.2.1 Laser beam sources and specific advantages of laser cladding

In the beginning, continuous wave CO_2- lasers were used for laser cladding since these were the first laser sources available with high power output (high power output in relation to laser cladding means at least a power of 500 W). During the years new laser sources such as Nd:YAG lasers, diode lasers, disc lasers and recently fiber lasers were developed with high power output and research and application of laser cladding have shifted almost completely to these sources.

Compared to CO_2-lasers the above mentioned laser sources exhibit an approx. ten times shorter wave length resulting in a much better absorption in metallic materials which cover most applications. Furthermore, the excellent beam quality of CO_2-lasers is usually not needed for laser cladding, which especially favours Nd:YAG and diode lasers. Laser cladding requires additive materials. These materials are either preplaced on the substrate before laser treatment (e.g. galvanizing, thermal spraying) or fed into the interaction zone as powder or wire. Since preplacing limits thickness and materials and requires an additional process which increases the costs, the direct laser cladding is established today. Laser cladding has specific features which makes it partly unique amongst the class of cladding techniques [1]:

- High precision cladding down to less than 100 µm in width and thickness of layers and volume
- Flexible tool for 3D cladding (only for powder based cladding)
- Minimized oxidation achievable even for sensitive materials like titanium
- Layer thickness ranging between 0.1 mm and 2 mm for a single layer, thicker layers achievable by multi-layer cladding
- Minimized heat input resulting in a small heat affected zone (HAZ) and low distortion of the bulk volume
- Suitable for all metallic materials and metal based composites
- High grade of automation possible thus achieving a high grade of reproducibility, reliability and robustness

6.3 Fundamentals of the laser cladding process

6.3.1 Fundamentals of laser remelting

The main physical fundamentals of any kind of laser remelting process are absorption of the laser radiation, heat conduction, melt pool dynamic and rapid solidification. Below the melt pool dynamic and the rapid solidification will be explained in more detail.

Melt pool dynamic

When a material is melted due to the absorbed energy of the laser radiation convective flows are created (provided that the melt pool is not covered by a solid oxide layer) which are related to temperature gradients on the surface of the melt pool. Assuming an intensity distribution with a maximum in the center of the laser beam a temperature gradient forms in radial direction since the temperature in the center of the melt pool is higher than at the edges (Figure 1, left).

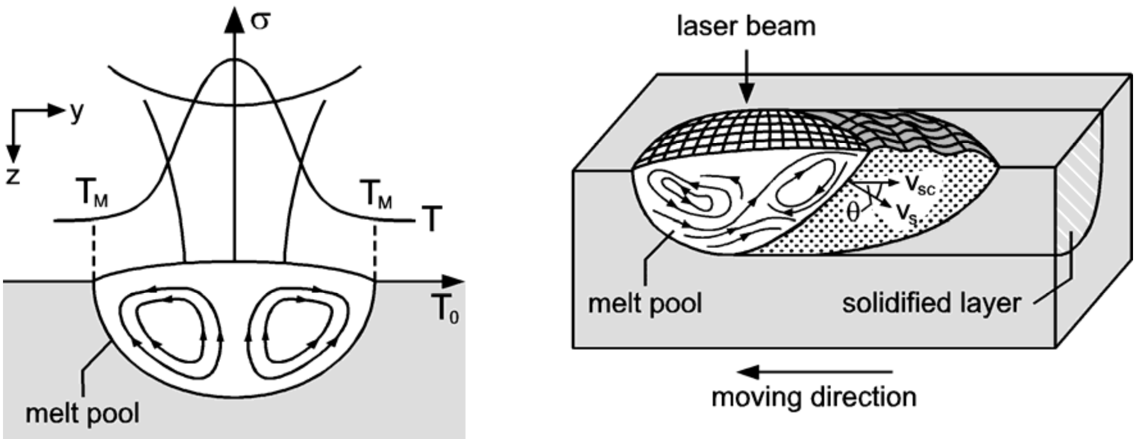


Figure 1: Schematic drawing of the melt pool convection during laser remelting for $d\sigma/dT < 0$; Left: Cross section of melt pool, right: Longitudinal section of the melt pool [13]

The temperature gradient causes a surface tension gradient since the surface tension σ is dependent on temperature. The gradient of σ in y-direction (Figure 1) can be written as follows:

$$\frac{\partial \sigma}{\partial y} = \frac{\partial \sigma \cdot \partial T}{\partial T \cdot \partial y}$$

For dσ/dT < 0 a tension field is formed with low tension in the center and high tension at the edges of the melt pool. This gradient causes a melt flow from the center to the edges. At liquid/solid boundary the flow of material is directed down. In the center of the melt pool the material flow rises to the surface again. The flow of the material and the thermal expansion causes a deformation of the melt pool (Figure 1, right). The convective flow driven by the surface tension gradient is known as Marangoni convection. The flow velocity is in the range of several meters per second which is 2-3 orders of magnitudes higher than the typical velocity during laser remelting (0.005-0.05 m/s).

The precondition for Marangoni convection is a free surface on the melt pool. A solid layer (e. g. oxide layer) prevents the formation of the convective flows. Therefore the shielding of the melt pool is of great significance in this respect.

Rapid cooling

The solidification morphology of a metal can be planar, cellular or dendritic (Figure 2). A planar solidification occurs when the real temperature of the melt is greater than the liquidus temperature of the material. If the planar solidification forms a stochastic bulge this would grow into a region of increased temperature which causes the breakdown of the bulge. Planar solidification is of significance mainly for single crystal growth, it requires either a metal with high purity or extremely high values of temperature gradient or solidification rate. If a metal contains impurities or alloying elements the constitutional undercooling plays an important role.

Undercooling requires a concentration gradient at the solidification front which is given for laser cladding. Under these conditions the melt at the solidification front enriches with impurity and alloying elements during solidification. As the liquid concentration decreases with distance from the solid /liquid interface, the liquidus temperature T_{liq} will increase. In case that the gradient of the actual temperature distribution in the melt pool is smaller than the gradient of the liquidus temperature a constitutional undercooling occurs [14]. A stochastic perturbation is now growing into an undercooled melt [14]. The planar solidification front breaks down and a dendritic solidification occurs. The growth morphology can be cellular-dendritic (also known as cellular) or dendritic. A cellular structure is generated when the crystals grow in columns without formation of secondary dendrite arms. If secondary or even ternary dendrite arms form the structure is called dendritic. Which morphology forms depends mainly on the solidification rate R.

Figure 2 shows the correlation between temperature gradient G and solidification rate v_s. The limits of cellular and dendritic growth are determined by the constitutional undercooling and the absolute stability which is characterized by a critical solidification rate which leads to a planar solidification independently from the temperature gradient.

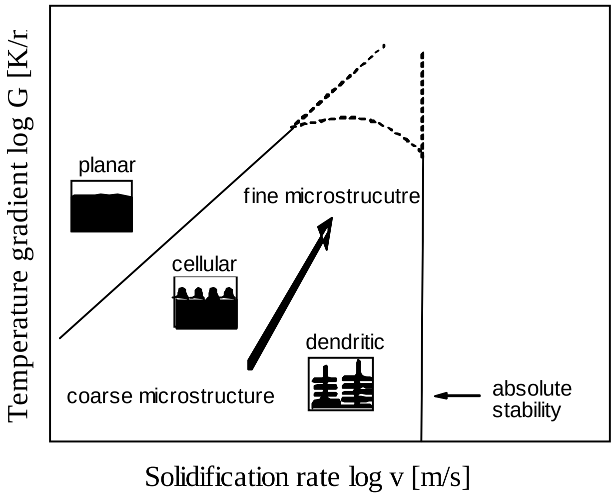


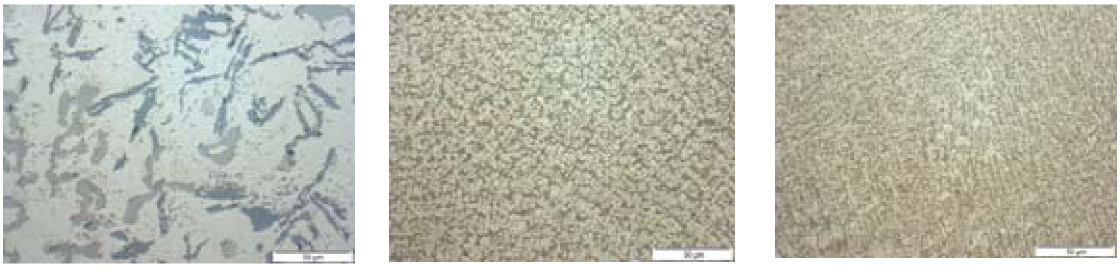
Figure 2: Schematic drawing of the solidification morphology as a function of solidification rate and temperature gradient [14]

The width of the melt pool generated during laser remelting is typically 0.1-4 mm, the melted depth in the range of 0.1 – 2 mm. Therefore the volume of the melt pool is small compared to the whole volume of the work piece. When the laser beam moves on or is shut down the heat is flowing rapidly into the cold bulk volume (self quenching). The melt solidified with high cooling rates (10^2 – 10^6 K/s) which are determined by the process parameters, the thermo-physical properties of the material and the geometry of the work piece.

Cooling rates up to 10^4 K/s lead to a cellular or dendritic solidification which is much finer than for conventional casting. The formation of metastable phases depends on the material. For some alloys even an amorphous solidification can be achieved [13-15].

The effect of grain refinement and homogenization is shown in
for the aluminum alloy AlSi10Mg. A scan velocity of 0.5 m/min leads to a significant refinement. For a velocity of v_v = 5 m/min a further refinement is observed. The rapid cooling

leads to a very fine precipitation of the Si phase which causes an increase in hardness. Refinement and hardness increase can improve the wear as well as the corrosion resistance.



85-105 HV0.1 128-130 HV0.1 135-140 HV0.1

Figure 3: Grain refinement in the alloy AlSi10Mg after laser remelting [16], P = 1 kW, d_L = 1 mm; left: substrate, centre: v_v = 0.5 m/min, right: v_v = 5 m/min

6.3.2 Principle and material requirements for the laser cladding process

Laser cladding involves the melting of an additive material and the melting of a thin layer of the substrate (**Fehler! Verweisquelle konnte nicht gefunden werden.**). The dilution between the additive material and the substrate is required to form a metallurgical bonding. However, this zone should be as small as possible (see Figure 4) to minimize the contamination of the clad layer with the elements of the substrate and thus to retain the desired properties of the layer. Additionally a heat affected zone (HAZ, typical in a depth of 100 to 1000 µm, Figure 4) is formed. Depending on the material the time-temperature-profile in the HAZ can lead to changes in the microstructure (e.g. hardening or softening in hardenable steels). This is essential to ensure the metallurgical bonding between substrate and clad layer. The additive material can either be precoated onto the substrate or directly fed into the interaction zone. Precoating, e.g. by thermal spraying or galvanic deposition, is limited to certain materials and simple geometries.

Furthermore, since two coating processes are required, it is time-consuming and expensive and thus only rarely used in industry. The more flexible and effective method is the direct feed of the additive material into the interaction zone. The additive material can be a powder, a wire or a viscous mixture of binder and powder (suspension, paste). Powders are the most beneficial regarding the variety of materials and the flexibility of the process (e.g. for 3D cladding) and therefore the mostly used in industrial applications. The requirement for the powders is a particle size between 20 and 200 µm (micro cladding requires smaller particles, see chapter 5.1) which is also typical for other cladding techniques. The powder flow ability is another important feature since laser cladding requires very steady powder feed rates at low values (typical are a few g/min). Therefore spherical powders are the most beneficial but blocky forms can also be used. In summary there is no need for most applications to use specific laser cladding powders. Almost all powders produced for other cladding techniques or for thermal spraying can also be used for laser cladding as well as the feeding devices.

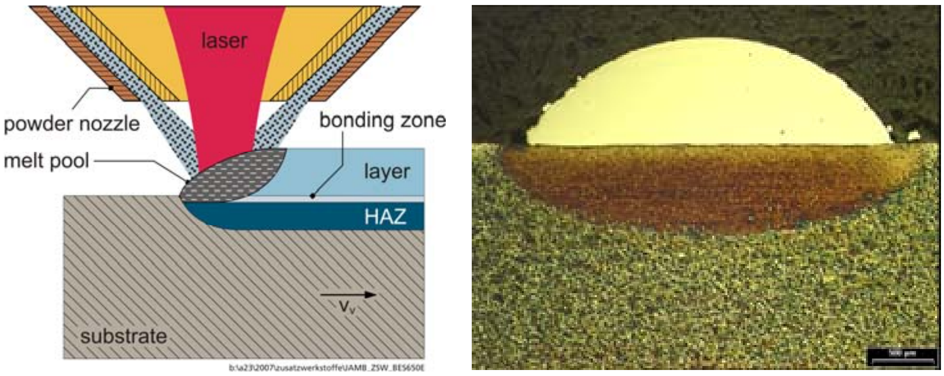


Figure 4: Schematic drawing of the laser cladding process with coaxial powder injection (left); cross section of a laser cladded layer (Stellite 21) on a steel substrate (right)

6.3.3 Powder injection

Powder feeding is a key factor in laser cladding. The quality of the powder gas stream determines the powder efficiency and the shielding of the melt pool .Three different concepts of powder injection can be used (Figure 5) [17]:

- Lateral powder injection (a single powder gas stream is fed lateral into the laser beam)
- Continuous coaxial powder injection (a powder gas stream cone is produced which encloses the laser beam)
- Discontinuous coaxial powder injection (three or more powder gas streams are fed coaxial to the laser beam)

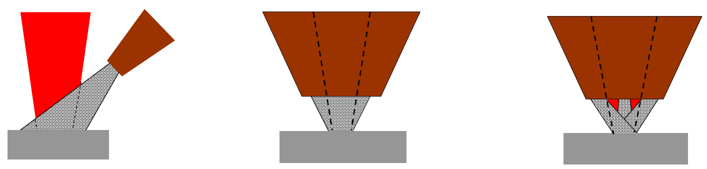


Figure 5: Different powder feeding concepts: left: lateral, center: continuous coaxial, right: discontinuous coaxial

Lateral powder injection

For the lateral powder injection the nozzle is positioned lateral to the laser beam. The position is determined by the angle between nozzle and work piece (typical values α = 45-70 °) and the distance between nozzle tip and work piece (typical values l = 8-15 mm). A nozzle designed by Fraunhofer ILT and the powder gas stream is shown in Figure 6 (left). The lateral powder injection is not suitable for 3D cladding since the efficiency is dependent of the feeding direction (see also **Fehler! Verweisquelle konnte nicht gefunden werden.**). Backhand cladding with a dragging angle (flow direction of the particles is the same as the moving direction of the work piece) and forehand cladding with a pushing angle (flow direction of the particles is opposite to the moving direction of the work piece) lead to a different powder efficiency and thus to a different layer thickness. The lateral injection is beneficial for rotationally symmetric parts where cladding is performed in one direction or for areas with difficult accessibility (e.g. grooves). The width of the lateral nozzles can be minimized to 2-3 mm. For a track width between 0.5 and 5 mm a circular cross section of the opening with a diameter of 1.5 to 3.5 mm is adequate (see Figure 6, centre). Cladding of broad tracks (5 – 25 mm) requires a rectangular cross section of the opening (e.g. 1.5 x 15 mm^2, see Figure 6, left). Since the nozzle is positioned close to the melt pool it is exposed to laser beam reflections. Therefore the nozzle should be water-cooled, to ensure long-term operation without any damage.

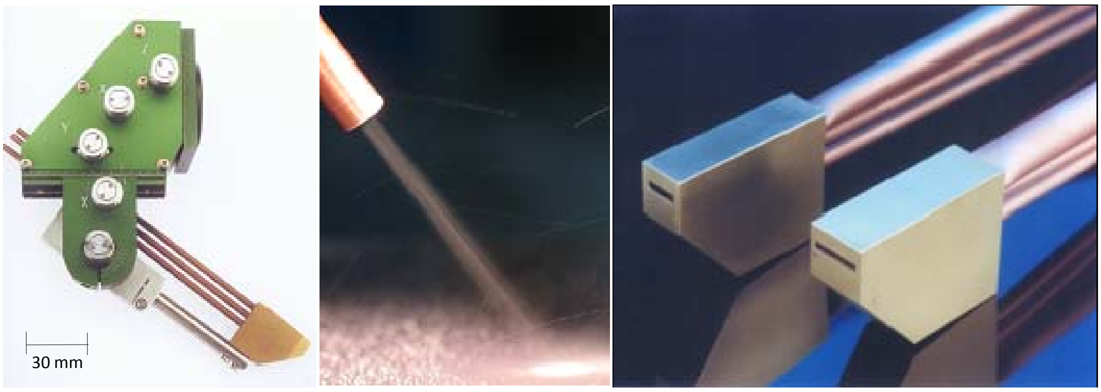


Figure 6: Lateral powder feed nozzle (left), powder gas stream (center); lateral nozzles with rectangular design for broad layers (right)

Continuous coaxial powder injection

In continuous coaxial powder injection (below named “coaxial powder injection”) a powder stream cone encloses the laser beam. Figure 7 shows a coaxial powder injection nozzle. For long-term operation it is essential that the nozzle is water-cooled. The powder stream cone is produced as follows: The powder stream of the powder feed unit is split into three identical streams which are fed into a ring-shaped expansion chamber inside the nozzle. In this chamber a homogenous “powder cloud” forms which then is fed into a cone-shaped slit. The powder leaves the nozzle in the form of a hollow cone. The diameter of the powder stream focus can be adapted to the laser beam area on the work piece. Depending on process parameters such as particle size, gas flow rate and powder mass flow, powder stream diameters below 500 µm can be achieved allowing a very high efficiency (up to 90 %).

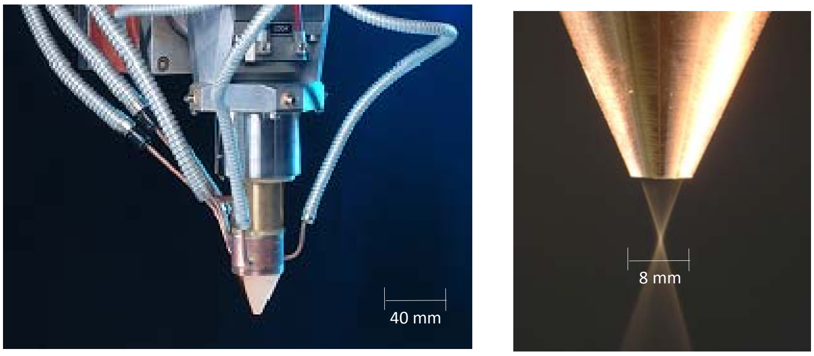


Figure 7: Continuous coaxial powder feed nozzle mounted on a laser optic (left) and powder gas stream (right)

The major advantage of coaxial powder injection compared to off-axis powder injection is the potential for 3D-cladding. However, tilting of the nozzle is restricted. Since the homogeneity of the powder stream cone depends on the powder distribution inside the expansion chamber of the nozzle gravity will affect the powder stream when the nozzle is tilted. Experiments have shown that a maximum tilt angle of approx. 20 ° can be accepted without significant effects on the geometry and quality of the clad layer.

Discontinuous coaxial powder injection

In discontinuous coaxial powder injection several individual powder streams are distributed around the laser beam, thus forming a powder stream focus. Figure 8 shows a nozzle with three individual powder streams (below named as “three way nozzle”). The core diameter of the powder stream focus depends on the angle between the individual powder streams, the diameter of the nozzle holes, the distance between nozzle tip and powder stream focus, the powder feed rate and the particle size. The major advantage of the three way nozzle is the potential for 3D-cladding including the potential to tilt the nozzle up to 180 °.

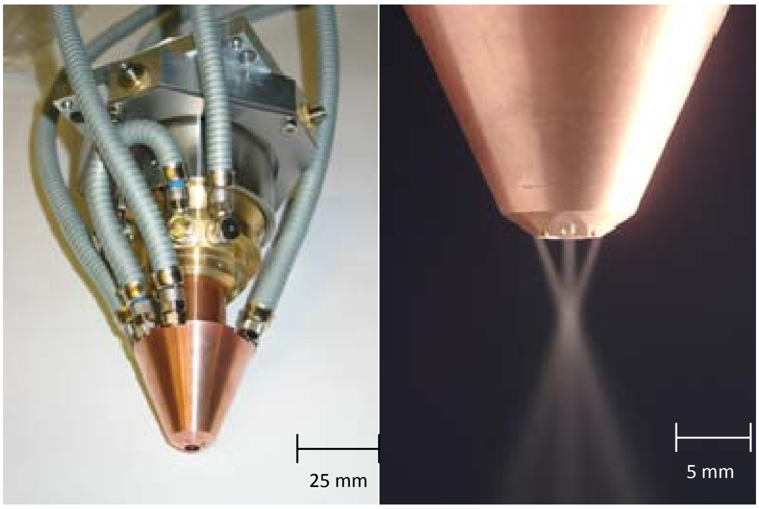


Figure 8: Discontinuous (three-way) powder injection nozzle (left) and powder gas streams (right)

For reactive materials an additional shroud can be used to improve the shielding of the melt pool from oxidation. Examples are shown in Figure 9.

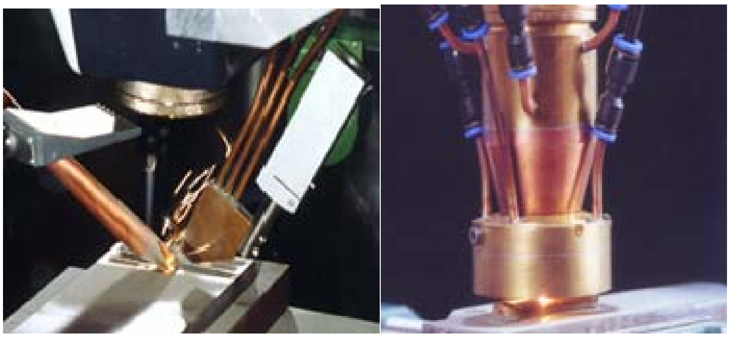


Figure 9: Additional shrouds for an improved shielding from oxidation during laser cladding; off-axis shroud (left) and coaxial shroud (right)

The powder feeding nozzles shown above are adapted to standard laser beam optics typical with a focal distance of 150-300 mm. However, laser cladding of internal areas cannot be done with conventional processing heads because of the limited accessibility which is restricted to an internal diameter of approx. 100 mm. For smaller diameters miniaturized heads are required with integrated optics and powder feed nozzles. Figure 10 shows a processing head suitable for internal diameters larger than 50 mm and a depth up to 500 mm. The head is laid out for a 2 kW diode laser.

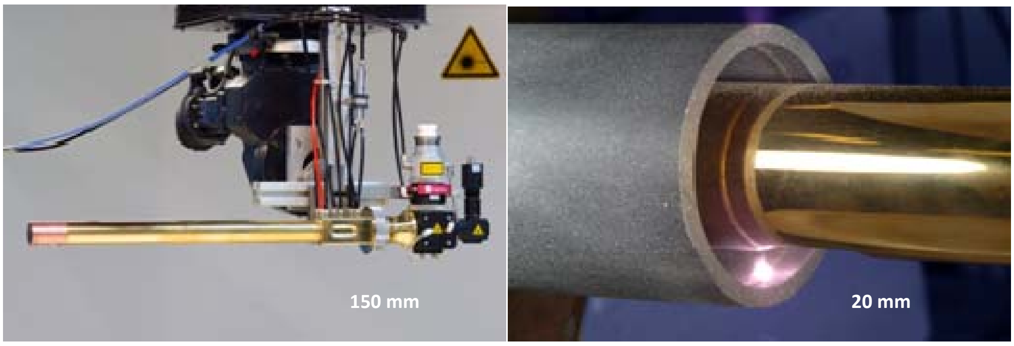


Figure 10: Internal cladding head with integrated optic and powder feed nozzle (left); cladding process (right)

The fields of application for the different powder feeding nozzles according to their specific features are summarized in .

Table 1.

Table 1: Fields of application for the different powder feeding nozzles

Powder feed nozzles	**Fields and examples of applications**
Lateral powder feed nozzle	2D cladding, preferred for rotationally symmetric parts, areas with limited accessibility Examples: Crank shaft bearing, valve, piston nut
Coaxial powder feeding nozzle	2D and 3D cladding, preferred for high precision cladding of sensitive materials Examples: repair of all kind of turbine parts (seals, aerofoil tips, housings, ..), repair or modification of injection moulding tools
Three-way powder nozzle	2D and 3D cladding, preferred for thick layers (high laser power) Examples: Repair or modification of forming and casting tools
Internal cladding head	2D cladding of internal areas (d > 25 mm) Examples: Wear resistance of bearing for offshore drilling equipment

6.4 Material aspects of laser cladding

6.4.1 Materials

All metallic based materials can be used for DLC, such as pure metals (e.g. Ag, Au for electric contacts, Zn for corrosion protection), alloys (e.g. Co-, Ni-, Ti- and Fe-based alloys for wear protection and repair) and hard metals (e.g. WC/Ni for wear protection). A selected list of materials is shown in Table 2.

Table 2: Selected materials and applications for DLC

Materials group for laser cladding	Examples of metals and alloys	Functions	Applications
Pure metals	Au, Ag, Zn	Electric contacts, corrosion protection	Fuel cell, electric switch, edge protection of sheets
Co-based alloys	Stellite 21, Stellite 6	Wear protection, repair	Diesel engine parts, bearings
Ni-based alloy	NiCrBSi-alloys, nickel super alloys	Wear protection, repair	Bearings, repair of turbine blades
Fe-based alloys	High alloyed hot and cold working steels (X38CrMoV5-1), PM steels (CPM 420 V), stainless steel (316L)	Wear and corrosion protection, repair	Machine parts, forming tools moulds, forging tools, bearings
Al-based alloys	AlSi alloys (AlSi20, AlSi10Mg)	Wear protection	Automotive magnesium parts
Ti-based alloys	TiAl6V4, Ti6242	Repair	Turbine blades and housings
Hard metals	WC/Ni (60/40), WC/Co	Wear protection	Bearings, rollers

Even more customized new materials can be created prior to or during laser cladding. Prior to cladding different powder material can be mixed in a tumbling mixer or by ball milling. In-situ new alloys can be formed in the cladding process by feeding two components simultaneously [18].

6.4.2 Microstructure

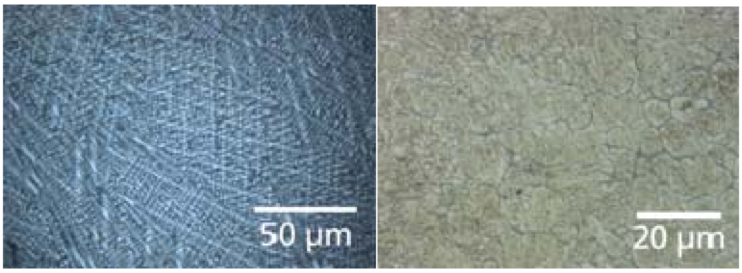
Since laser cladding is a melting process the resulting microstructure is always a cast structure but compared to conventional casting the grain or dendrite size is orders of magnitude smaller. The most commonly is a dendritic structure as shown in

Figure 11 (top left). But also an equiaxed structure can occur (

Figure 11, top right). In high alloyed materials a dispersed microstructure with hard precipitations in a metallic matrix (

Figure 11, down left) can solidify. Such structures can also be produced by using mixed powders of a metal and a high melting point material (carbide, nitride, boride,

Figure 11, down right). Which morphology and phase composition is formed depends mainly by the solidification parameters (determined by process parameters such as laser power and velocity) and by the chemical composition of the material.



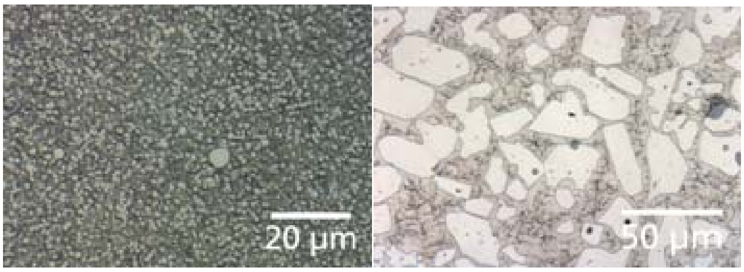


Figure 11: Various solidified structures of laser cladded layers; Dendritic structure of Stellite 21 (top left); Cellular structure of high alloyed steel X100CrMoV5-1 (top right); Primary solidified vanadium carbides in a martensitic matrix (FeCrV, down left); Dispersed structure of a TiAl alloy with embedded TiB_2 particles (down right)

6.5 Applications

Today's most important application for direct laser cladding is the repair and the modification of high value parts such as moulds, tools or turbine and engine components [19-24]. In the field of wear and corrosion protection laser cladding is used only for unique parts and small-lot production such as oil drilling components, engine components of big diesel engines. For mass production the technology is still too costly compared to other cladding techniques. Below some actual applications are presented.

Repair of moulds and dies

Direct laser cladding is well established for the repair of injection moulds [22] and the repair of dies for metal sheet forming is getting more and more established [23]. Laser cladding allows the repair of critical areas e.g. near polished or ground (chemically etched) surfaces which are not allowed to be affected by the heat input. Figure 12 shows a repaired car lamp mould. The mould was worn out in the front area and a layer of 0.15 mm thickness has been applied. No damage was allowed on the polished top surface. This type of repair cannot be performed with any other welding techniques (e.g. TIG welding).

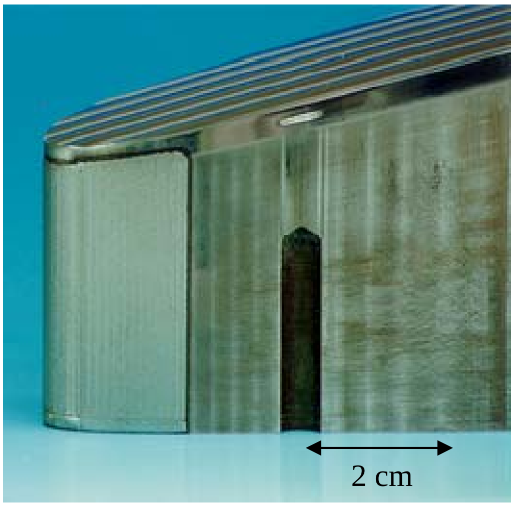


Figure 12: Repaired area of a worn out lamp mould (automotive application) [24]

Modification of moulds

Once a mould has been manufactured design changes where material has to be added are difficult to carry out. In the worst case a new mould has to be manufactured which is time and money consuming. By direct laser cladding the missing material can be added near net shape in a much shorter time. The mould is finished by milling processes to the final geometry and can be used in production again. Figure 13 shows an example for the modification of an injection mould for a car lamp housing. A volume of several mm thickness was added by multi-layer cladding.

Figure 13: Modification of an injection mould for a car lamp housing (material: hot working steel) [24]

Repair of turbine components for aero engines and power generation

The repair of turbine components (sealing, housing, turbine blades, vanes, etc) is performed with conventional techniques like TIG welding, PTA welding and thermal spraying. In the last years, direct laser cladding has been established as an alternative technology [24]. Figure 14 shows the repaired rotating seals on a cooling plate for a gas turbine (nickel based alloy). Multiple layers were applied on a sealing with a width of 0.6 mm.

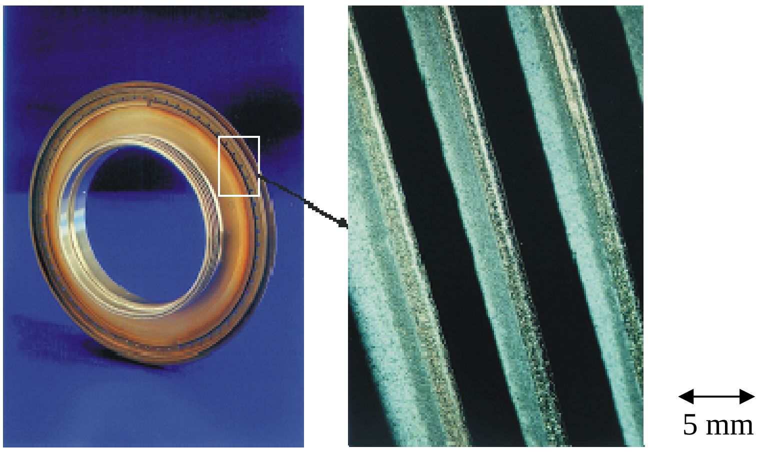


Figure 14: Repaired rotating seal of a cooling plate for a gas turbine (Ni based alloy) [26]

Gears and axes

In the area of heavy machines (e.g. ship engines, offshore drilling equipment) large and valuable components like shafts, gears and gearboxes are cladded for the repair or the wear protection. Figure 15 shows a repaired axis of a centrifuge and Figure 16 the repair process of a gear component with DLC.

Figure 15: Repair of centrifuge axis [21]

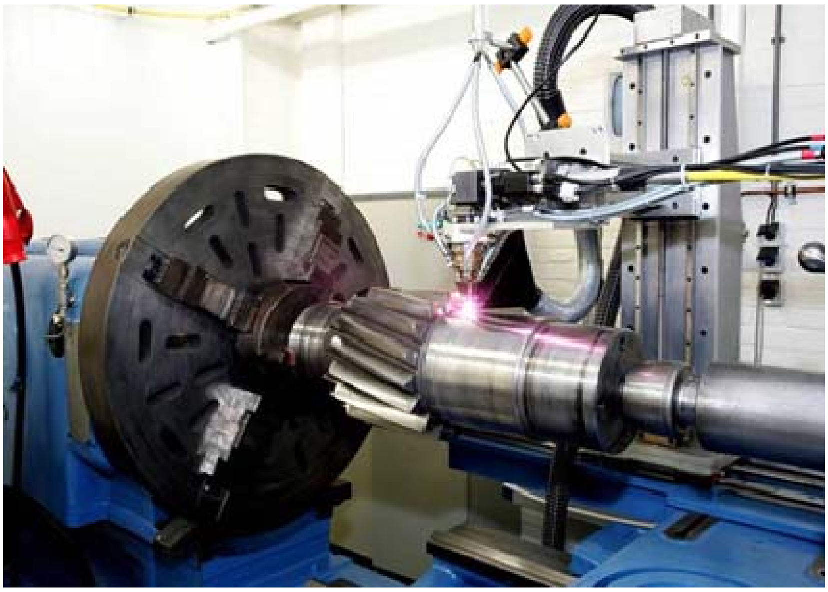


Figure 16: Repair of gear components with DLC (source: Stork Gears & Services) [17]

Wear protection of valves for power plants

Valves for cooling circuits of power plants are exposed to high temperatures (350 °C) and high pressure (300 bar) and materials with a high resistance against wear and corrosion have to be used. Among other parts gate valves which are activated in case of a pipe burst have to be cladded with an iron-based alloy which consists of a duplex microstructure of ferrite and austenite. To provide the best performance a ferrite fraction of 50% is required (Figure 17). Since this can only be achieved by rapid cooling laser cladding is superior to the other cladding techniques. A 2 kW diode laser was used for the cladding. The layer thickness is around 1 mm. After cladding the layer is machined to the final thickness and the part is heat treated to further increase the hardness. The valves have been running for several years in a power plant.

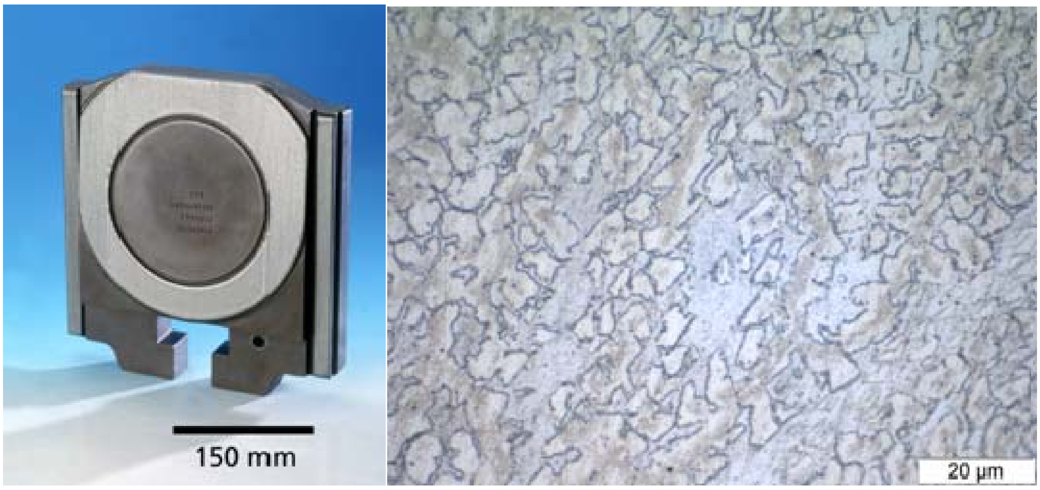


Figure 17: Laser cladded gate valve (left) and microstructure of the clad layer with ferrite (blue) and austenite (grey) [Annual Report of Fraunhofer ILT 2005]

6.6 Future trends for laser cladding

6.6.1 Micro laser cladding

New cw (continuous wave) laser sources like fibre and disk lasers offer the possibility to produce laser cladded structures below 10 µm thickness and widths below 100 µm. In the last years effort has been made to downscale the laser cladding process [9, 10]. One major task is the feeding of fine powders with a grain size in the range of 10 µm. These powders cannot be fed by conventional powder feeders due to the tendency to agglomerate which results in a significant loss in flow ability. New concepts of powder feeding have to be used like brush feeders [10]. Furthermore, the feeding nozzles have to be adopted to avoid any blockage during the cladding process. E.g. for lateral powder feeding the internal diameter of the nozzle must be well below 500 µm. Potential applications (Figure 18, Figure 40: Increasing x-ray visibility by depositing tantalum on nitinol stents

Figure 41: Selective DLC of gold contacts on stainless steel switches

Figure 42: Selective LMD of gold contacts on bi-polar plates for fuel cells

Figure 43, Figure 44) are medical engineering, electronic devices and new power generation technologies (fuel cell, solar cell). One of the most interesting applications is the cladding of single gold contacts on a bi-polar plate instead of coating the plate completely with gold. This would reduce the consumption of gold by a factor of 100.

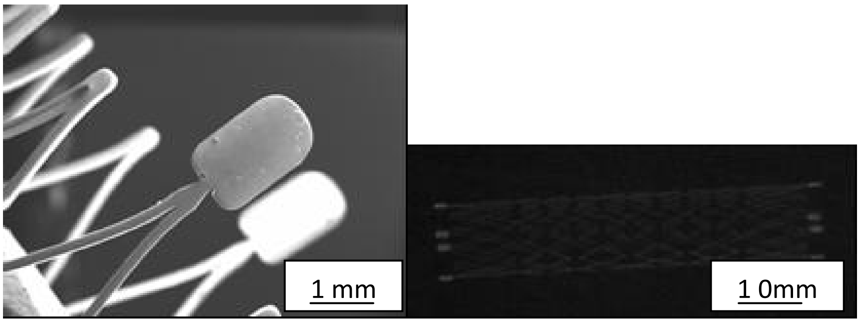


Figure 18: Increasing x-ray visibility by depositing tantalum on nitinol stents

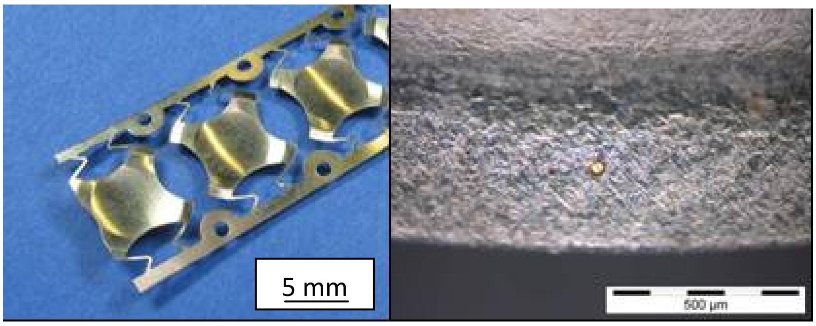


Figure 19: Selective DLC of gold contacts on stainless steel switches

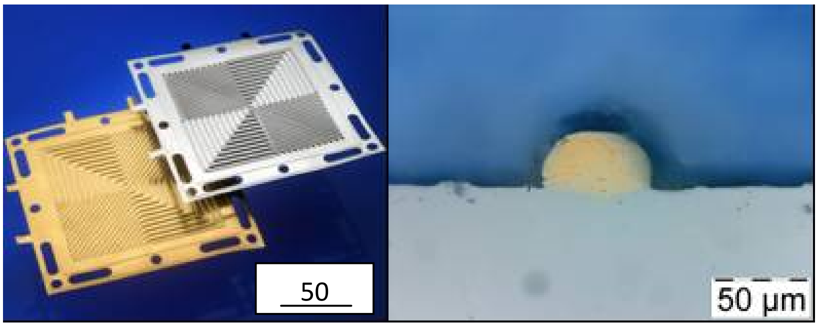


Figure 20: Selective LMD of gold contacts on bi-polar plates for fuel cells

6.6.2 Novel materials

Laser cladding can also be used to create new materials with customized properties during the cladding process. An example is a graded layer [19, 26]. Changing the composition of the additive material in each layer can lead to a graded layer by multi-layer cladding. This can be used for combinations of materials with different thermo-physical properties like copper and steel for mould cores of injection tools. The copper provides a high thermal conductivity to dissipate the heat very quickly and the steel layer provides the wear resistance for the required life cycle. With the gradient thermally induced stresses can be minimized during operation leading to an increase in life time.

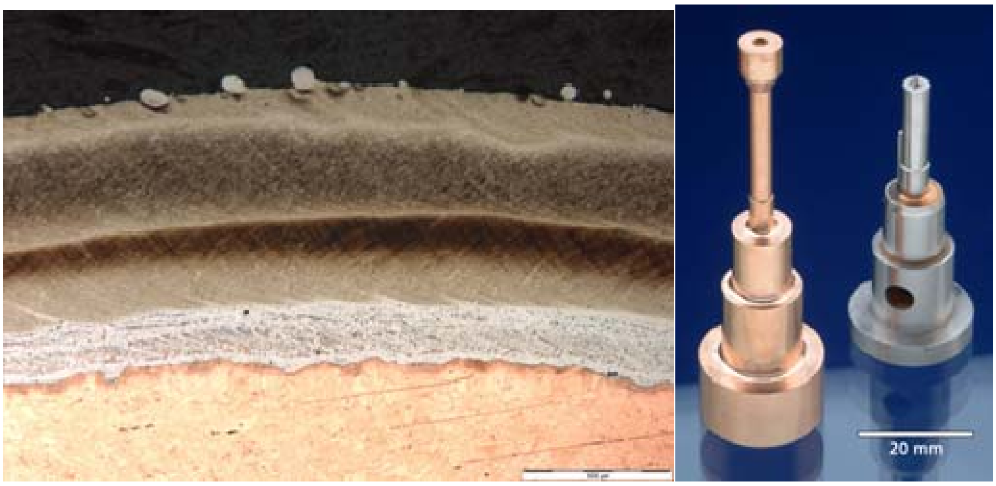


Figure 21: Steel based graded layer on a copper substrate (left); potential application: tool inserts for injection molding

Another new approach is the cladding of metal-matrix-composites with ceramic nano particles with a size of 20-50 nm [27-28]. The nano particles (e.g. Al_2O_3, Y_2O_3) act as nuclei during solidification leading to an extremely fine microstructure which can prohibit cracking and improve ductility. Furthermore, the fine particles can improve high temperature strength and creep resistance by blocking the dislocation movement. Compared to micro particles these effects are much greater and only small addition of particles is required (0.5-2 Vol.-%).

6.7 Additive manufacturing

Additive manufacturing by laser cladding is another feature which arises (again) more and more interest in industry. The first attempts were made in USA more than 10 years ago [29]. However, at that time the equipment and the process technology was not developed to make it a profitable manufacturing technique. Nowadays efficient high power lasers, improved powder feeding nozzles, software tools for offline programming and the increased demand for a customized and individual production led to new research activities [11, 12, 30]. In the future additive manufacturing can be used for functional prototypes as well as for unique and small lot parts (e.g. blades, BLISKs, housings for turbine engines, medical implants). Figure 22 shows blades that have been manufactured on a shaft directly from CAD data as a demonstrator.

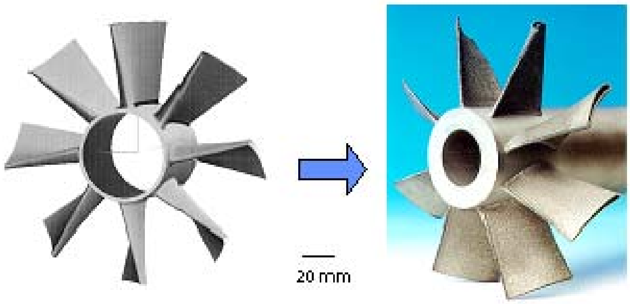


Figure 22: Additive manufacturing of blades on a shaft

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Figure captions

Figure 23: Schematic drawing of the melt pool convection during laser remelting for $d\sigma/dT < 0$; Left: Cross section of melt pool, right: Longitudinal section of the melt pool [13]

Figure 24: Schematic drawing of the solidification morphology as a function of solidification rate and temperature gradient [14]

Figure 25: Grain refinement in the alloy AlSi10Mg after laser remelting [16], P = 1 kW, d_L = 1 mm; left: substrate, centre: v_v = 0,5 m/min, right: v_v = 5 m/min

Figure 26: Schematic drawing of the laser cladding process with coaxial powder injection (left); cross section of a laser cladded layer (Stellite 21) on a steel substrate (right)

Figure 27: Different powder feeding concepts: left: lateral, center: continuous coaxial, right: discontinuous coaxial

Figure 28: Lateral powder feed nozzle (left), powder gas stream (center); lateral nozzles with rectangular design for broad layers (right)

Figure 29: Continuous coaxial powder feed nozzle mounted on a laser optic (left) and powder gas stream (right)

Figure 30: Discontinuous (three-way) powder injection nozzle (left) and powder gas streams (right)

Figure 31: Additional shrouds for an improved shielding from oxidation during laser cladding; off-axis shroud (left) and coaxial shroud (right)