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Laser Cladding vs. Laser Alloying – a Comparative Study

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ABSTRACT: Both laser cladding and laser alloying are related techniques for surface modifications of tools – mainly used for increasing wear and/or corrosion resistance locally. While laser cladding is nowadays already well established but has certain competitors (e.g. PTA-welding and flame gunning), laser alloying is a unique technique with currently only one single industrial implementation but lots of prospective applications. This article will introduce the principles and differences of laser cladding and alloying and give a brief synopsis of the advantages compared to its competitive techniques. Finally a few selected applications are presented.

1. LASER CLADDING

1.1 Principles of laser cladding

Laser cladding nowadays is a well established technique for surface modification of metallic tools and is mainly used when abrasive and/or corrosive behaviour is of interest. Its principle is quite simple, as illustrated in Fig. 1: metallic powder is inserted into a laser beam impinging onto the tool surface at rather high incidence angle.

Fig. 1: Principle of laser cladding

The used laser power is rather low and the interaction times are quite high compared to other laser processes like e.g. laser welding. The powder is inserted into the weld pool and is completely molten due the comparable long lifetime of the weld pool, thus forming a surface cladding with metallurgical bonding to the tool. In contrary to a plasma arc or a flame the laser beam is fixed in orientation, time-invariant and not influenced by the base material. Therefore it can be controlled very precisely in its dimensions, power density and thus in its energy input per unit length, allowing the realisation of small subtle claddings and/or claddings with minimal intermixture between base material and cladding.

It should be mentioned that the cladding material is not necessarily in powder form – it may also be a solid rod. But since cladding using solid materials is quite seldom used, this technology shall not be discussed further. Using powder technology the powder is supplied by a reservoir and delivered by a powder conveyor and further through a hose via a gas stream (typically Argon gas) to the laser head. The last stage is typically a coaxial nozzle which ideally produces a concentric homogeneous powder flow. Fig. 2 shows a typical setup of such a conveyor, while Fig. 3 shows the nozzle.
By variation of laser power, focus size, powder rate, cladding velocity, and trail distance a wide range of different cladding tracks from a few tenth of a millimetre to several millimetres can be produced. By cladding one layer onto another also different layer thicknesses can be achieved. While this is a rather expensive technique for cladding simple surfaces compared to PTA-welding or flame gunning, it is self-evident that complex surface topologies and/or subtle cladding tracks can only be achieved using the laser cladding technique in combination with CNC-machines or with automated robots. More detailed discussions of this technique can be found elsewhere [1-4].

A wide variety of commercial metallic or ceramic powders nowadays is available. Those powders were developed for the use in PTA welding and flame gunning, but are also fit for use in laser cladding, because the intended functional properties are the same. However, there are certain limitations:

An essential aspect of laser cladding is the achievement of a strong bond over the entire interface between the substrate and the cladding. Therefore certain combinations of cladding and substrate – especially ceramic claddings – are very difficult to achieve. The application of sandwich layers between the intended surface coating and the substrate or the use of binders can be helpful, as well as pre-heating of the substrate. The basic requirement is that the two coupling materials are soluble in each other and there is the question of phase equilibrium between them [5]. For most alloys this requirement poses no difficulty, but pure metals can sometimes be difficult to clad on top of each other. Aluminium and cobalt, for instance, are not soluble in each other – phase equilibrium exists only between aluminium and some intermetallics or between cobalt and other intermetallics, thus the only way to bond them together is to sandwich them with intermetallics. Multilayers can also be applied in metal-metal combinations to reduce residual stress due to repeated heat input [6] and to form a functionally gradient layer with a low dilution and the intended properties on top [7].

Convection is the single most important factor influencing the geometry of the weld pool, including pool shape and ripples. It is also the main mechanism for intermixture of cladding material with the substrate [8-10]. Since the microstructure of the cladding strongly depends on the degree of mixing and the cooling rates afterwards, parameters controlling these mechanisms are important to the laser cladding process [11]. The main material properties that influence these mechanisms are the melting point and the thermal conductivity. The melting point of the substrate must preferably be higher than that of the coating material, otherwise it is possible that during solidification and subsequent cooling of the clad layer, the substrate region just underneath it can be heated to a temperature over the melting point and, due to the stress of the clad above, hot tear will occur along this region [5] and result in porosity along the interface. The formation of cracks in the clad layer is mainly caused by the thermal stress created by the high thermal gradient built up during cooling, and by the difference between the thermal expansion coefficients. Especially layers that are characterised by the presence of hard and brittle particles, such as carbides, are prone to cracking. Ceramic layers are also vulnerable to cracking, because of their limited ductility combined with their difference in thermal expansion coefficients to metals. Residual
stresses can be reduced by a reduction of the cooling rate, which can be achieved by preheating.

It goes without saying that the goal is always a pore- and crack-free cladding with continuous bonding to the substrate. An extensive listing of combinations of powder and substrate found in literature is given in [2].

1.2 Applications of laser cladding

1.2.1 Laser cladding of finned walls used as heat exchangers in incineration plants

The central chambers in incineration plants are backed with finned walls made of stainless steel to achieve the water circulation for heat exchanging. Due to the very high temperatures these components are especially prone to corrosion. To increase their corrosion resistance, experiments have been made to clad them with a special Ni-based superalloy (2.4846 = NiCr22Mo9Nb = “Inconel 625”), since Ni-based alloys are well known to give additional protection against corrosion. Fig. 4 shows a sketch of the profile of such components, while Fig. 5 shows a photograph of one “brick” of the finned wall. Because of their complex surface and the size of the “bricks”, challenges were manifold.

First, since parts of the surface are in rather steep angle against horizontal, it had to be assured during preliminary experiments that the cladding would not trickle down during the process, which could be achieved by tilting the whole component. The major challenge was the thermal tension occurring during the process. While this was negligible in the preliminary experiments on small parts, it resulted in immense torsions during cladding a large brick. Although this could be repaired by stress-relieving annealing afterwards, the occurring forces made a powerful fixture necessary. The still occurring torsions – in all dimensions – also made it impossible to clad the whole brick in one step, since the geometrical conditions changed permanently. Solution was found in cladding one small part of the surface after another and fixing inhomogeneities at the boundaries afterwards, which luckily was possible with this combination of cladding and base material. Fig. 6 gives an impression of the forces and tensions arising, while Fig. 7 shows the final result of a cladded brick.
Cladded “bricks” are currently installed for a field test in an incineration plant together with other “bricks” and performing quite well until now.

1.2.2 Laser cladding of drilling heads used in oilfield technology

Nowadays oil field technology makes use of moving the drill strings in turns towards the oil field. Due to the sensors installed in immediate vicinity to the drilling head the base material has to be non-magnetic, which is fulfilled by high-alloyed Chromium-Manganese-steels which have high corrosion resistance and ductility. However, their wear resistance is quite low, which results in unacceptable high wear at field conditions. Up to several years ago this problem was overcome by means of brazing hard metal platelets onto the surface, which had the disadvantages of high thermal load, impossible automation and the need of subsequent machining. This fact and the increasing complexity of drilling head surfaces led to the development of a laser cladding process that would be ready for serial production.

The necessary development steps consisted of (Fig. 8 and Fig. 9):

- Process development including metallurgical processes.
- Testing of reproducibility and long-term stability of the process with geometrically simple drill string components.
- Testing and optimisation with drill string components having complex surface shapes. This included testing of different geometrical cladding strategies and the solving of CAD / CAM / CNC challenges.

The used cladding material was a combination of a Ni-based alloy and spherical tungsten carbides. The cladding process was controlled in a way that only the Ni-based alloy got molten completely whereas the tungsten carbides mostly remained in their original solid state. The whole layer is designed as a multilayer allowing a gradation of the properties. To improve bonding to the base material and to avoid peeling off, the first layer is a so-called buffer consisting of only the soft highly corrosive-resistant Ni-based alloy. On top of it any desired number of layers can be added, in our case three, as shown in Fig. 10. The separation into different layers allows the compliance with the required narrow tolerances of ± 0.2 mm, even when the total layer thickness goes up to several millimetres. The resulting surface roughness is very low, thus avoiding the need of grinding afterwards.

The high wear resistance is due to the high hardness of the tungsten carbides (≈ 2500 HV) in combination with the grain encapsulation into the comparable soft Ni matrix of 300 to 600 HV only. At the border between the tungsten carbide grains and the Ni-based alloy an interface zone is formed, which is the larger the more the tungsten carbide particles get solved, thus giving a good fixing of the particles. The controlling of the laser power allows a precise and stable tuning of the solving degree of the particles, as shown in Fig. 11. The solved fraction of the particles precipitates in compounds of mixed carbides, thus increasing wear resistance and decreasing ductility. More details on this application can be found elsewhere [12, 13].
1.3 Excursus - 3D laser cladding (Prototyping)

Since the technology of laser cladding allows the build-up of claddings up to any layer thickness by cladding one layer on top of another, this technique can also be used for producing real three-dimensional shapes. In this case two strategies can be pursued. One is to clad layer after layer and to remove spare material by milling at certain production steps in between and after finishing. The other one is to produce extremely fine cladding beads in combination with a 5-axis CNC-machine, which may require also a certain amount of software programming when prototyping for complex geometries. Fig. 12 to Fig. 14 show examples of what can be achieved with this technology – further details and references can be found elsewhere [14-17].
2. LASER ALLOYING

2.1 Principles of laser alloying

In laser materials processing unfortunately often no difference is made between laser alloying and laser cladding. Both techniques have the use of the laser as a focused energy source for the generation of a weld pool and the use of additional material – mostly in form of powder – in common. While in laser cladding, the properties of the final surface are only determined by the use of the cladding material, the base material into which the additive is alloyed has also an important influence in laser alloying. Due to the similarity between laser cladding and other cladding processes (PTA welding, flame gunning, ...) there is always a competitive situation, which the laser can only win when minimal thermal load and/or highest precision is needed. In contrary, due to its special process parameters, there is currently no competitive process to laser alloying, which implies the possibility to offer technological solutions not feasible using other techniques. The principle illustrated in Fig. 15.
The laser beam is moved continuously over the surface producing a weld pool with high convection dynamics. Powder is inserted into the weld pool at much lower rates than in the laser cladding process. Powder particles get solved completely in the overheated weld pool thus leading to a different chemistry. Homogenisation of the weld pool is achieved by the high convection dynamics, which can be influenced by surface-active substances. This allows design of the alloyed track due to the desired requirements. Fig. 16 and Fig. 17 show the cross-section of two identical tracks – i.e. produced with identical parameters – geometrically influenced by the use of surface-active substances. Due to the small melt pool in comparison to its surroundings solidification occurs very quick, thus generating a very fine microstructure.

The technique of laser alloying can either be used directly for producing certain alloys or – which is the more prospective application – to change the alloy composition directly on defined areas of the surface on certain tools, i.e. the generation of a compound material which, starting from the base material, gives the potential of a local design of different surface properties.

In contrary to laser cladding, where properties like wear or corrosion resistance are pre-destined by the selection of the cladding material and the intermixture with the base material is desired to be as low as possible, using the laser alloying technology the intermixture with the base material can be chosen continuously thus changing the properties as desired locally. Degrees of intermixture are typically between 5 % and 25 %. As an example, Fig. 18 shows two different microstructures achieved by different seeding concentration.
Surprisingly there is not too much reference and/or use of this technology found in literature in the last decade: several articles – with no claim of completeness – about general research on this technique and its capability to solve a specific challenge [18-27], but not one industrial application. It should also be mentioned that several articles found with the phrase “laser alloying” in title or keywords are dealing with other laser surface technologies (cladding, hardening, remelting) instead.

2.2 Applications of laser alloying

2.2.1 Laser alloying of non-return valves used in injection-moulding machines.

Until now the only application that is developed already into a serial process is the laser alloying of non-return valves which are used in injection-moulding machines for synthetic materials. Such a non-return valve is a central component of the plastification unit and exists in various dimensions. Fig. 19 shows the alloying process, where parts of the bearing surface are modified via addition of hardening components, while Fig. 20 shows the semi-finished product after alloying.

The flexibility of the technique allows for the application in all desired dimensions, ranging from a valve diameter from 18 mm to 200 mm. For the larger dimensions several tracks are alloyed, as can be seen in Fig. 21. As hardening material monocarbide creators such as VC, NbC and TiC are used. These particles, after being fully melted, precipitate again as monocarbides, but – due to the fast solidification process – in a fine and dense distribution with high bonding to the metallic matrix. Morphology, size, distribution and hardness (typically in the range from 2000 HV to 2500 HV) of the monocarbides in combination with the comparably soft steel result in an alloy system which has excellent ductility properties and simultaneously highest wear resistance.

This application has been developed together with Engel Austria GmbH, transferred into a serial process, patent-registered and is still used and developed further [28].

2.2.2 Laser alloying of forming tools

Another prospective application is the laser alloying of cold forming tools, which are exposed to extreme stresses and strains at the edges during operation. In addition with the high hardness of such tools this leads to cracks and ruptures reducing their lifetime. Laser alloying allows a modification of the base material in a way of reducing hardness together with a simultaneous increase in ductility and plasticity, thus reducing the probability of cracks and ruptures in the critical areas.
3. SUMMARY

Laser cladding and laser alloying are related techniques both using a laser beam and the addition of powder material to be molten in the weld pool to modify the surface.

However, there are several other competitive techniques to laser cladding (e.g. PTA-welding, flame gunning, …) which cause the laser technique – due to its higher costs – only to be chosen when minimal thermal load and/or high precision are demanded. Besides, the properties of the past-process surface are determined by the cladding powder, where one is restricted to the available powders.

In contrary there is no competitive technique to laser alloying until now. Furthermore, since the properties of the post-process surface are destined both by the original base material and the added alloying powder, there exist a huge number of theoretically possible surface modifications to be tailored to the required demands. All the more it is amazing that besides the presented application (2.2.1) no other industrial application has emerged out of this technique so far.

4. REFERENCES


