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Technical Note

Laser Beam Build-Up Welding: Precision in Repair, Surface Cladding, and Direct 3D Metal Deposition

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Surface coating, repair, and rapid design changes of high-value components and tools are demanding challenges of modern manufacturing technology. In this field, advanced laser-based techniques are of outstanding importance for the related applications in mould and tool, aircraft and aerospace, as well as automotive industry. Many laser cladding solutions have been transferred into industrial series production within the last years. The motivations for the raising interest are given by the typical features of the technology: on the base of closed CAD/CAM chains, a quick and comprehensive treatment even of complex shaped and highly stressed components is possible. The heat input into the workpiece is less compared to TIG or PTA welding, although a metallurgical bonding to the substrate is guaranteed. Furthermore, the precise material deposition even at small partial areas is an advantageous characteristic. The coating materials include metal alloys (Co, Ni, Cu basis, Titanium, and steel), hard metals (e.g., WC/Co, TiC, and VC with metallic binders), and oxide ceramics (Al_2O_3/TiO_2). Typical base materials are steel, cast iron, and lightweight metal alloys based on Aluminum, Titanium, and Magnesium. The accuracy of the produced 3D structures in the range of 0.1 mm is the highest possible in the group of welding techniques. On the other hand, the available system technology (lasers, powder feeders and nozzles, CAD/CAM systems) permits a very easy and successful integration of the laser technology into manufacturing systems. Examples of application are the surface protection of lightweight automotive motor components, repair and quick modifications of metal forming tools as well as the complete restoration of damaged blades and disks of aero engines and gas turbines.

Keywords aero engine repair, direct metal deposition, laser cladding, surface protection, system technology

1. Process Specification

The development of cost-effective laser beam sources like the High-Power Diode Laser gave strong impulses to materials processing technologies. The compact construction, the high-degree of efficiency, and the moderate costs make procedures beside the alternative ones economically efficient. So, laser beam hardening, alloying, and cladding were increasingly established in the industry during the last 10 years, and the tendency is still raising (Ref 1). Laser beam cladding as basis technique is used for applications that require precision coatings on complex-shaped tools and components. The process is complementary to plasma powder (PTA) and TIG build-up welding, but the heat input into the substrate as well as distortion and intermixing are less. The economic benefits of the process are determined by a number of characteristics such as the dosed material utilization, high-welding speeds, minimal pre- and post-processing requirements, the possibility to fully automate and integrate the process, and by the performance advantages of the laser treated workpieces.

The principle of the process is shown in Fig. 1. The laser beam generates a localized melting bath on the workpiece surface. The filler material is fed as a powder or wire and gets heated when moved through the laser beam. However, it only melts once it is in the melting bath. The formation of a metallurgical bond requires a slight melting of the base material, which happens through thermal conduction. Thermal conduction into the cold substrate is also the reason for the rather rapid solidification of the molten filler material, which results in the typical formation of the deposition tracks. The width of these tracks can typically be varied between 0.2 and 6 mm. The height depends on the application and is between 0.1 and 2 mm. Tracks can overlap and thus coat entire areas. Multiple layers can be deposited to form 3D structures. The characteristic deposition rate is 0.1-1.5 kg/h. Naturally a higher deposition rate leads to a reduced precision of the depositions.

The most important beam source for cladding applications is currently the high-power diode laser. This type of laser is available in the power range of up to 6 kW. Compared to other beam sources is has the highest available power efficiency of 35-50%. The equipment costs are comparatively low. Since diode lasers are very

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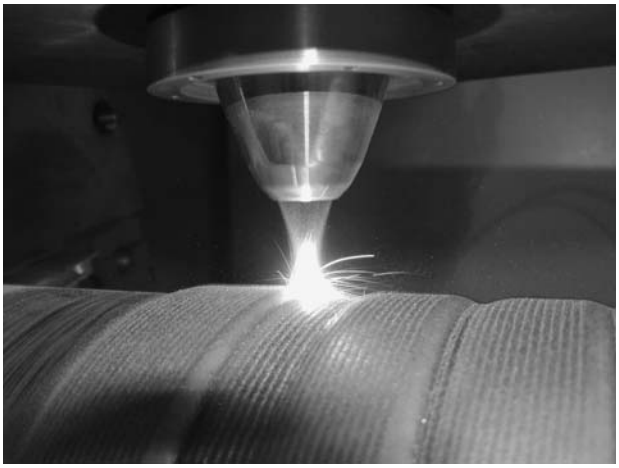

Fig. 1 Laser beam cladding in the industry process with coaxial powder supply

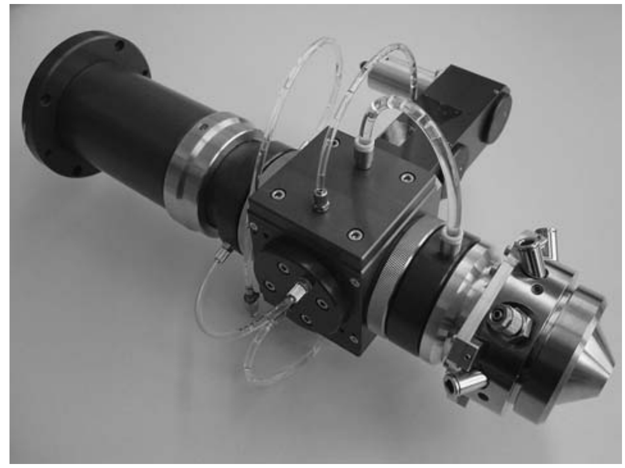

Fig. 2 Cladding head, consisting of the laser optic, a sensor cube, media supply, and the coaxial nozzle

compact, they can be directly integrated into a machine tool or robot system without the need to transport the laser light via fibers. However, the low-beam quality of this laser type usually limits the minimum laser focus dimensions and thus the accuracy of the deposit. Therefore, Diode Lasers are not suitable for high-precision and microprocessing.

The Fiber Laser, a special type of the solid-state laser, represents a new generation of high-power lasers for materials processing. The Yb-doped core of a YAG glass fiber is the active medium in a Fiber Laser. Therefore, it is a glass laser with light waveguide properties. The beam quality is increased about four times compared to convectional Nd:YAG slab lasers. This results in an extremely improved possibility to focus the laser beam, which can be as small as 100-10 μm at large and advantageous working distances (Ref 2). Using fiber laser enables us to reach a completely new dimension in precision for laser cladding applications, which cannot be achieved with any other laser source.

2. System Technology

The current availability of use-friendly and industrial-proven system components supports successfully the application. All the necessary system technology can be integrated easily into CNC machines or robots as add-on kits. Besides the laser source, the cladding head has a key function in the manufacturing system. For the generation of an extra stable and direction-independent powder stream, the principle of the coaxial nozzle is the most common solution.

An example of a typical coaxial laser cladding head shows Fig. 2. It consists of the laser focusing optics, optionally sensors for process monitoring, an *xyz*-adjustment system, and the coaxial nozzle. The powder nozzle itself can be assembled from a set of differently designed nozzle bodies and tips to address the particular needs of the process in an optimized fashion with respect to workpiece geometry, accessibility, and coating material.

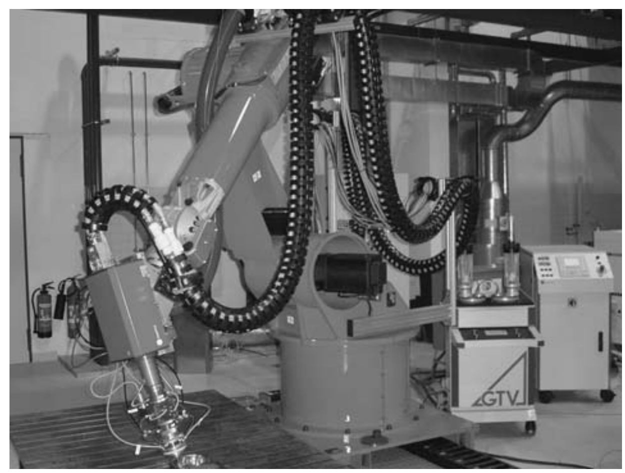

Fig. 3 Multi-purpose robot system for laser cladding and hardening for the repair and surface treatment of tools

For the practical use it is getting more and more popular to use robot systems, which are coupled with High-Power Diode Lasers or Fiber Lasers. Such systems are flexible and inexpensive, and the accuracy of the common robots is mostly sufficient for the characteristic laser track formation. Figure 3 shows a robot unit—equipped with a 3 kW Diode Laser, coaxial cladding head, and standard powder feeder—as an representative example. This system is in use for laser cladding and hardening for the repair and surface treatment of metal-forming tools.

3. Materials

A large number of metallic, carbidic, and ceramic powders are available as filler materials to fabricate coating structures that meet the particular requirements of the application. In general the coating is formed due to direct build-up of the coating materials on the functional surface with low and well-defined intermixing with the substrate material. For example, the iron content in Ni- and Co-alloy coatings on steel is commonly at about 5%.

Co- and Ni-alloy coatings can be deposited crack-free reaching a hardness of up to 48 HRC. Figure 4 shows a typical multi-layer build-up made from the Co base alloy Stellite 21. Using simultaneously inductive heating (Ref 3) enables one to reach a hardness of up to 63 HRC.

Hard metal coatings can be deposited as dispersion coating with a volume fraction of up to 60% of coarse grain hard metal particles (Fig. 5) or as a quasi-homogeneous coating with very fine-grained carbide precipitations (Fig. 6). A technical variant of laser beam cladding is the remelting of pre-deposited coatings. An example of this is the fabrication of abrasion and erosion resistant single-phase Fe_2B coatings using laser beam down melting of diffusion borided deposits (Ref 4).

Ceramic coatings are a special application for the laser cladding technology. A very adhesive ceramic coating with a high-fraction of α-Al_2O_3 has been deposited for wear protection on lightweight aluminum components.

4. Industrial Applications

The repair of wear-damaged components and tools is currently the most important application of laser beam cladding. The primary goal is to restore the original shape and properties of the workpiece. Using the laser as a tool offers the additional possibility to further influence structure and properties of the deposited materials. So, even very sophisticated Ni-based single crystalline materials can be made available for the manufacturing process (Ref 5).

Figure 7 shows for example an integral rotor of an aircraft engine, which is commonly known as bladed disk or ''blisk''. These rotors are made of Titanium alloys and get locally damaged over larger areas of the blades. Repair is very challenging since the aerodynamic profile has to be precisely regenerated and the dynamic mechanical strength has to be completely equal to the new part. An additional complication is introduced by the high-reactivity of the Titanium with air oxygen and nitrogen, which leads to undesired hard phases in the solidifying microstructure. The solution is to perform the build-up welding process in a closed inert gas chamber. The undesired reaction can be reliably suppressed. Figure 8 shows the cross section of a laser-generated compressor blade. The

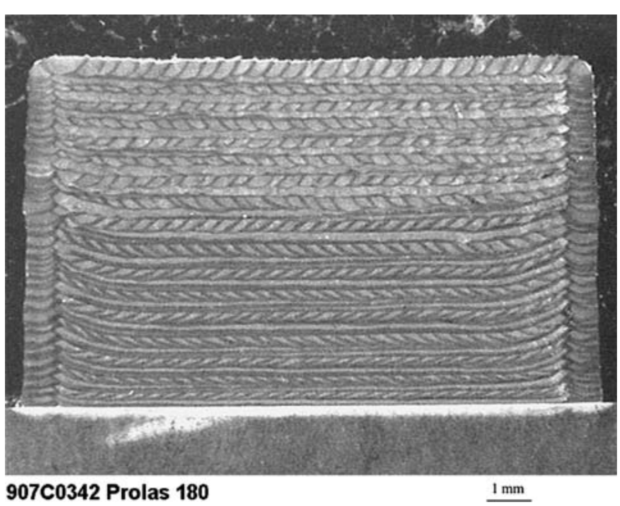

Fig. 4 Cross section (etched) of a multi-layer structure of Stellite 21

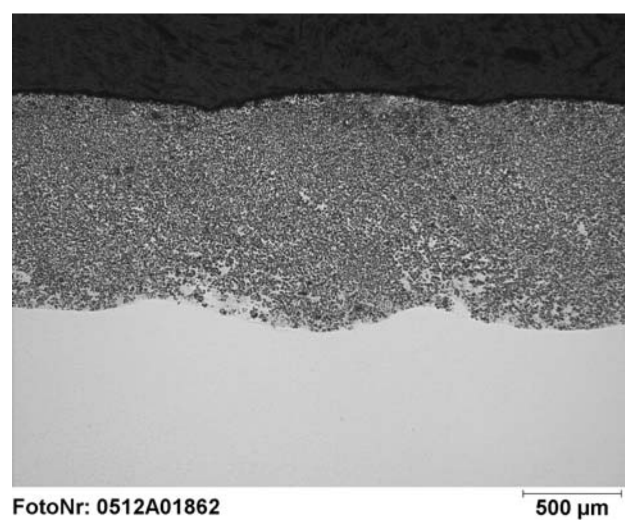

Fig. 6 (Ti,Mo)(C,N)-28Co coating with fine-grained carbide precipitations (cross section)

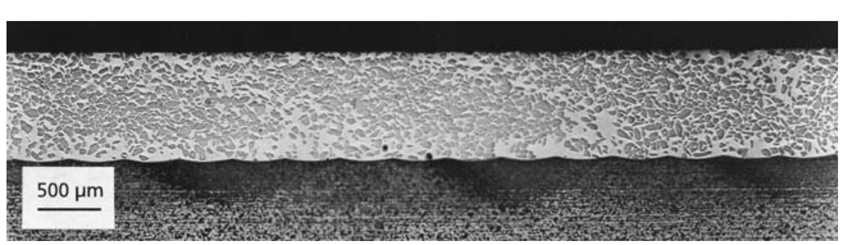

Fig. 5 WC/W_2C-NiCrBSi coating containing 60 vol.% coarse-grained carbide particles (cross section)

Fig. 7 Repair of damaged Titanium blisks

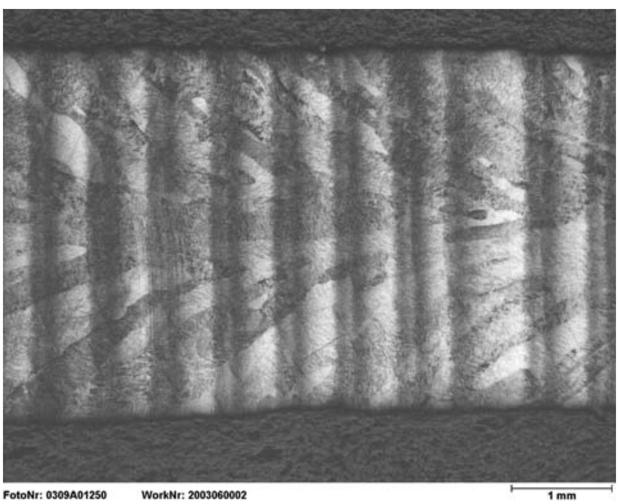

Fig. 8 Microstructure (etched) of the laser-generated Ti6242 build-up

image shows in detail the dense and fine crystalline microstructure as well as the flawless transition between the welding layers. The also-visible and coarser-appearing super structure points toward an epitaxic growth of the solidifying material from layer to layer.

By selecting the appropriate process parameters and welding strategy, it is possible to achieve tensile and fatigue strengths, which are at least equal to the original material. Figure 9 demonstrates the results of High-Cycle Fatigue tests. The maximum stress is shown in arbitrary units (a.u.). The data point with the arrow corresponds to specimens that have passed 10 million cycles. All specimens fractured outside the laser-generated zones in the base material. Thus, the fatigue strength of the laser-deposited structures apparently exceeds that of the base material. It can also be seen from the diagram that the fatigue strength of the Ti6242 material used for the cladding experiments is slightly higher than that of the previously tested Ti6242 reference material.

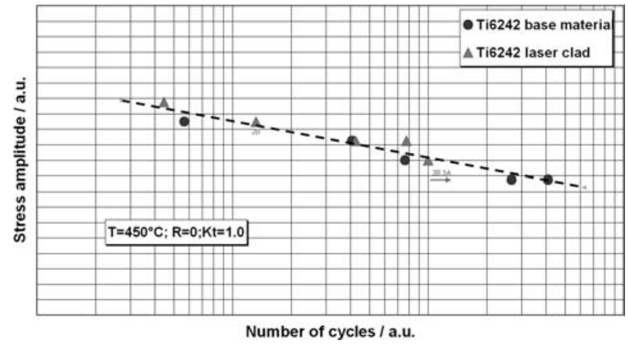

Fig. 9 Results of HCF tests of laser-generated Ti6242 samples in comparison to the equivalent base (reference) material

In this context, the technical variant ''direct metal deposition'' (DMD) is of importance not only for repairing applications. It summarizes all laser cladding applications, which directly deposit the material based on 2D and 3D CAD data models. The metallic 3D structure can be generated on a simple platform as well as on a real workpiece. By using the laser beam, the material deposition can be very accurately controlled so that the fabricated structures are near net-shape within a few tens of a millimeter. The welding process is very stable so that it is possible to flawlessly weld hundreds of individual tracks. Sensors can help to even further increase the process stability. For example, optical height control systems can monitor the coating growth layer by layer (Ref 6). In general, the generated structures are completely dense and able to sustain high-mechanical loads. Industry is using this process variation therefore to repair high-value components, to modify tools, to directly fabricate metallic prototypes, and to generate structures on inside contours and surfaces that are difficult to reach.

Surface protection is a still niche application for the laser process. It is used for those applications that do not justify the utilization of other spraying or welding technologies. This can be the case due to the specific geometry, special loading conditions, or economic criteria. Examples are components for the oil industry or valve seats for lightweight motors (Ref 7).

5. Outlook

Laser beam cladding is an established industrial precision process in the field of aero engine and gas turbine repair. In addition, it is being introduced as a flexible technology for repair and rapid design changes in the tool and die industry. First applications for protective coatings in lightweight motors for cars and highly stressed hot-work tools are also already implemented in production. The commercial availability of powerful, reliable, and cost-effective laser and system technology helps to promote this development. The current development focus is on the integration of the laser technology into machine tools and into manufacturing processes. Here, highly integrated CNC machining centers for combined laser cladding and finish machining are innovative technical achievements.

The combination of laser technology with PTA welding as well as inductive heating permits to connect the technical and economic advantages of the individual processes. The new Fiber Lasers exhibit the potential to realize a completely new dimension of laser cladding applications. They are distinguished by an extreme high-beam quality, the possible rapid beam oscillation, a very compact size, uncomplicated adjustability, and moderate costs. As a consequence current research additionally aims at the development of new applications in medical technologies, engine and tool repair, and micro-material processing.

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