Laser materials processing of complex components. From reverse engineering via automated beam path generation to short process development cycles.

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Abstract. The article presents an overview of what is possible nowadays in the field of laser materials processing. The state of the art in the complete process chain is shown, starting with the generation of a specific components CAD data and continuing with the automated motion path generation for the laser head carried by a CNC or robot system. Application examples from laser welding, laser cladding and additive laser manufacturing are given.

1. Introduction
In modern production technology one trend goes into producing complex parts in small batch sizes or even as single part. Therefore the corresponding R&D times need to be kept as short as possible. Therefore in laser processing one is frequently confronted with the demands of developing laser processes for complex components in rather short times to keep the whole project within a reasonable economic frame.

When dealing with complex components without available CAD data, reverse engineering via laser-based scanner systems is a suitable solution. Such systems nowadays have no more problems with reflecting metallic surfaces, and also the resolution has become sufficient even for delicate laser processing applications.

Out of the CAD data complex laser beam paths for welding and/or cladding can be generated automatically using appropriate software, including the consideration of tool orientation and collision issues for any customary robotic system or CNC gantry unit.

Combining laser cladding of different materials with intermediate or post-process machining (milling and drilling) within one system leads to enhanced possibilities for additive manufacturing solutions.

2. Technology
The paper is dealing with the technologies of laser welding, laser cladding and laser additive manufacturing of metallic parts. Further information about these technologies is found elsewhere [1].

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3. Challenges

3.1. Small batch sizes
As mentioned in section 1, industrial demand in special components produced in small lot sizes is ever-increasing. This in turn leads to the necessity of low R&D times in order to make such specialized components economically reasonable. Therefore the corresponding process development times have to be short, which is only feasible when automating as much as possible even during R&D.

3.2. Lack of sufficient CAD data
Although normally the CAD data of components to be processed is available, every now and then this may be not the case:

- If parts are transferred during the process several times from one company to another, there might be no easy access to the original manufacturers CAD data.
- Parts to be processed after being in use. Such parts may be deformed in a way that the original CAD data is no more valid.
- Parts which are on the market for a very long time. Manufacturing has started long time ago, before CAD was common, and the corresponding CAD data has never been generated later on.

3.3. Generating complex motion paths
Laser material processing means that there is a laser head – mounted on a CNC or robot system – that needs to be moved along certain tracks above the component. If these tracks are in any way mathematically describable, the corresponding programming of the motion paths may get any complexity, but is always feasible. An example of such a complex motion path for laser cladding of an extruder screw is shown in figure 1.

![Figure 1](image)

**Figure 1.** (a) Laser cladding of an extruder screw with decreasing diameter and truncated screws at the end. (b) Exaggerated display of corresponding motion path.

Exact programming of motion paths is not possible when dealing with mathematically not describable topologies, like free form surfaces. Such complex motion paths could only be taught, which means that the (robot) system is manually moved and the positions get stored. It is easily to understand that teaching soon exceeds any reasonable timeframes and is therefore not feasible in most cases.
4. Solutions

4.1. Reverse engineering
Reverse engineering refers to procedures that start with any real component and deliver its CAD data. One possibility is the use of laser-based scanner systems for 3D digitalization [2,3]. Such systems nowadays show sufficient spatial resolutions of less than 0.05 mm, and also the problem of highly reflecting surfaces that was common when dealing with metallic parts has been overcome. Furthermore, the corresponding software supports complex automated measurements. For example, the scanner system can be mounted onto a robot, and the measurement of large complex parts is done automatically. Figure 2 shows examples of the current state of the art.

![Figure 2. (a) Robot-based automated measurement of a larger car body part [2], (b) 3D digitalization of a car tyre [2], (c) 3D digitalization of a coin [2], (d) Complex part generated via additive manufacturing and partly finished by subsequent milling, 3D digitalization of that part in (e) lower resolution of 0.1 mm and (f) higher resolution of 0.05 mm.](image)

After such 3D digitalization the resulting CAD data can easily be imported in any standard CAD software for further adaptation, if desired.

4.2. Automated motion path generation
As described in section 3.3, general goal is the generation of corresponding motion paths for laser materials processing technologies, which is not mathematically solvable for components containing free form surfaces. Up to several years ago there was no universal and commercially available solution
to this challenge, only several academic institutions were in possession of automation software tailored to specific applications and/or geometries. This situation is not satisfying when dealing with a wide range of different applications.

A few years ago a quite universal software solution was developed by the market leader of laser systems [4] and distributed along with their complete laser processing systems. In cooperation with another software company a special version of this software called TopLas3D [5], which can be adapted for all standard CNC and robot systems, is commercially available now.

We have implemented this software into an ABB robot system [6]. TopLas3D is capable of importing any standard CAD data format. In the next step the user selects the surfaces or edges that shall be processed. TopLas3D then gives a simulation of the motion path, where surface discontinuities (holes, edges, sharp folds,…) are considered. Since the complete workstation CAD data – including the mounted laser head – is also stored in the software, optimum tool orientation and automated collision detection is included. A lot of details like different motion strategies (rectangular, circular,…), basic CAD operations and many options for the user to set constraints or override the suggested simulation exist. A detailed description of all its capabilities would exceed this article by far, the interested reader is referred to the TopLas3D webpage [5]. When satisfied with the simulation results, NC data for the specific workstation is exported. Figures 3-5 show selected applications.

Figure 3. (a) View of the TopLas3D screen with the complete robot system and the CAD data of the component shown in figure 2d imported. (b) Screenshot of a motion path simulation on that component’s surface.

Figure 4. (a-c) Motion paths on various complex surfaces. (d) Screenshot of a motion path simulation of the path shown in figure 4a. The orange cone is the visualisation of the laser beam.
There are certain cases – especially when working with a robot station - when although the motion path is programmable in principle, its simulation is a good alternative. Consider for example a gyration movement, which origins in a complex interplay between the different robot axes to result in a smooth gyration movement of the tool. Figure 6 shows such a case.

Figure 6. (a-d) Screenshots from the simulation of a gyration movement. (e-h) Images of a laser cladding process using a gyration movement in reality.

5. Application example
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 Cr-Mn-steels which have high corrosion resistance and ductility. However, their wear resistance is quite low, which results in unacceptable high wear at field conditions. A laser cladding process was developed in cooperation with one of the global players in the drill string production market [7], whereby the following challenges had to be solved:

- Thermal load both to the cladding nozzle and to the cladded components because of cladding times up to several hours.
- Since subsequent machining should be avoided, a constant total layer thickness of $4.0^{\pm 0.2}$ mm was demanded. This was all the more a challenge, since the complete layer system consisted of four sublayers. Details of that layer system can be found elsewhere [8,9].
Due to the complex surfaces of the drilling heads the motion paths for cladding had to be programmed by external software and fed into the machine. This was done at that time (2005) by tailoring available software to the specific needs. If a powerful software like TopLas3D had been available then, R&D times would have been drastically reduced.

Figure 7 shows an example of a programmed motion path and an image of the cladding process.

![Figure 7](image)

**Figure 7.** (a) Programmed motion path from 2005. (b) Image of the laser cladding process.

This process is still state of the art in oilfield technology and meanwhile running at the customers sites on four laser cladding stations performing multi-shift operations [7].

6. Additive manufacturing solutions

The technology of laser cladding is used mainly for the following applications:

- Deposition of protection layers (wear, corrosion, …) onto metallic components
- Repair of worn out metallic components
- Additive manufacturing of metallic components. In the context of additive manufacturing this technology is often referred to as LMD (laser metal deposition).

When using LMD for additive manufacturing there will always arise height differences in the generated part during the process. To level them out it would need very complex programming and/or fast and subtle online corrections of process parameters. A more expedient solution is frequent levelling out by intermediate milling, but which is only economically reasonable when it can be done without re-clamping of the component in formation.

Such a combination – but with standard wet milling – was brought to market by one of the big players in the production of tooling machines in 2014 [10], but was developed as special model – with high-speed dry milling – for JOANNEUM RESEARCH about 15 years ago. Figure 8 shows our combined laser and milling station as well as an additive manufactured part. In figure 2d already a part generated via LMD was shown, with one half remaining as it is immediately after LMD manufacturing and the other half finished by subsequent milling.
During the last decade the technology of SLM (selective laser melting) has come to a considerable maturity level in the field of additive manufacturing [11,12]. Unjustly LMD and SLM are often regarded as competing technologies, which they clearly are not when looking at the details. Both technologies have different strengths and limitations, which in fact makes them complementary. Whereas LMD is not capable of producing such fine and complex structures that are feasible with SLM [13-16], SLM fails in the combination of different materials. Other drawbacks of SLM are the still extremely long fabrication times and limited maximum part sizes. Figure 9 shows examples of so-called “functional tools” consisting of different materials fabricated by LMD technology.

Figure 9. (a) Cooling insert made of inexpensive material for the most part, but with a copper layer beneath a special abrasion-resistant surface. (b-d) Functional complex cooling insert with copper beneath the surface (b) directly after LMD fabrication and (c) after final machining. (d) Microsection of the part.
7. Summary
In the field of laser materials processing of metallic materials the tools existing nowadays enable the automation of important process steps even during R&D phase, thus fulfilling the industrial needs for short development times.

These steps in particular consist of the generation of CAD data of any given metallic component and the automated generation of the corresponding motion paths for laser processing. Such automation tools can also be used for the production of additively manufactured components, even consisting of different materials.

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