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The final steps towards guaranteed quality and first-time-right - 3D printing with powder and wire enabled by OCT sensor technology

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Abstract

Today's manufacturing processes, especially 3D printing with powder or wire, presuppose Industry 4.0 solutions, which require supervision of every single production step. Transforming machine elements into intelligent cyber-physical systems involves the integration of smart sensors for condition and process monitoring. As photonic solutions are by nature contact-free processes it would be advantageous if the sensor is based on light as well, if the light could be coupled into the beam path of the processing laser and if the sensor can measure surface topography in micrometer resolution. In this case, the production process can be directly connected to the CAD data set, the process could be controlled to eliminate geometrical deviations to the desired geometry and first-time-right is not a pious hope anymore. We talk about controlled individualized lot size 1 production based on OCT sensor technology.

Keywords: DED-LB; LMD; 3D Printing; OCT; Low coherence interferometry; Industry 4.0

1. Introduction

Sensors based on OCT (optical coherence tomography)/ low coherence interferometry are different from all the other technologies because the measurement is not affected by the process emissions [1], [2] and thus open new horizons in laser materials processing. The use of this method in laser applications has risen in the last years. Since its first appearance in 2008 [3], application examples were shown for laser cutting [4], selective laser melting [5], laser micromachining [6], laser drilling [7], and laser welding [8]. For the latter, a huge potential is foreseen [9][10].

Many industries are working to make products more durable and efficient. For this, it is necessary to increase the surface properties concerning abrasion, corrosion, and erosion resistance of the workpieces. For

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this modification of surfaces, laser cladding has become established as a key technology. Unlike other coating technologies, such as e.g. flame spraying a laser offers the possibility to precisely control the introduced energy. This allows a defined application of single layers right up to full generative production. Not only surface treatment has established itself as a field of application for the Direct Metal Deposition process, direct "printing" or the production of near net shape structures is an essential field of application for laser DED.

Although the nozzle technology has been continually improved, the powder efficiency is below 100%, which correlates directly with the track width. According to the datasheet, the best powder nozzles have an efficiency of 98% at the optimum track width [11]. Compared to other processes, such as plasma build-up welding, laser cladding convinces with a minimal heat load on the component and extremely low distortion of the workpiece. In the field of repair processes, it has become established especially for the regeneration of worn blade tips of aircraft and gas turbines [12].

Especially sensor technology is a leading part related to Smart Factory and predictive maintenance and even process control. Transforming machine elements into intelligent cyber-physical systems involves the integration of smart sensors for condition and process monitoring.

2. New sensor concepts for direct energy deposition (DED-LB)

2.1. Low-coherence interferometry in laser materials processing

OCT technology (Optical Coherence Tomography) is an imaging technique based on low-coherence interferometry (LCI). It is a long-established medical examination procedure [13]. An interferometer with a light source of low coherence length is used to measure distances and the composition of human tissue, e.g. the cornea. The short coherence length is achieved using light sources that emit broad-spectrum light. The applied light sources are typically superluminescent diodes (SLDs) with a range of some 10 nanometers or a Swept Source Laser. In 2006, Precitec Optronik GmbH launched a thickness and distance sensor based on spectral-domain OCT and this was adapted to material processing applications with laser sources of high beam quality. The adapted technology allowed distance measurement to the required accuracy of about 10 microns, even over long distances.

However, the real innovation and thus the basis of a technological leap in the field of process monitoring/control is the fact that the accuracy of the interferometric measurement is not affected by the electromagnetic emissions from the vapor capillary or the adjacent areas. The intensely bright emissions caused by the high-power beam material interaction are not coherent with the light emitted by the low coherent light source of the measuring system and thus only the measurement system light is involved in interference between the reference and the measuring path. Based on an accurate adjustment of the measurement beam coaxial to the processing laser, this technology for the first time provided an exact measurement of the depth of the keyhole, independent of seam geometry or processed material. The only restriction is in the dimension of the measurement point compared to the spot size of the processing beam and the measuring range in the axial direction.

2.2. OCT Measuring Principle

Interferometric measuring principles are found in several applications. Most of these implementations are based on the interference of coherent light with itself. The basic interferometer hereby consists of a light source, a beam splitter, two reflecting surfaces, and a photodetector. The relative distance between the two reflecting surfaces affects the interference pattern of the reflected light beams. The most prominent interference patterns are hereby found in the temporal or spectral domain. The subsequent analysis of the interference pattern reveals the relative distance between the two surfaces. As these interference patterns are the results of the coherence of the light used, they are only affected by the light source itself and the relative displacement of the mirrors; external illuminations, in particular process emissions, do not interfere with the interference pattern and have no influence on the measured distance.

The integration of this measuring principle into laser welding optics allows the measurement of the distance to a surface in proximity to the focal spot. This surface plays the role of one of the described mirrors. The measuring beam is focused onto the surface by using the same focusing optics as the working laser Figure 2. A separate real mirror and the beam splitter are mounted in an enclosure apart, whereas the light source and the photodetector are installed in an electrical device. By tilting or translating the light beam coupling into the welding head, the position of the measuring spot can be varied relative to the focal spot of the working laser. Hence, any kind of topography measurements can be achieved by scanning the surface with the measuring beam. If the measuring beam is aligned to the working laser, it will enter the keyhole and reflect at its bottom: the penetration depth can be measured.

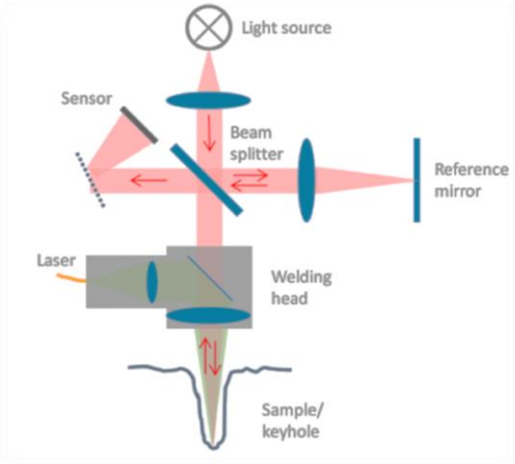

Fig. 1. Interferometric measuring principle through a welding head

Fig. 2. Ruggedized sensor light collimation (top) and fiber coupling - (back) mounted on a modular laser welding head Precitec YC52

3. Application example: Feed rate control in 3D printing

Concerning demands for complete monitoring or even control the additive manufacturing processes – nowadays sometimes labeled 3D printing – like LMD and LPBF are not distinguished from other laser applications. Precitec demonstrated in miscellaneous applications, that OCT is the promising sensor technology for acquiring the most dominant information, the topology of the processing result and due to the coaxial adaptation, this is possible in-situ. Possible process error situations in 3D printing with LPBF like pores, distortion, coating defects, layer offsets, or even the so-called balling effect result in topography changes and therefore are picture-perfect to be detected and measured with the OCT technology.

Just recently this year Siemens and Precitec demonstrated a fully close-loop-controlled LMD process by integrating the OCT technology into the SINUMERIK control. What is true for other laser manufacturing processes also holds for LMD, even the metal powder blown to the work-piece surface does not change the exact surface topology measurement and so the metered value can be used as input for a control loop.

This work was carried out in a funded project by the European Commission called PARADDISE http://www.paraddise.eu] - A Productive, Affordable, and Reliable solution for large scale manufacturing of metallic components by combining laser-based ADDItive and Subtractive processes with high Efficiency [14].

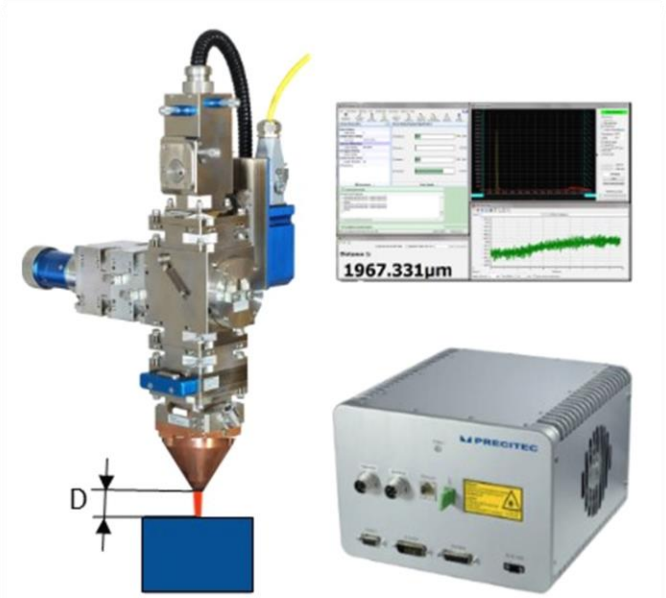

Fig. 3. Adaptation of the OCT sensor to an LMD head

As described earlier in this paper the integration of the OCT system to a processing head is straightforward as this is a point measuring system and the transmissivity/ reflectivity of the optical components in the head can be fixed to the wavelength of the sensor device. Especially in this application, the measuring spot is fully co-axial to the processing laser and together with SIEMENS and RWTH Aachen a model was developed and implemented into the SINUMERIK which exactly derives the final wall/ track height from the distance measurement. In the closed-loop program module, the height variations are compensated by feed rate adaptation.

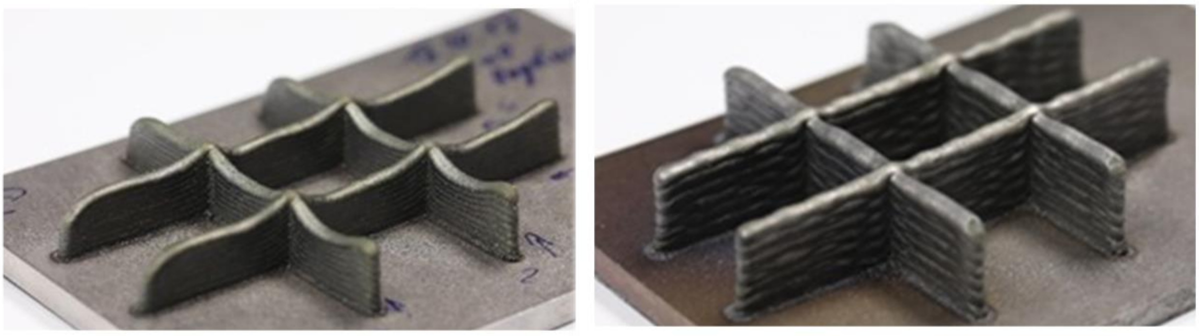

Fig. 4. Results of the closed-loop-controlled process in comparison to a non-controlled

4. The best of both worlds

Processing heads with coaxial supported wire, e.g. the CoaxPrinter by Precitec, are the tools of choice when it comes to DED-LB with wire. Precitec has developed a processing head for the DED-LB wire process where the laser beam itself is ring-shaped and focused right at the interaction point between wire and workpiece surface. This application-specific intensity distribution is the ideal one when it comes to smoothening the process – because of pre-heating of the wire – and to full direction independence – because of the symmetrical laser beam geometry. The resolution of a part printed with this technology is only dependent on the wire diameter, there are no limits for the size and orientation of the final component. And even hybrid manufacturing is easy to achieve. The processing head mounted on a gantry system or robot can build up special function-relevant adapters or fixtures on already existing parts e.g., turbine housings. This helps speeding up the production time and dramatically reducing material use.

Talking about material use, in contrast to powder-based printing technologies using wire as raw material guarantees 100% material use. Especially in the context of hybrid manufacturing, the production process is 100% residue-free. There is no need to take care of the remaining powder with all restrictions related to it.

Fig. 5. CoaxPrinter processing head

What makes this solution so specific is the choice of sensor technology. Precitec has combined the best of both worlds, the most flexible DED-LB -wire laser processing had with the unique features of the OCT technology. The advantages of OCT are already described before.

The OCT measurement spot is continuously rotating around the wire and so the height of the original surface, resp. the previous layer is measured as well as in trailing position to the process the new layer height. As the machine information (speed, direction) is combined with the topography data the comparison to the CAD dataset can be derived and process parameters can be changed to keep the process window.

Fig. 6. OCT controlled DED-LB wire part made of AlMg5

Fig. 7. DED-LB wire part printed with TA6V

5. Conclusions and outlook

Low-coherence interferometry is a technology rapidly finding its way into laser material processing applications. It has a very high temporal and spatial resolution and is suitable for coaxial integration. Robustness against any kind of process emissions makes it suitable for all kinds of process monitoring and process control tasks that are based on distance or topographic measurements.

Various sensor technologies are used for different tasks in the field of laser welding. Although these technologies are mature, improvements in closed-loop control, pre- and post-process monitoring of complex joint geometries, and remote welding, as well as more accurate in-process monitoring, are required.

This paper demonstrated the abilities of the In-Process Depth Meter [15] to fulfill these tasks. Using it as a tool to measure the keyhole enables understanding of the laser welding process. The combination of the sensor with a quality assurance system such as the Laser Welding Monitor [16] allows autonomous detection of weld defects that remain unseen by conventional sensors. By feeding the laser source with a power signal, the sensor offers closed-loop control of the penetration depth. The fourth shown application example demonstrated the ability to compete with current pre- and post-process sensors.

Upcoming developments might include the 3D modeling of the keyhole's geometry, all-in-one sensors for simultaneous pre-, in-, and post-process monitoring, and self-tuning welding robots. Also, other laser applications, such as 3D printing by LPBF or LMD, will benefit from the advantages of low-coherence interferometry.

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