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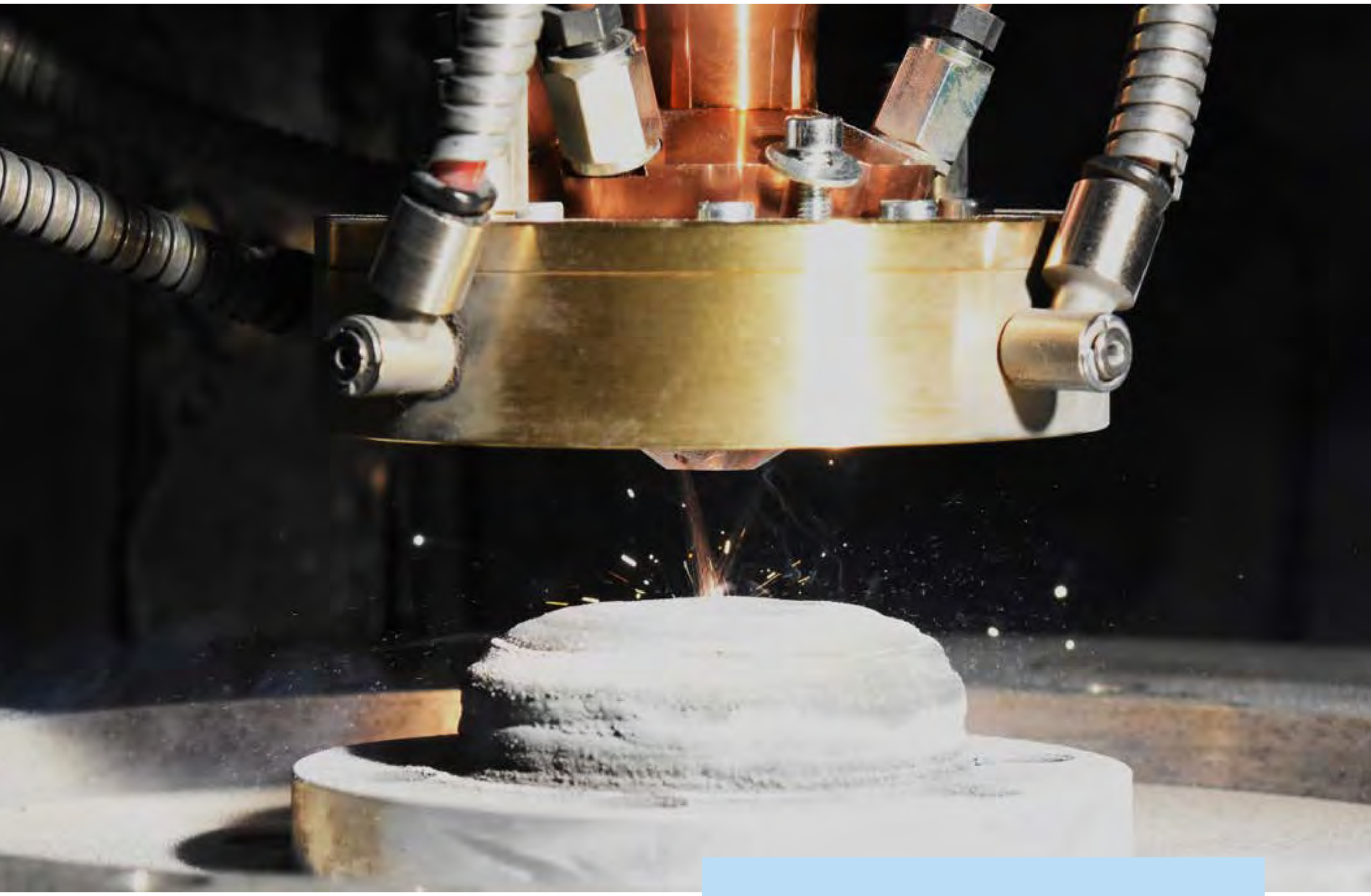

Special Issue

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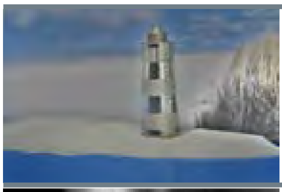

Laser Materials Processing
Increased Laser Polishing Rates of LPBF Components

Process Monitoring
Closed-loop Control of Penetration Depth in Wire-based Laser Cladding

published in media partnership with EPIC European Photonics Industry Consortium

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Contents

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Things Are Moving Forward

No Laser Applications Forum, no face-to-face meetings, but R&D continues!

Uncertainty was high last year and will remain so this year due to the global pandemic. This does not stop at the R&D sector. Quite the contrary, the current and future challenges will not diminish, and therefore the R&D intensity to provide solutions must continue and even increase.

Turning to the future of BIAS – Institute of Applied Beam Technology, I see great potential for lasers in manufacturing technology, not only in lightweight construction, for example by producing topography-optimized and function-integrated components or realizing new multi-material structures, but also in finding and applying new alloys through high-throughput alloy development or in establishing a complete hydrogen value chain. We want to provide solutions for an increasingly resource-efficient, flexible, adaptable and customizable production. Combined, these efforts will support an ecological, sustainable transformation.

One contribution to the industrial use of laser applications in production technology is the biennial Laser Applications Forum (LAF) in Bremen. As a platform for exchange between users, developers, service providers, manufacturers and researchers, the BIAS Institute, as the organizer, aims to support and increase the transfer between academia and business, in particular business-to-business. In my experience, the forum's character is shaped not only by the accompanying exhibition and plenty of opportunities for communication and discussion, but also by the warm familiarity of the many participants, creating open and inspiring discussions while developing new ideas and impetuses to take home.

However, the 12th LAF has had to be postponed until 2022. Therefore it is great that PhotonicsViews has decided to present the short contributions of the young scientists of BIAS, who would otherwise be answering questions during the BIAS OpenHouse, within this e-special, making them available to all.

So join me in looking optimistically toward the future: things are moving forward, laser material processing is advancing, and the LAF will be back stronger than ever in 2022!

Peer Woizeschke

Source: Andreas Klett

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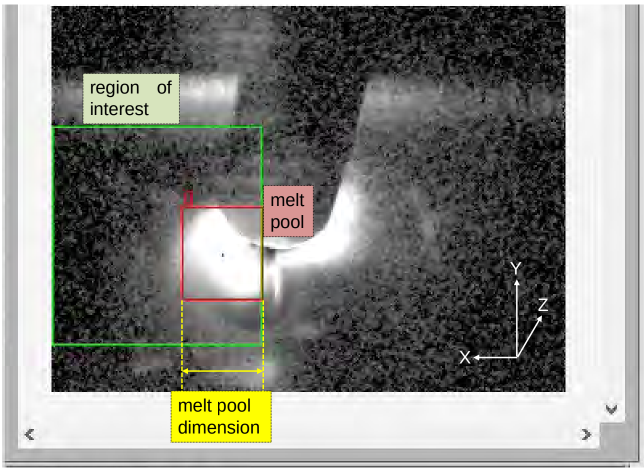
laf 2020

Online Monitoring in WAAM

Using a two colored pyrometric camera for temperature field monitoring in wire arc additive manufacturing

Christoph Halisch, Tim Radel, Dieter Tyralla, and Thomas Seefeld

An extensive online monitoring of the process influences, and a possible regulation of the process parameters is seen as a promising solution to reduce the qualification effort for additively manufactured components using WAAM. Many weld imperfections are related to the temperature history of the part. Due to its low thermal conductivity the online monitoring of the temperature field in WAAM of Ti-6Al-4V is of central interest. This paper shows the applicability of a two colored pyrometric camera for temperature field monitoring in wire arc additive manufacturing process.



Halisch 2019 BIAS ID 190859

Fig. 1 Temperature field measurement using Pyrocam and determination of the melt pool size

The wire arc additive manufacturing (WAAM) of titanium parts offers great potential for use in the aerospace sector. Due to the high build up rate, the process enables the economical production of large, near-net-shape milling blanks. The ratio of the mass of the milling blank to the finished component, the so-called "buy to fly ratio", can be drastically reduced. This means significant cost savings, especially with expensive titanium alloys.

The high potential for cost savings is, however, reduced by the additional qualification effort for additively manufactured components. Another challenge currently facing WAAM is the reproducibility of material properties across the entire component. An extensive online monitoring of the process influences, and a possible regulation of the process parameters is seen as a promising solution. The range of process influences that can be online monitored is large. These include arc current and voltage, shielding gas flow and content, wire feed speed and torch travel speed, acoustic and optical signals, and local temperature development.

Many weld imperfections are related to the temperature history of the part. The high heat input of the WAAM also induces high local stresses, warpage and leads to a very coarse grain in the microstructure. Titanium is prone to heat build-up due to its poor heat conduction properties. Therefore, online monitoring of the temperature field in the titanium WAAM is of central interest.

The temperature field can be measured with common infrared (IR) thermal cameras. These systems are dependent on the emissivity of the respective material, which in turn is also dependent on the temperature. At BIAS, the applicability of a quotient pyrometric camera with a high dynamic range (Pyrocam) in an additive arc process was examined. Due to its quotient pyrometric principle the changes in emissivity are compensated. The calibration for different materials required for IR thermal cameras is not required here. In contrast to the IR thermal camera, the Pyrocam measures in the visible wavelength range of light from 450 nm to 750 nm and is therefore susceptible to interference radiation from the arc. Using spectroscopic measurements of the arc, it was possible to identify a range from 625 nm to 750 nm in which the interfering radiation of the arc is minimal.

Using suiting high and low pass filtering, the Pyrocam was integrated into

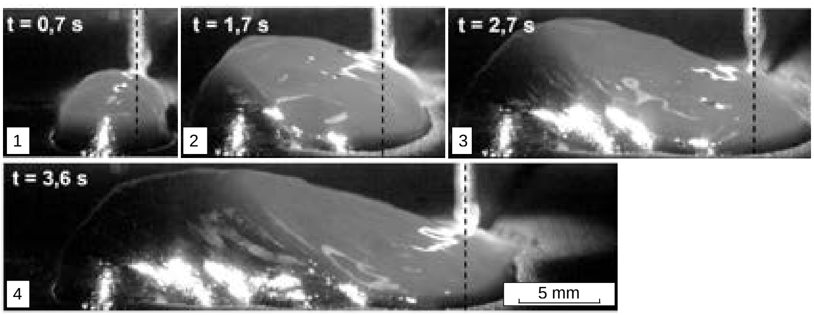


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Fig. 2 Temperature field measurement using a high-speed camera and determination of the melt pool size

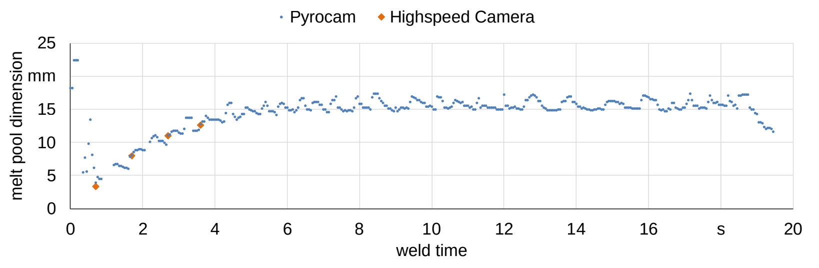

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Fig. 3 Comparison of the weld pool length, determined by the Pyrocam and the high-speed camera

the WAAM process and the temperature field was measured over the entire weld of a test specimen. Using the melting temperature, which for Ti-6Al-4V is 1650 ± 5 ° C, the solidification line and thus the size of the melt pool were determined, as shown in Fig. 1. In comparison, the same weld was observed with a high-speed camera. Based on the "freezing" of the melt pool movement, the solidification lines and the pool size were also determined, as shown in Fig. 2. The melt pool length, which was determined using the temperature field, corresponded well with the values from the high-speed camera recordings [1], as shown in Fig. 3. These results suggest that temperatures are being measured correctly. The influence of the arc radiation on the measurement was sufficiently reduced and its interference with the heat radiation of the weld pool was significantly reduced.

Fig. 3 shows that the weld pool size increases steadily at the beginning of the weld until it then reaches a constant level. A small periodic increase and decrease in the weld pool size can also be seen, which correlates to the oscillating torch movement. In a metallographic longitudinal section of the test specimen these reversal points are found again, as shown in Fig. 4. A correlation between increasing weld pool size and an increasing prior beta grain size at the beginning of the layer could not be found. In the metallographic lateral cross-section, the strongly anisotropic grain structure known from the literature could also be found. The grains grow over several layers in the direction of build-up, as Fig. 5 shows.

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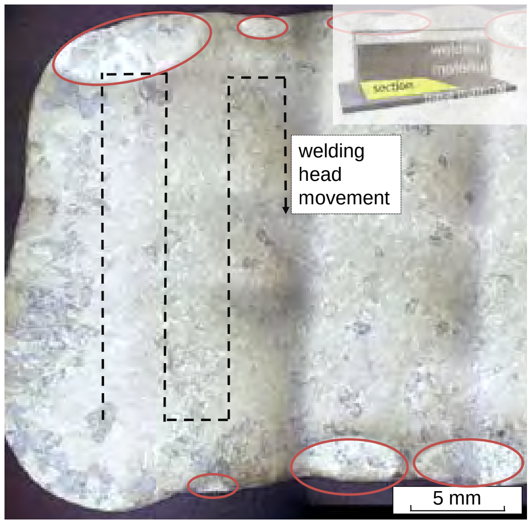

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Fig. 4 Metallographic longitudinal cross section with marked areas showing the correlation to reversals points of the torch oscillating movement

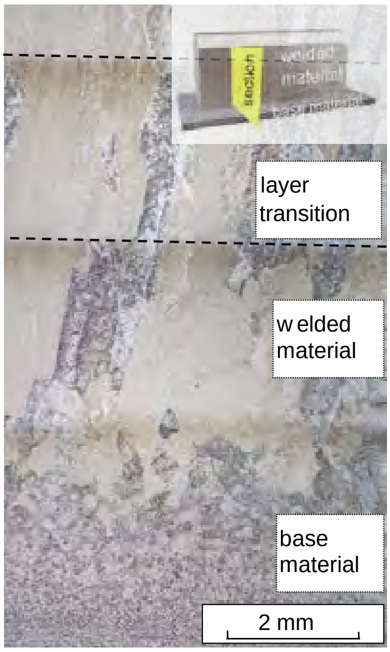

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Fig. 5 Metallographic lateral cross section showing the epitaxial grain growth over several layers

Digital Holographic Measurement System

Robust digital holographic measurement system for production environments

Fabian Thiemicke, Achim Gesierich, Wansong Li, Claas Falldorf, and Ralf B. Bergmann

Quality assurance of functional surfaces on micro-components is often not done in the production cycle due to the high production rates. This means that testing is usually only conducted on a random sample basis. For this purpose, tactile shape measurement methods or confocal microscopic techniques are commonly used. These techniques usually provide highly accurate results, but in practice they are usually not fast enough to handle the production speed of the manufacturing line. Furthermore, the accessibility of inspected functional surfaces, especially with the tactile techniques, creates a limitation. Therefore, a 100 % inspection of the manufactured parts is usually not possible. To overcome this gap in quality assurance, a robust digital-holographic measuring system was developed at BIAS in cooperation with VEW-Vereinigte Elektronikwerkstätten GmbH, Bremen, which allows the inspection of functional surfaces with a diameter up to 2 mm and a measurement uncertainty of a few micrometers inside within a production environment. In addition, this measuring system allows quality assurance during the production process with a short inspection time of less than 1 s, even up to a 100 % inspection.

By using digital holography [1], the shape of a measured object can be recorded and reconstructed from the image of two holograms. The measuring objects can have a lateral extension in the millimeter range. The resolution of the height values is in the micrometer range. This enables fast two-dimensional shape detection for in-line inspection of microcomponents.

The developed measuring system is based on a digital holographic microscope with a working distance of 34 mm. Due to the large working distance, many different workpiece geometries can be measured. These are functional surfaces in cavities of deep-drawn components, which cannot be adequately measured with tactile methods. Fig. 1 shows the measuring system with its essential optical components. The optical light paths are completely sealed by a tube system inside the measuring system to protect them against dust and other ambient influences. The light that is used for illumination will be divided into two separate beams by the beam splitter. One light beam is used to illuminate the measuring object and is scattered on its surface (object wave). The object wave is passed through the microscope objective, which magnifies the object of interest. The second beam acts as the reference wave and is reflected by the reference mirror and combined with the object wave on the camera. The actual measurement signal of the system consists of the superposition of the object and reference wave. This superposition generates an interference pattern on the camera, which includes the 3D shape information of the measured object. This information will be obtained by method of digital holography [2] and will be provided for further analysis. It is possible to achieve height resolutions in the nanometer range with a single hologram on optically smooth surfaces, but these resolutions are only unambiguous for height differences up to half a wavelength. In the case of technical components with an optically rough surface, the surface structure itself already shows height differences in the range of the wavelength. The range in which the height information can be unambiguously assigned must be enlarged to be able to measure such components as well. For this purpose, two-wavelength contouring is used. Two holograms with different wavelengths are recorded and subsequently evaluated in combination [3]. With this method, it is also possible to unambiguously measure component defects with height differences of more than 50 µm at the object surface.

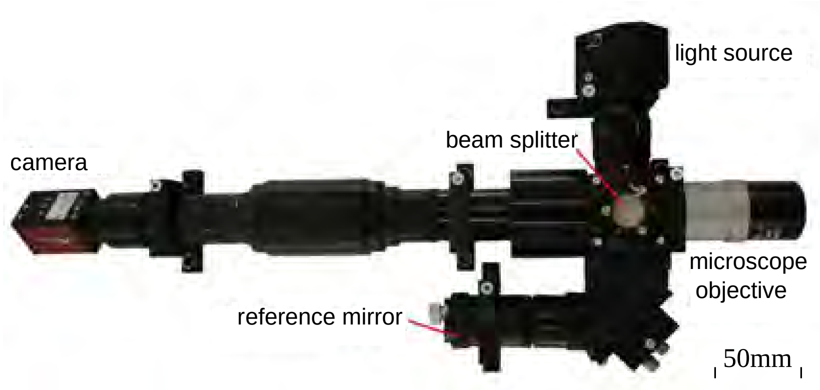

Fig. 1 Photograph of the digital holographic microscope with the essential optical components.

To make the measuring system adequately robust for use in a production environment, the entire light path was encapsulated. The purpose of this is to protect the optical components against contamination and to shield the system from external light which can influence the measuring process. Finally, to compensate for the vibrations that occur in the production environment, the interferograms for the two wavelengths are recorded with very short exposure times of less than 1 ms. To be able measuring also components with a height difference, which exceeds the depth of field of the measuring system, by two holograms, the recorded holograms will be refocused during the evaluating process.

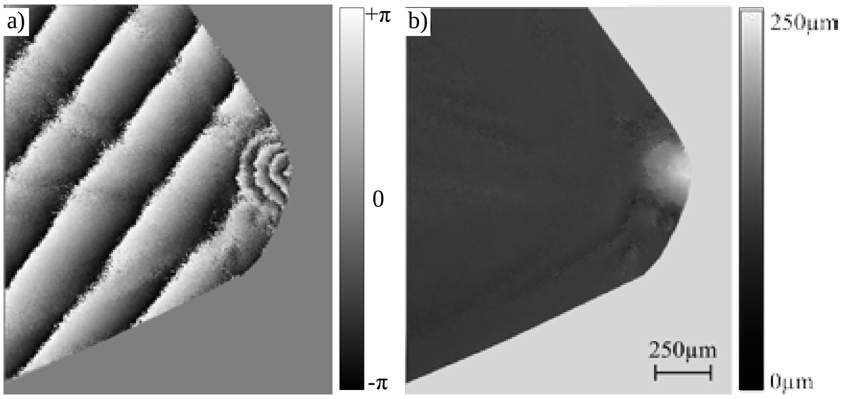

Fig. 2 Measurement results from the functional surfaces of a carbide insert. Phase values of the measurement showing a significant defect of the functional surface at the tip (right corner; a). Shape data of the carbide insert with the chipping at the tip of the cutting sheath, the chipping has a diameter of about 225 µm and a height difference of more than 200 µm.

This approach can also help to compensate deviations within the component positioning. Furthermore, the evaluation algorithms allow the comparison with a nominal component shape and the determination of the deviation from this shape for the measured object. This allows simpler detection of critical errors and avoids false rejects.

During tests in vibration stressed environments, it was possible to reliably identify component defects with a lateral resolution of 5 µm and a depth of at least 5 µm. In these tests, the measurement and evaluation time was less than 1 s. These tests were carried out in the laboratory with specific vibration stimulation, and in a real production environment.

Fig. 2 shows measurement results of the functional surfaces of a hard metal cutting insert. Fig. 2a shows the phase values of the measurement. The defect of the functional surface is clearly visible at the tip of the insert. For a better assessment of the dimensions of the defect, the shape data were calculated from the phase values, and are shown in Fig. 2b. This defect at the tip (white area) has a diameter of about 225 µm and a height difference of more than 200 µm.

The authors especially thank the Central Innovation Program for small and medium-sized enterprises (ZIM) for funding the research work within the project “Robuste digitale Holografie in der Produktionsumgebung” (RobuHoP) with the grant number 4587201LT8.

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Melt Pool Width Monitoring

In-situ measurement of the melt pool width in powder bed fusion processes

Raik Dörfert and Dieter Tyralla

Additive manufacturing processes are comparatively new manufacturing technologies that are becoming increasingly widespread due to their unique possibilities in terms of almost free design and the efficient production of small series and individual parts. In particular, the process of laser powder bed fusion (LPBF, also known as selective laser melting, SLM) has become established to produce metallic components.

However, the further widespread use of the process is limited by process-induced defects and the lack of reproducibility of the generated components. These defects occur during the process in the form of metallurgical pores, cavities, or insufficiently interconnected component layers [1], leading to huge investments in the necessary quality control. Among other things, the use of a fixed set of process parameters prevents sufficient adaptation to local changes in heat dissipation in the case of changing component geometries. For example, the increased heat accumulation on overhanging structures can lead to increased defects in the corresponding areas. Therefore, approaches must be developed to reliably detect and record local changes in the process conditions.

To achieve the desired component properties, process monitoring can not only be used for the early termination of defective construction jobs but also plays a crucial part in the development of in-situ capable control concepts. These concepts can make it possible to dynamically adapt a parameter set by, e.g., reducing the laser power in areas of overheating to achieve homogeneous part properties rather than selecting a global parameter set that does not adapt to changing boundary conditions.

Together with other developed approaches like process simulation as well as data preparation [5] for the identification of such critical component areas, the in-situ capable approach contributes to the overall goal of high part reproducibility and the dissemination of this manufacturing technology.

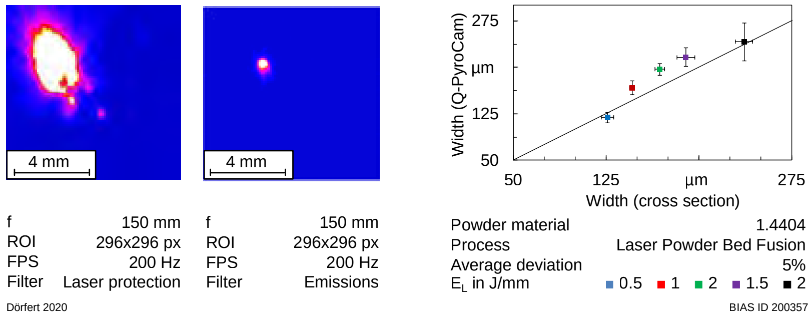

Fig. 1 (from left to right) Coaxial process monitoring without and with extensive filtering against process emissions as well as the metallographic cross-section of a single track and the measured deviation of the melt pool width between Q-PyroCam images (contains data from [2]).

To this end, measurement systems must be robust and able to cope with the high dynamics and scanning speeds of the LPBF process. For the recording of the heat dissipation and accumulation during the process, the temperature field in the process zone must first be reliably recorded. For this purpose, an HDRC® Q-PyroCam from IMS Chips was implemented in a commercial Realizer SLM 250 system from Realizer GmbH (part of DMG Mori AG) with a 200 W single-mode 1070 nm fiber laser from IPG Photonics. The Q-PyroCam is an imaging ratio pyrometer camera that facilitates the emissivity-compensated, spatially resolved acquisition of temperature and geometry data and has been successfully used in laser materials processing, e.g., in laser cladding [4]. The Q-PyroCam was integrated coaxially into the beam path of the LPBF system, allowing a high spatial resolution. The camera uses two channels with the wavelengths λ_1 = 661 nm and λ_2 = 667 nm, respectively [3]. The different wavelengths were realized by alternating IR filter stacks on the silicon camera chip. A particular challenge in the temperature field detection during the LPBF process is the large number of process-induced emission types, such as argon plasma, metal vapor, fume, and spatter. These emissions make it difficult to determine the absolute temperature values and must be filtered out of the signal. For this purpose, the following were used: a 1064 nm notch filter to protect the camera chip from the emissions of the processing laser as well as a 625 nm long-pass filter, and a 750 nm short-pass filter to isolate all emissions that were not directly in the range of the camera wavelengths. In addition, neutral density filters were used to suppress stray light and prevent the overexposure of the camera chip. For the integration of the Q-PyroCam, the optical components were replaced for the improved reflection of the returned process emissions through the beam path. The pinhole of the optical system was replaced with a custom-made beam splitter to allow the Q-PyroCam to be coaxially integrated into the beam path with a dichroic mirror from Precitec GmbH & Co. KG. The dichroic mirror had a higher reflectivity of the wavelengths of the Q-PyroCam as well as a very high transmission of the processing laser wavelength of 1070 nm. The beam splitter mirror was designed for a maximum laser power of 1 kW. The x-y mirrors of the scan unit were coated with a dielectric metal coating for a reflectivity of more than 97 % of the processing laser and a higher reflectivity of wavelengths between 600 nm and 900 nm for the Q-PyroCam. The S4LFT3260/105 F-theta lens from Sill Optics GmbH & Co. KG was also coated for the maximum possible transmission of the processing laser as well as the reduced reflectivity for a wavelength range of around 660 nm to improve the intensity of the returned process emissions for the Q-PyroCam through the optical system. The calibration of the camera system with all filters was pixel-based and performed through the entire optical system. The calibration was necessary to measure identical absolute temperature values for each pixel. Due to the significantly different wavelengths of the process laser and the used wavelengths of the Q-PyroCam, an overhaul of the optical system was also necessary to minimize the influence of chromatic aberration.

With the described method, a Q-PyroCam can be coaxially integrated into a scanner-guided system. The used filters enabled the melt pool size to be visually displayed (Fig. 1) without overexposure due to large quantities of recorded process emissions. The measured melt pool widths were validated with the corresponding metallographic cross-sections [2]. With only a notch filter to protect the camera against the emissions of the processing laser, a high degree of spatter and metal vapor was detected covering the melt pool area. However, the use of long-pass and short-pass filters, and especially neutral density filters, significantly reduced the number of visible emissions. This measuring system allows the melt pool width to be recorded as a function of the process parameters used for a measuring frequency of 200 Hz. Different energy inputs lead to increasing or shrinking melt pool widths. The average deviation of the measured melt pool widths from the metallographic cross-sections was 5 %. The selected resolution of 296×296 pixels provided a high spatial resolution of the process zone with 16 µm per pixel. Due to the coaxial implementation, this resolution can be achieved for any position on the build platform. Additionally, the resolution can be further reduced in exchange for a higher frame rate of up to 1 kHz if needed, allowing a trade-off between size and spatial resolution to be achieved. The system offers a robust and fast way to capture transient temperature fields, providing not only current temperatures and temperature gradients but also geometric data in the form of the melt pool width for further development of a control concept based on the melt pool width.

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Measurement of High-Precision Components

Testing of specular surfaces with phase-measuring deflectometry

Jonas Bartsch

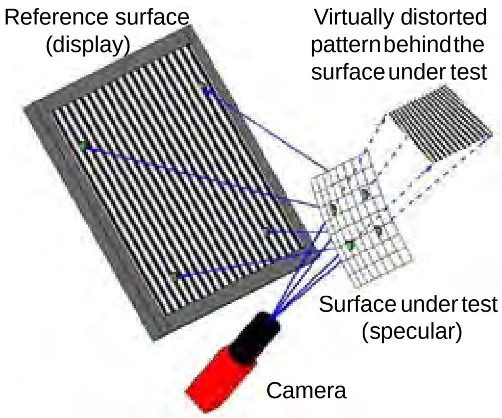

Fig. 1 Illustration of the principle of Phase Measuring Deflectometry. A camera observes sinusoidal fringe patterns displayed on a monitor in reflection on the surface under test. Displayed patterns are distorted due to the slope of the specular surface. Figure from [4].

Highly accurate, three-dimensional shape measurement is a base requirement for manufacturing of high-precision components. Deflectometry is a metrology technique specifically suited for specular surfaces. Based on the principles of geometric optics, it provides fast, full-field, and non-contact measurement and finds worldwide applications in testing of optical components like mirrors and lenses as well as in quality control of varnished surface for example in car manufacturing.

Phase-measuring deflectometry (PMD), also known as fringe reflection technique, yields measurement resolutions in the range of few nanometers. This technique is comparatively simple in terms of instrumentation, requiring only a commercially available CCD camera and a computer monitor. As shown in Fig. 1, the surface under test is placed in the field of view of the camera, enabling it to capture images of sinusoidal fringe patterns displayed on the monitor in reflection. Local slope of the surface under test causes distortion and deformation of these patterns from the camera's perspective. In a calibrated setup with known relative positions and orientations of the components, these recorded patterns provide information for determination of local surface slope and therefore allow the calculation of global surface shape. This simple approach is excellently scalable. Given appropriate setup geometries, measurement fields ranging from square centimeters to square meters can be realized. Since PMD measures surface gradients, it is particularly sensitive towards high spatial frequency surface structures like scratches and tool marks. Fig. 2 shows the measured microstructure of a plane mirror manufactured with diamond turning. Toolmarks with amplitudes in the range of few tens of nanometers can be detected.

Capturing images of series of sinusoidal fringe patterns shifted by constant phase angles allows to relate the individual camera pixels the observed phase angles. This so-called Phase Shifting Technique is used to achieve a unique mapping of observed positions on the displaying surface to the camera pixels. Since phase angles repeat with each fringe period, this mapping is initially ambiguous. Solving this ambiguity is called unwrapping and is typically performed by evaluation of multiple phase measurements of different fringe periods. Absolut two-dimensional coordinates of observed positions on the display surface are determined by performing two phase measurements with perpendicularly aligned fringes while combining measured phase angles with knowledge of the applied fringe periods. When measuring optically rough, so-called technical surfaces, reflected light is scattered into a solid angle depending the surface properties. This effect can lead to systematic measurement errors which is especially the case for anisotropic surface from grinding processes, where surface structures exhibit predominant direction. At BIAS, we investigate the effects of technical

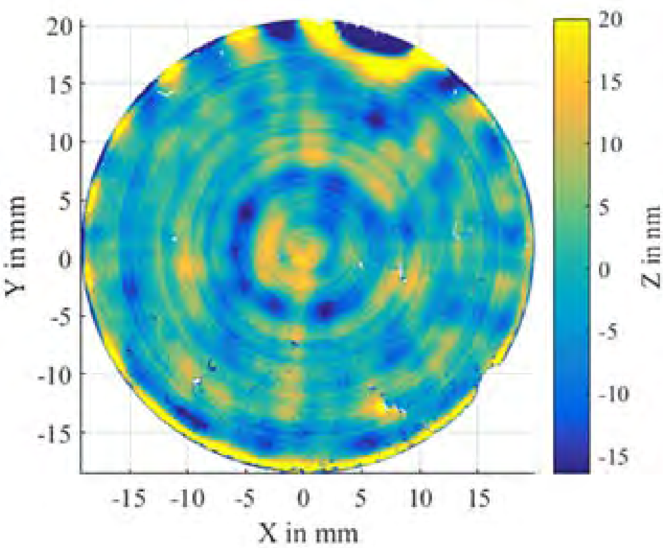

Fig. 2 Microstructure of a plane mirror manufactured with diamond turning. Measured with PMD. Figure from [1].

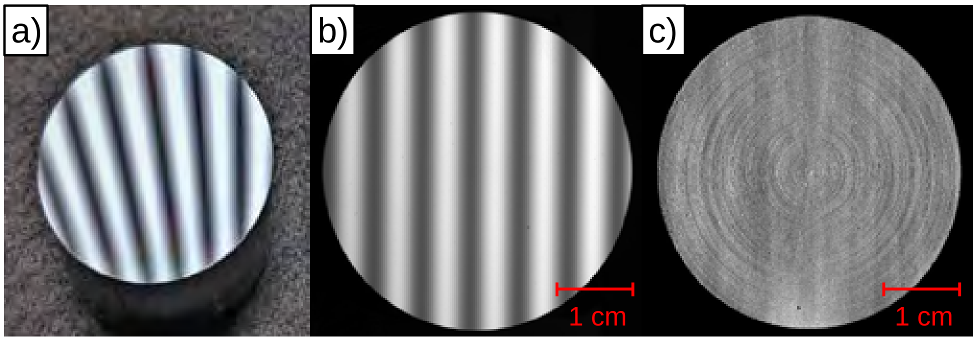

Fig. 3 Phase measurement on a mirror manufactured with diamond turning and subsequently coated with nickel-phosphorus: image of the surface under test captured with a mobile phone camera. The reflection of a sinusoidal fringe pattern can be seen on the surface (a). Single fringe image taken from a series of phase-shifted patterns from phase measurement, captured with the measurement setup (b). Residuals of measured and unwrapped phase angles after polynomial fit clearly exhibit circular tool marks (c).

surfaces on PMD aiming towards mitigation as well as utilizing the effects caused by scattered reflection on phase measurements for surface characterization [1].

Measurement and unwrapping of phase angles do not require system calibration. However, such measurements already allow a qualitative evaluation of the surface under test. This is illustrated in Fig. 3 on the example of a mirror manufactured with diamond turning and subsequently coated with nickel-phosphorus. The high spatial frequency components of measured phase angles were determined by subtraction of a polynomial fit. Microscopic tool marks from the machining process of the surface are clearly visible.

Measurement of absolute shape using PMD is based on tracing the inverse path of light received by the individual camera pixels towards the related positions on the display while determining those positions and local slopes of the surface under test yielding a valid path. This procedure requires a camera calibration which provides a vision ray pointing toward the source of received light for each camera pixel. At BIAS, we utilize displays as calibration targets instead of conventional marker plates. Continuous, full field spatial coding of the display surface by Phase Shifting Technique enables determination of independent vision rays for each camera pixel. In contrast to classical camera calibration techniques based on the pinhole model, this approach also incorporates locally confined errors of the imaging system [2].

Transformation of measured display surface coordinates into the reference system of the vision rays requires knowledge of relative position and orientation of camera and display. Such a geometric system calibration is typically achieved using a plane reference mirror. However, also the shape of the display surface needs to be known. Assuming a flat display surface as an approximation causes systematic errors. The effects of display flatness deviations as well as further non-ideal display properties like refraction at the coverglass were quantified in investigations at BIAS [3]. We demonstrated that systematic shape measurement errors are reduced by more than 90 % by a simple polynomial model for the shape of the display surface. The corresponding polynomial coefficients can be determined without prior knowledge during system calibration [4].

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Characterization of the Powder Jet in LMD Processes

Dieter Tyralla, Annika Bohlen, and Thomas Seefeld

Powder jet-based laser cladding processes are more and more used in additive manufacturing. Laser beam and powder jet parameters must match each other for a stable welding process and a homogeneous quality. Up to now, there is only little information on the powder jet and few methods for its characterization and monitoring.

Additive manufacturing is a key technology in production and is an energy-efficient type of manufacturing. Laser powder bed welding (LPBF) is already commercially used in many applications but is limited by the deposition rate and in the component dimensions due to the protective gas chamber. Powder jet-based additive manufacturing enables larger component dimensions and a hybrid manufacturing, in which functional elements can be applied to existing, large semifinished products.

In laser powder cladding, the energy of a laser beam is used to create a molten pool on the workpiece. A powder-shaped filler material is fed into the process zone through a powder nozzle using a gas flow. A welding bead is generated on the surface by the relative movement between the processing head and the workpiece. If several beads are placed next to each other, a continuous layer is formed. If the process is repeated layer-by-layer, 3-dimensional geometries are also possible.

The introduced energy and the powder quantity must be exactly matched to obtain a stable process and to produce well-defined weld beads. Although laser powder cladding is a manufacturing process that has been used for many years, the direction-independent multilayer process of additive manufacturing requires the development of new characterization methods for measuring the powder flow. Here, we see a lack of measurement methods and uniform standardization.

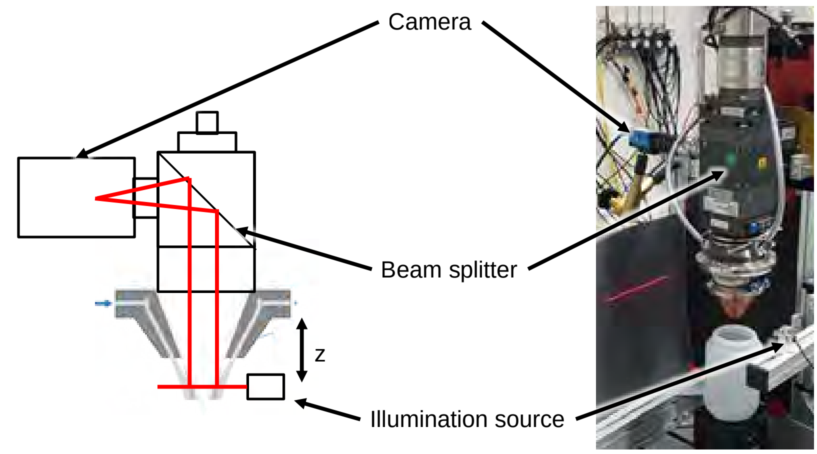

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Fig. 1 Experimental setup of powder jet measurement.

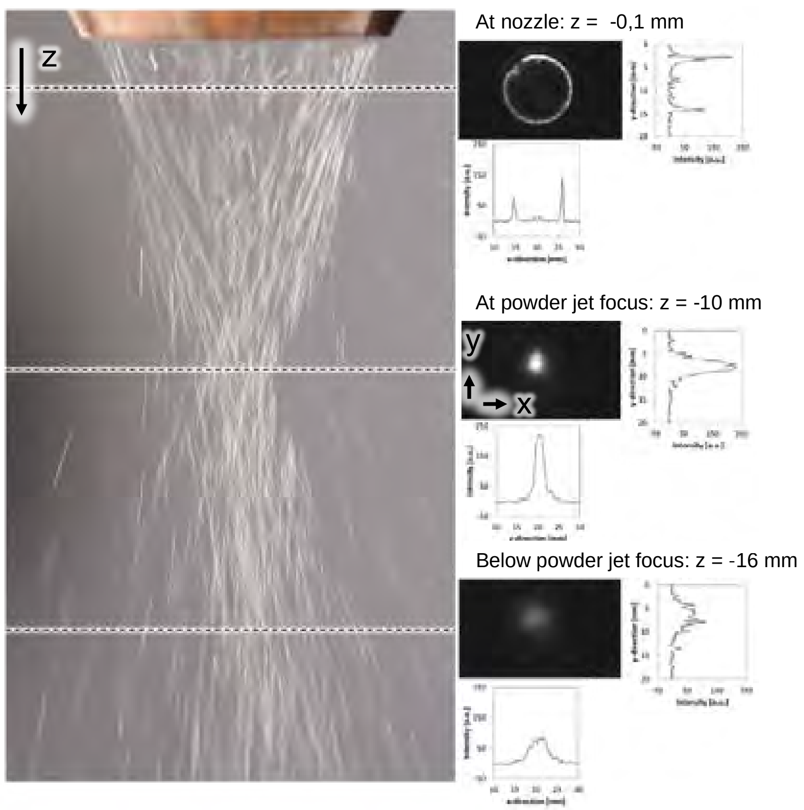

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Fig. 2 Powder jet analysis: Particle distribution in x-y-plane at different distances to nozzle.

Therefore, a measuring principle was developed that allows the characterization of the powder jet. These measurements obtain a validation base for accurate process simulation and are supposed to expand scientific knowledge of particle flow and LMD process. Thus, a new method is developed that will allow the optimization of powder nozzles and the prediction of applicable process parameters.

Fig. 1 shows a measurement setup that uses a commercial industrial camera, which is coupled into the laser processing optics via a beam splitter. This enables a coaxial observation of the process zone along the laser axis. A simple line laser is aligned perpendicular to the powder nozzle to illuminate one plane of the powder jet. The line laser or the processing head must be moved vertically in steps and illuminate the shape slice by slice to obtain a complete measurement of the entire powder jet. When the laser beam hits a powder particle, the light is reflected. The higher the particle population at one point, the brighter the corresponding area in the camera image. Thereby, the measured brightness distribution can be used to infer the particle density in the x-y-plane of the powder jet, as Fig. 2 shows. The line width of the laser determines the vertical resolution of one of these planes, while the number of pixels of the camera determines the lateral resolution.

Up to now, the method has been successfully tested with typical nozzle geometries and has been used to characterize the powder jet and to extract characteristic values. Most important values of the jet are the particle density and distribution in different x-y-planes, the powder focus, the rel. position and the tilt of the jet, the jet diameter, the aperture (divergence) and the alignment of jet and laser beam axis. In addition, the measurement also enables an assessment of the nozzle condition. Defects and damages to the nozzle, which have an influence on the powder jet and often cause imperfection during process. They can be analyzed, and detected based on the jet characteristics. Fig. 3 shows a damaged nozzle and the resulting jet analysis.

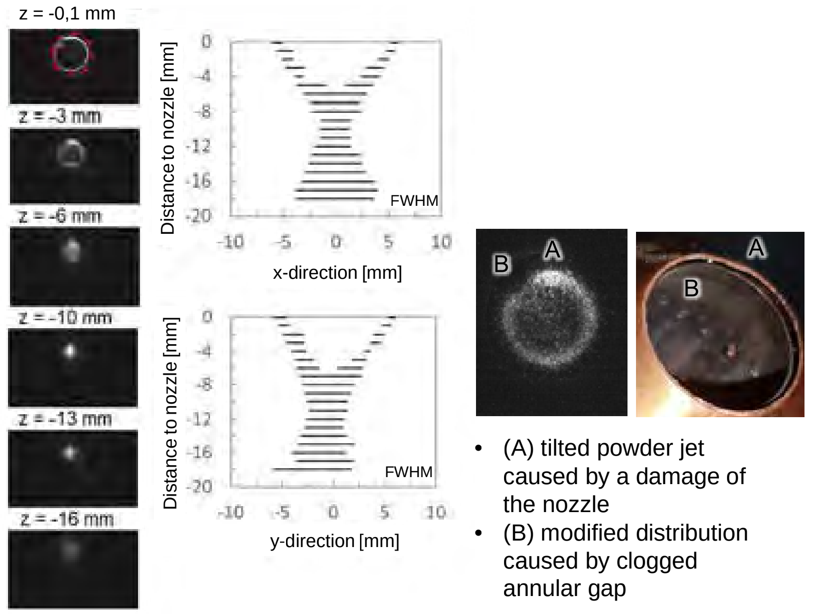

Fig. 2 Powder jet characterization of a annular gap powder nozzle. The measurement enables the recognition of nozzle damages that cause tilted jets or faulty powder distributions and may affect the weld quality.

Further, a method was developed which can also measure the powder jet during laser processing. Thus, a permanent online-monitoring provides information to the nozzle condition and detects deviations as quickly as possible.

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Closed-Loop Control of Penetration Depth in Wire-Based Laser Cladding

Dieter Tyralla, and Thomas Seefeld

Up to now, powder based cladding processes are used to produce high-quality coatings with low dilution. However, the productivity of the process is limited and is accompanied by complex handling and the health hazards of powder materials. In comparison, the wire-based cladding process allows higher deposition rates, and the wire-shaped filler material is much cheaper compared to powder. However, the dilution and the geometrical shape of the layer usually fail to comply higher quality standards.

Laser cladding is a well-established production technique for the generation of functional layers on a parts surface and for the reconditing of worn work pieces. The process uses the energy of a laser beam to create a melt pool on the surface of the substrate. The filler material is fed into the melt pool, where it melts and mixes with the substrate. The additional material forms a welding bead on the surface by the relative movement between processing head and the workpiece. If several welding beads are placed side-by-side, a consistent layer is formed.

In most applications, the layer should provide the properties of the filler material and thus, as little substrate material as possible must be melted and mixed to achieve a high purity of the layer. However, enough must be melted to create a metallurgical bond. The relation of substrate and filler material is called dilution which is one of the most important quality features in laser cladding.

In the AiF project “Kontrolliertes Laser-Heißdrahtbeschichten” a new variant of wire cladding processes was developed that provides low dilution and high deposition rate in once [1]. For this purpose, a laser hot-wire cladding (LHWC) setup is used where the wire is fed at a 45° angle in a trailing arrangement. In addition, a laser beam oscillator is used to distribute the laser energy over the process zone. Thus, an applicable energy distribution can be achieved in the process zone which introduces most of the energy directly into the wire and only a small part into the substrate material. Thereby, more wire can be melted without increasing the size of the melt pool as is common with the conventional method. This enables high deposition rates and low dilution in the same process. In the present case, laser beam oscillation enables a deposition rate of more than 5 kg/h and a dilution of less than 10 % with a laser power of 4 kW. The new method has been successfully tested on the two most common filler materials stainless steel (316L) and a nickel-based filler (inconel625). Initial tests suggest similarly promising results for stellite and hardfacing wires.

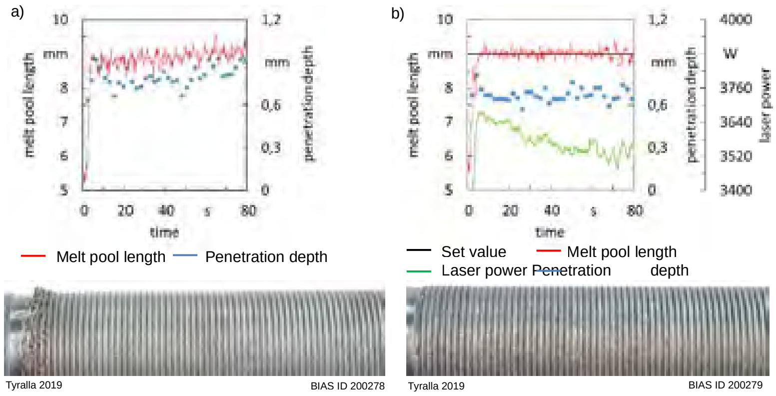

Fig. 1 Comparison of laser cladding process with online-monitoring (a) and closed-loop control system (b). In the first case, the process applies a laser power of 3.5 kW, whereas the power is adjusted to maintain a constant melt pool length in the controlled case.

As a further innovation, process monitoring is used in the project to monitor and control the LHWC process. A special two-channel-pyrometer camera observes the process with a high frequency of up to 1000 frames per second. The camera detects special thermal based indicators to evaluate the process. The melt temperature is used to determine different melt pool related values like width, length and size which are used to recognize variations in the process behavior and forms the valuation basis for the control algorithm.

In the present case, a LabView-based algorithm was developed to connect and control the different components of the system. The algorithm maintains the melt pool length constant to a given sat-value by an adjustment of the laser power to generate a homogeneous penetration depth and thus, achieve consistent layer properties. The set-value is determined in a reference process.

Fig. 1 shows the results of the mentioned control approach compared to the reference without control. Melt pool length and penetration depth are shown. In Fig. 1a, the process applies a constant laser power of 3,5 kW. In this case, the low wall thickness of 5 mm leads to heat accumulation in the part and increases the melt pool size which results in higher melt pool length and penetration depth. In the second case that is shown in Fig. 1b, the laser power is controlled by the algorithm. The variations of melt pool length are recognized, and the laser power is adjusted to a lower level to prevent heat accumulation. Thus, the penetration depth can be maintained constant to the given set-value. In addition, the control achieves a significant lower standard deviation in melt pool length, which commonly indicates a stable, homogeneous melting process. The starting behavior of the process can also be significantly improved by the control which is illustrated by the images of the specimen. In contrast to the reference which applies constant laser power, the controlled case adjusts the laser power to a higher level at the beginning to preheat the cold part and thus, the layer comply the requirements from the beginning.

The prototypically setup was transferred during project to a common laser cladding system in an industrial environment to demonstrate the applicability of the new principle for small and medium-sized companies. Therefore, the components were integrated into the system technology of the project partner LaserCladding Germany GmbH. The cladding of a real component in form of a 300 kg shaft was performed as functional demonstration of a common application of a job shop manufacturing task. Fig. 2 shows the setup. The demonstration proofs the transferability of results regarding high deposition rate and accessibly dilution.

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Fig. 2 Experimental setup at project partner LaserCladding Germany GmbH.

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Directed Energy Deposition with Aluminum Alloy

Directed energy deposition of high-strength aluminum alloy with local hard particle reinforcement

Anika Langebeck

Directed energy deposition (DED) is an open space process of additive manufacturing (AM) technologies. Due to its high deposition rates, DED processes are well suited to produce large components in small quantities or for customer-specific individual production. During the manufacturing process the laser is used to create a melting pool on the substrate and to melt the added powder as well. Welding tracks are manufactured from which the large AM component is built.

As powder material steel powders like 316L or aluminum alloys from the 4xxx series with a good weldability are used. The use of high-strength 7xxx aluminum alloys in particular meet the increasing demands for energy-efficient lightweight construction of components. However, 7xxx alloys have a poor weldability, which makes their processing by DED a challenge. In addition to the use of a single powder material in DED-based additive manufacturing, process setup also allows the tailored use of powder mixtures. These material combinations include MMC materials (metal matrix composite), in which a metallic matrix material is reinforced with hard particles. This is done, among other things, for wear protection purposes.

The combination of a high-strength aluminum alloy as a matrix material with a highly hard reinforcement material, such as spherical fused tungsten carbide, makes it possible to combine lightweight construction and wear resistance in an outstanding way. One application for these components are rolling bearings, which must be lightweight for energy-efficient operation and highly wear-resistant for a long service life.

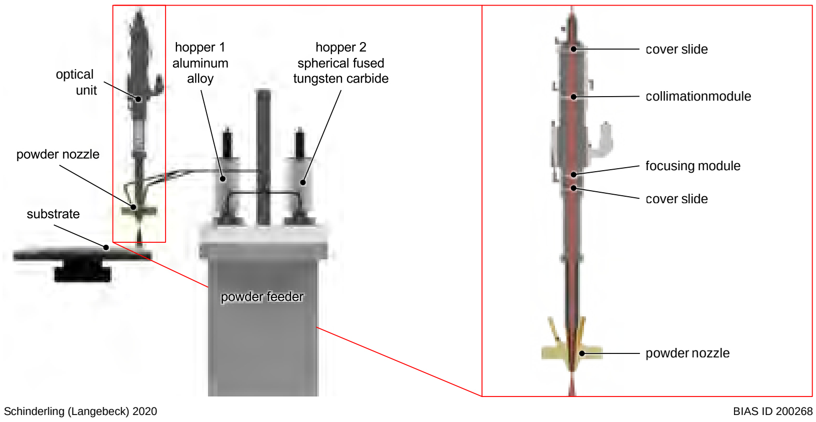

Fig. 1 Sketch of experimental setup directed energy deposition of large components made of a high-strength aluminum alloy with a local hard particle reinforcement. The optical unit used is shown enlarged on the right

Directed energy deposition of EN AW-7075

The implementation of directed energy deposition of large components made of a high-strength aluminum alloy with a local hard particle reinforcement of spherical fused tungsten carbide is carried out with a solid-state laser. The experimental setup is schematically shown in Fig. 1.

By adjusting the process parameters via a parameter study, the aluminum alloy EN AW-7075 with a poor weldability can be processed by DED with low imperfection. An additional shielding gas shroud, coaxial to the powder nozzle, reduces the pore volume. The remaining porosity in the welding track can be reduced to less than 0.1 % by increasing the energy input per unit length from 3000 J/cm to 6000 J/cm at a constant feed rate (400 mm/min) and a defocused laser spot with a diameter of 4.5 mm.

The DED-manufactured parts are made up of many individual welding tracks with a horizontal and vertical overlap in between. It can be shown that a high degree of overlap significantly increases the porosity. Compared to a single track with a pore volume less-than 0.1 %, the porosity of several tracks with a horizontal overlap of about 50 % is larger than 2.0 %. The reason for the increase in porosity is most likely attributed to the surface of the preceding welding track. This surface is very rough and covered by an oxide layer, which can cause the porosity when it is re-melted during the process of the subsequent welding track. Therefore, the smaller the overlapping area between two individual welding tracks, the lower the porosity. A degree of overlap in the horizontal direction of about 30 % can be recommended to produce surfaces that are as even as possible with low porosity in the cross-section. For the offset in vertical direction, a degree of overlap of about 13 % is advantageous. Higher values can lead to clogging of the powder nozzle due to the reduced distance to the specimen's surface.

Directed energy deposition of EN AW-7075 with local reinforcement by spherical fused tungsten carbide

To locally reinforce areas with hard particles during the DED-process, spherical fused tungsten carbide particles are also fed to the process zone in addition to the aluminum powder. The powder flow of the two materials can be adjusted independently of each other. The aim is to ensure that the hard particles do not melt and are homogeneously distributed in the solidified aluminum alloy. Due to their high density of 16 g/cm³ to 17 g/cm³, the tungsten carbide particles

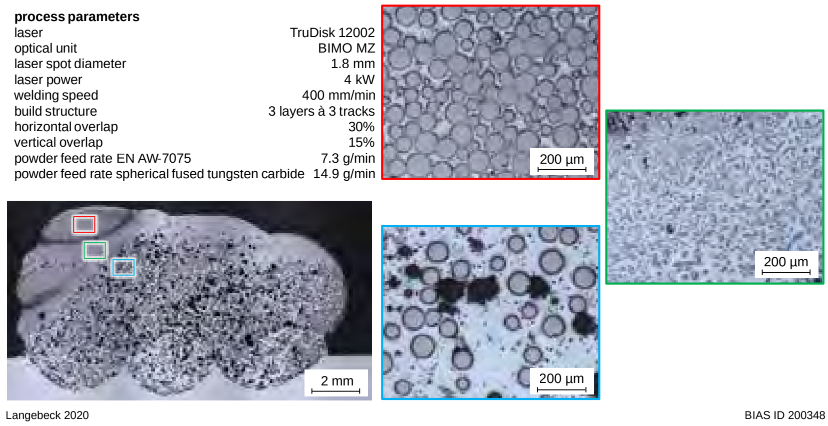

Fig. 2 Cross-sections of a specimen manufactured by directed energy deposition from the high-strength aluminum alloy EN AW-7075 and spherical fused tungsten carbide particles in a single process step (Source: D. Loske)

sink down in the melt pool. At a volume fraction of the hard particles of about 50 vol% and more in the powder jet, the embedding of the hard particles to the aluminum alloy matrix is disrupted. At lower volume fractions the hard particles are better embedded in the matrix. In multilayer specimens manufactured with 26 vol% tungsten carbide, a distinction can be made between three zones in the cross-section (Fig. 2). In the first layer of the additively manufactured specimen, the hard particles are well distributed in the aluminum matrix, but this area (Fig. 2, blue frame) shows an increased porosity. In each of the last welding tracks of the subsequent layers above, a high hard particle content is achieved. Additionally, this area shows nearly no imperfections such as pores (Fig. 2, red frame). This condition of the reinforced layer is desirable. The mentioned two areas are separated by a third area (Fig. 2, green frame). This one contains no spherical fused tungsten carbide particles and shows a very low porosity.

In conclusion, directed energy deposition is a suitable technology for additive manufacturing of larger parts with local hard particle reinforcement, although the process control is challenging.

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Hard Particle Reinforcement for Micro-forming Tools

Hard particle reinforcement of microforming tools via laser melt injection for improved wear resistance

Anika Langebeck

Microinjection molding is an important manufacturing technology for the mass production of small plastic parts. In this industry, the molding tools are undergoing locally high loads and wear, which significantly reduce the service life of the tool and thus also the maximum service life. One approach is to reinforce the microinjection mold's surface by laser melt injection to achieve a metal matrix composite (MMC) with a high wear resistance.

A typically used material for molding tools is hardened steel. Machining hardened steel is problematic due to the severe chemical wear of micro-milling tools. Alternative materials for microinjection molding tools are easily machinable copper-based alloys. However, molding tools made from these materials have significantly shorter service lives due to their lower wear resistance. This is particularly evident when processing plastics with fillers. Via laser melt injection a wear-resistant MMC surface can be obtained. During this process, hard particles are introduced into the melt pool at the workpiece surface without melting the particles themselves. Typically, carbides such as titanium carbide, chromium carbide or tungsten carbide are used as hard particles [1]. Investigations on MMC surfaces made of an aluminum bronze with spherical fused tungsten carbide showed a significant decrease in abrasive wear mass due to hard particle reinforcement [2]. Further experiments show that increasing the hard particle content can lead to an increase in wear resistance [3].

Increasing the hard particle volume fraction in MMCs

A solid-state laser was used to generate MMC surfaces. The laser beam was guided to the processing optics via an optical fiber. A melt pool was generated in the aluminum bronze with a defocused laser spot with a diameter of 3 mm and with a laser power of 2 kW. The powder material, spherical fused tungsten carbide, was fed to the process zone via a powder nozzle from GTV.

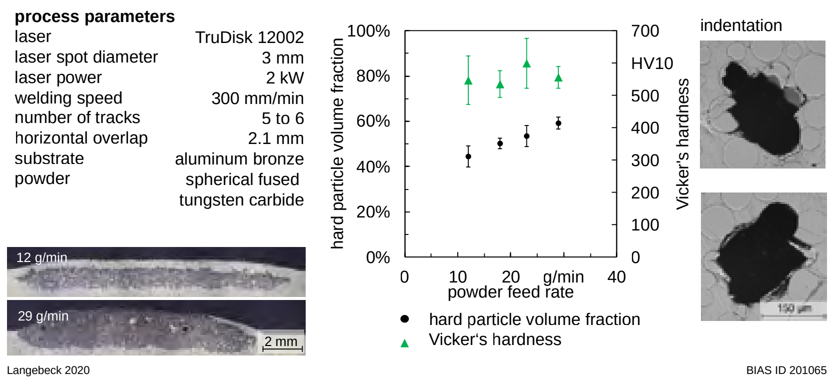

Fig. 1 Cross section of MMC layers with different powder feed rates; hard particle volume fraction and Vicker's hardness with respect to powder feed rate; indentation of Vicker's hardness measurements in MMC surface

The hard particle volume fraction within the MMC layers can be adjusted via the powder feed rate, with all other process parameters remaining constant. With an increase in the powder feed rate from 12 g/min to 29 g/min, not only the layer thickness but also the hard particle volume fraction within the MMC layer increases from (44.5 ± 4.8) % to (59.2 ± 2.6) % (Fig. 1). For the spherical fused tungsten carbide, the apparent density determined according to DIN EN ISO 3923-1:2018-10 is (10.2 ± 0.1) g/cm³. This corresponds to 60.0 % to 63.8 % of the bulk density of spherical fused tungsten carbide, which is specified by the manufacturer with 16 g/cm³ to 17 g/cm³. Therefore, it can be assumed that a further increase in the hard particle content above (59.2 ± 2.6)% is hardly feasible.

In addition to the hard particle volume fraction, the overall hardness of the MMC layer can also be determined. Since the microstructure of the MMC layer is very heterogeneous in its properties, only a limited statement on the layer hardness can be made here. A test load of 98 N is used, to obtain an indentation as large as possible, to determine the hardness of the MMC microstructure and not of an individual hard particle or the matrix material. During the test, the hard particles can break out of the matrix, which makes it difficult to measure the length of the diagonal left by the indenter (Fig. 1). The results as a function of the set powder feed rate are shown in Fig. 1. No significant change in the measured hardness can be detected.

MMC surface for micro injection molding tools

The path planning for the laser melt injection of a functional model of a micro injection molding component is carried out using the Fusion 360 CAD software from Autodesk and a MatLab-based program for creating the specific G-code. Fig. 2 shows the CAD model of the functional model and the planned path for laser melt injection. To best reproduce the surface geometry of the functional model, a smaller laser spot diameter of 1.5 mm was used, and the power applied was reduced accordingly. The MMC layer (Fig. 2) can then be reworked, for example, using micro milling. This provides surfaces on the micro injection molding tool with hard particle reinforcement for increased

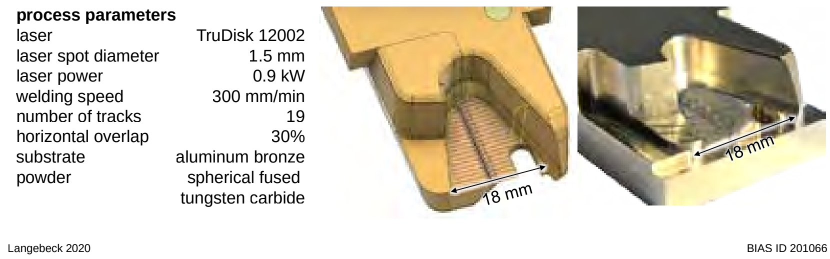

Fig. 2 CAD model of functional model as well as planned path for laser melt injection; MMC surface on micro injection molding component after laser melt injection

wear resistance, which also have a high surface quality.

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Laser Chemical Machining with High Process Pressure

Increase of the removal rate in laser chemical machining by increasing the process pressure

Marcel Simons and Tim Radel

In order to meet the increasing demands on complexity and multifunctionality of the components to be produced, so-called non-conventional machining processes are being developed [1], including laser chemical machining (LCM). Laser chemical machining is a surface treatment that removes material by the effect of laser induced thermal activation of heterogenous chemical reactions between the electrolyte solutions and a metallic surface [2].

Laser chemical machining depend on raised temperature at the interface of laser radiation, material, and electrolyte solution to function. The quality of the LCM process is largely determined by boiling in the interaction zone due to local overheating [3]. The resulting laser-induced boiling bubbles, see Fig. 2, adhere to the workpiece surface and shield it. The transition of the laser radiation from an optically dense medium (electrolyte solution) to an optically thin medium (boiling bubble) causes a deflection of the laser radiation [4]. The adhering gas bubbles act as scattering centers which deflect part of the incident laser radiation, resulting in a reduction of the removal quality, in terms of surface quality, shape accuracy etc.

To minimize the formation of boiling bubbles during laser chemical machining, the approach of increasing the process pressure was chosen. the boiling temperature of the electrolyte solution rises with an increase of the process pressure, which minimizes the electrolyte solution boiling process. As shown in Fig. 3, the process window increases with increasing process pressure. The increase of the process pressure allows the laser chemical process to be performed at increased laser power. Due to the correlation between removal rate and surface temperature of the workpiece, which is directly determined by the applied laser power, the removal rate increases with increased laser power. By increasing the process pressure to 6 bar (max. laser power: 2.2 W), the removal rate could be increased by a factor of 2.46 compared to machining at ambient pressure (1 bar; max. laser power: 1.4 W).

Furthermore, it can be stated that the increase in process pressure has no effect on the characteristics of the laser chemical cavities. The resulting cavities at elevated process pressures are comparable in terms of shape accuracy and surface roughness to the resulting cavities at ambient process pressure, see Fig. 3 and 4. As mentioned above, the widening of the process window is due to the reduction of the electrolyte solution boiling process. This reduction of the laser-induced electrolyte solution boiling process is described in particular by the reduction of the gas bubble diameters as well as the adhesion time of the gas bubbles to the workpiece sur-

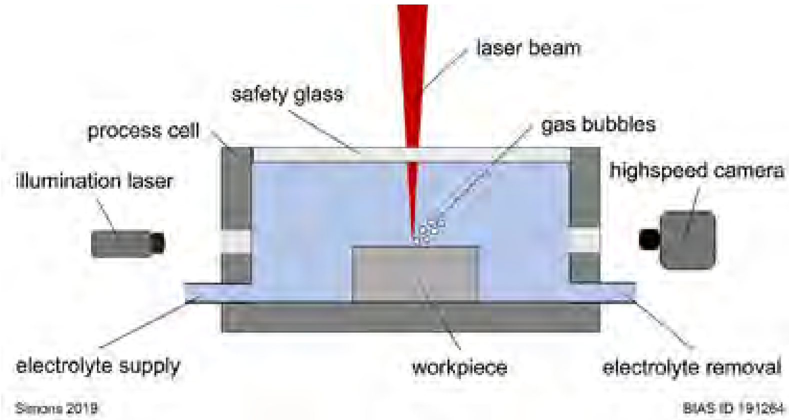

Fig. 1 Schematic representation of the laser chemical test setup

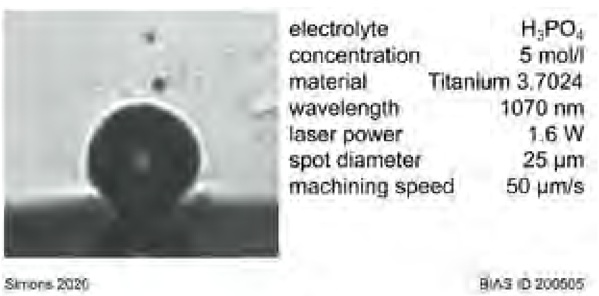

Fig. 2 High-speed shadow image of a laser-induced boiling bubble

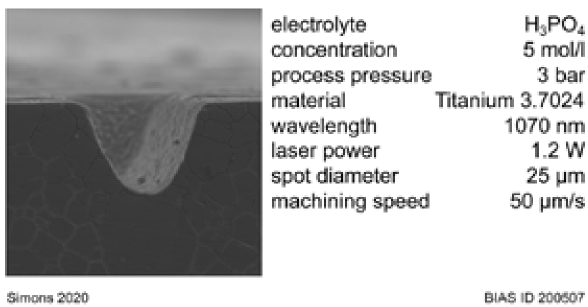

Fig. 4 Exemplary laser chemical cavity, generated with a process pressure of 3 bar

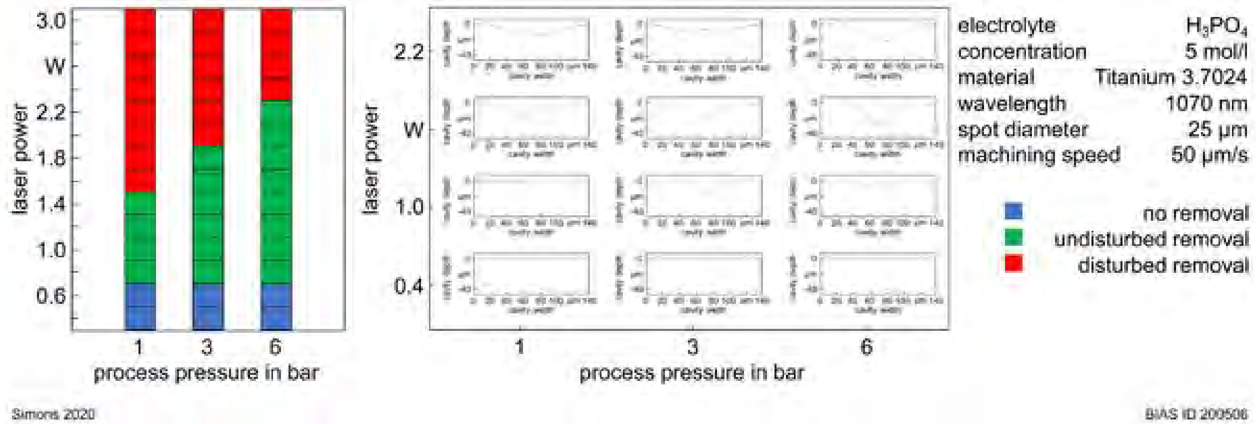

Fig. 3 Schematic representation of the laser chemical process window and the associated cavity profiles

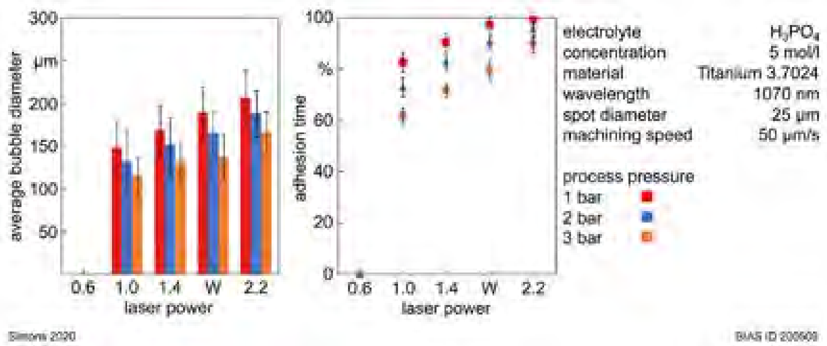

Fig. 5 Representation of the averaged boiling Bubble diameters and the percentage adhesion times at varying laser powers and process pressures

face. By increasing the process pressure, the boiling bubble diameter could be reduced by up to 27 %, when machined at 6 bar process pressure, see Fig. 5. In addition, Fig. 5 shows the adhesion time of the boiling bubbles to the workpiece surface in percent of the total machining time. At increased process pressures the workpiece surface is free of the gas bubbles for a longer period of time.

In summary, increasing the process pressure during laser chemical machining minimizes the laser-induced electrolyte solution boiling process, thus enabling an increase in the removal rate.

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Generating MMC Coatings by Laser Melt Injection at High Process Speeds

Reinforcing highly thermally conductive copper tools for pressure die casting by fused tungsten carbide particles

Philipp Warneke

Highly thermally conductive copper alloys are used for various tools in forming and joining technology. In pressure die casting, pistons made of these alloys are used. The pistons press the melt into a mould and dissipate a part of the process heat. Due to the high thermal conductivity, short process times can be achieved. A decisive disadvantage of these alloys is their low wear resistance, which results in short piston service lives and high set-up costs.

By dispersing extremely wear-resistant spherical tungsten carbide particles into the rim zone of the workpiece, a significant improvement in wear resistance can be achieved. While a layer of a foreign coating material is applied to the base material in most wear protection processes, laser melt injection generates a coating of a metal-matrix composite (MMC). The base material works as matrix material. Fig. 1 shows the principle of the process. Thanks to this process, it is possible to combine the properties of the filler material with those of the base material within the rim zone of the part. Copper alloys pose a special challenge in laser material processing because of their very high reflectivity in the infrared wavelength range. In addition, due to the large difference between the absorption coefficients in the solid and liquid state, there is a risk that an unstable melt pool and thus irregularities in the coating occur. A further challenge is the realization of large dispersing rates, which are necessary to achieve a sufficient productivity. As an approach to overcome these challenges, high laser beam intensities of up to 223 kW/cm² were applied. To avoid damage due to back reflections, the processing optic is tilted by 20° from the vertical.

These changes in the process made it possible to process the copper alloy Hovadur® CNCS (thermal conductivity 220 W/mK, average value between 20 °C and 300 °C) with infrared laser radiation. Homogeneous coatings with an SFTC particle content between 20 vol% and 40 vol% could be produced. Process speeds of up to 8.75 m/min – corresponding to a dispersing rate of 8750 mm²/min – were achieved. Typically, process speeds below 1 m/min are used for laser melt injection. Fig. 2 shows three micrographs at different dispersing rates. The energy per unit length and the powder mass per unit length were constant in all tests. Increasing the laser power from 3000 W to 5000 W showed that deformations of individual particles occurred due to stronger interactions with the laser beam. At a laser power of 7000 W, not only deformations but also agglomerates of several particles were formed. These agglomerates were oriented on the geometry of the individual weld seam.

Hardness measurements on the SFTC particles and agglomerates showed that the deformations of SFTC particles and the formation of agglomerates did not result in a decrease in hardness. The micrographs in Fig. 2 also show that the dispersing rate has an influence on the MMC layer thickness. To investigate this

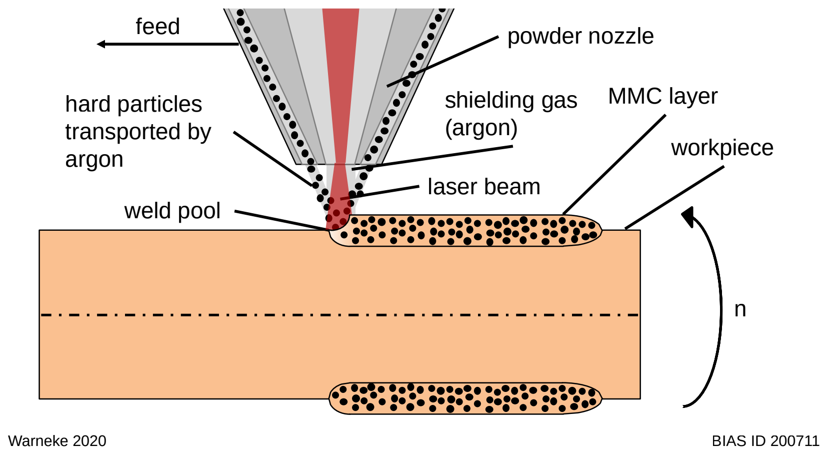

Fig. 1 Principle of laser melt injection. A laser beam generates a weld pool on the workpiece in which a powdered filler material is fed by a powder nozzle.

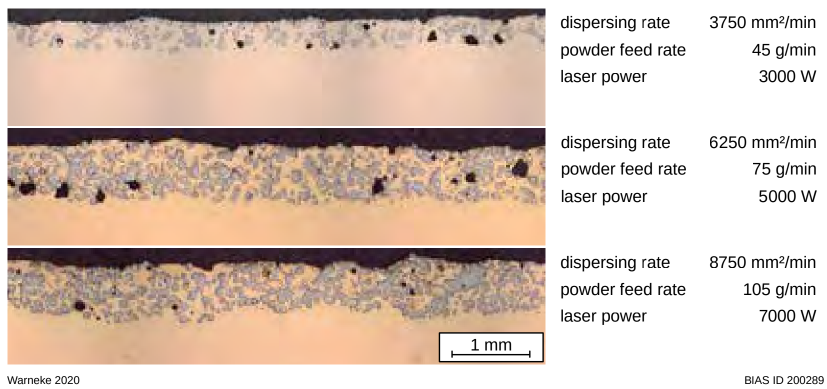

Fig. 2 Cross sections at three different dispersing rates. The dispersing rate was increased at a constant energy per unit length and powder mass per unit length. At a high laser power, more SFTC particle deformations and agglomerates could be detected.

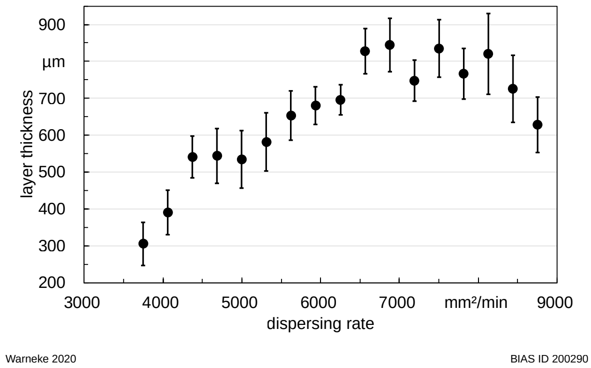

Fig. 3 MMC layer thickness depending on the dispersing rate. First, the layer thickness increased with the dispersing rate. From a dispersing rate of 8125 mm²/min on, the layer thickness decreased.

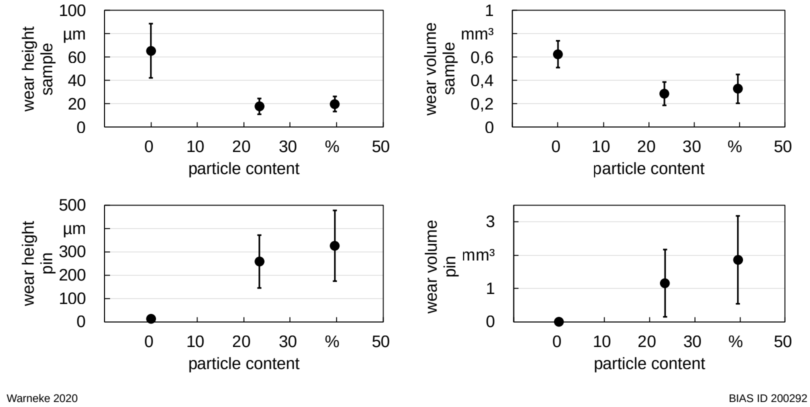

Fig. 4 Wear height and wear volume depending on the SFTC particle content on uncoated and coated Hovadur® CNCS samples and the corresponding counter bodies (pins). The wear of the Hovadur® CNCS samples was reduced significantly by an SFTC particle reinforcement. However, the wear of the corresponding counter bodies increased considerably.

relationship in more detail, dispersing rates between 3750 mm²/min and 8750 mm²/min at a constant energy per unit length and powder mass per unit length were investigated. Two opposite effects can be used to explain the course of the diagram shown in Fig. 3. By increasing the dispersing rate and thus the process speed, the process efficiency increases. At high process speeds, a greater proportion of the energy absorbed in the workpiece is used to produce the weld seam than at low speeds. This increases the layer thickness. A further effect is the shadowing of the weld pool by the powder material. The powder feed rate is increased proportionally with the dispersing rate to keep the powder mass per unit length constant. However, the volume flow of the powder feed gas remains constant. Therefore, the shadowing of the weld pool by the powder material increases with an increasing dispersing rate, which has a diminishing effect on the layer thickness.

A model test in a tribometer was carried out in order to investigate the wear behavior. At a test load of 30 N and a test time of 4 h, counter bodies made of the tool steel 1.2343 in a hardened and gas-nitrided condition with a spherical surface oscillated on uncoated Hovadur® CNCS samples as well as on samples with an SFTC particle content of 23 vol% and 40 vol%. With the help of a confocal microscope, the wear height and wear volume were determined. The SFTC particle reinforcement made it possible to reduce the wear height of the Hovadur® CNCS samples to one third and the wear volume to half, see Fig. 4. An increase in the SFTC particle content from 23 vol% to 40 vol% showed no further improvement in wear resistance. The wear of the counter bodies that had been moved on uncoated samples was minimal. The SFTC particle reinforcement of the Hovadur® CNCS samples led to a significant increase in wear of the counter bodies.

*

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Increased Laser Polishing Rates of LPBF Components

High path overlaps to reduce surface features at laser polishing of LPBF components with high process speeds

Lucas-H. Beste, Florian Schadewald, Tim Radel, Brodan Richter, Patrick J. Faue, Frank E. Pfefferkorn, and Frank Vollertsen

The production of components using laser powder bed fusion (LPBF) offers a wide range of applications. The selective local energy input and layer-by-layer melting of powder particles allows high design flexibility and a wide range of component geometries. It is often necessary to apply post-processing steps in the process chain to meet the design requirements. Besides metallurgical reasons, which may, for example, require a heat treatment, a subsequent treatment may be necessary due to the surface topography. During the LPBF process, partially-melted powder particles often remain on the surfaces. Additionally, the layer-by-layer melting of the powder particles can contribute to the waviness of the surface. Therefore, LPBF components usually have a process chain with post-processes such as machining, grinding, mechanical polishing, shot peening and similar techniques. Laser polishing is an alternative that allows complex surfaces to be polished contact-free and non-abrasively without tool wear. Thus, it is not only possible to smooth the surfaces by remelting, but also to reduce the porosity close to the surface. Typical polishing rates are in the range of a few mm²/s. The melt pool dynamics and the associated waviness limit the melt pool size and processing speed and therefore the achievable polishing rates. Nevertheless, an increase of the polishing rate is desirable.

The polishing rate depends on beam diameter, process speed and path overlap. According to the literature different approaches to increase the polishing rate are possible. For example, this problem can be countered by beam shaping or adjusted intensity distribution. Within this study, the approach of using high process speeds in combination with high path overlaps is investigated. It is based on the hypotheses that the high path overlaps can limit the resulting waviness and therefore enable high polishing rates.

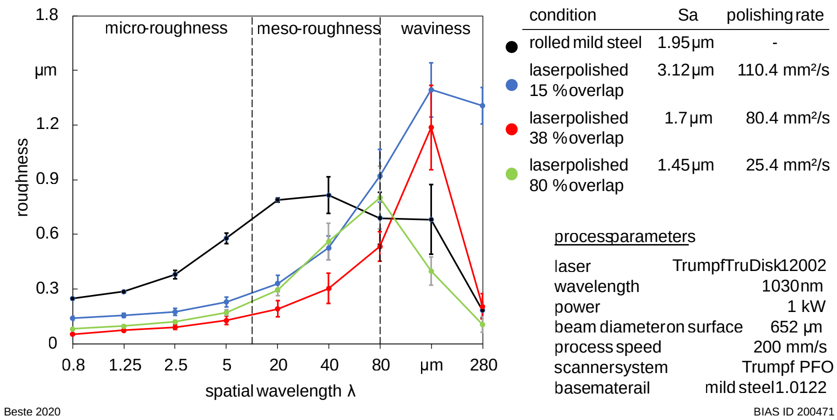

Fig. 1 Roughness as functions of the spatial Wavelength λ of rolled mild steel 1.0122 surface and of laser polished surfaces with different path overlaps

The laser polishing was done with a TruDisk 12002 by Trumpf with a cw-wavelength of 1030 nm. The beam diameter on the material surface was 652 μm and the laser power was set to 1 kW. The influence of the path overlaps on the surface topography of mild steel 1.0122 was analyzed. Subsequently, the obtained results were transferred to cuboids made of CoCr-alloy (Stellite-21), which were produced via LPBF. The process speed was set to 200 mm/s, while the path overlap was varied between 15 % and 80 %. With the results obtained here the LPBF components were processed afterwards. For this purpose, the laser polishing parameters were a process speed of 1000 mm/s, a power of 1.25 kW, and path overlaps of 80.5 % and 90 %. Surface topography measurements were made by confocal microscopy to analyze the results of the laser polishing process. These microscopic images were processed using a fast Fourier transformation (FFT) to determine the amplitude of the spatial wavelengths of the surfaces with a focus on the waviness as well as the micro- and meso-roughness.

The results of the FFT analysis of the surface topography measurements are shown in Fig. 1 for the mild steel surfaces and in Fig. 2 for the CoCr-LPBF-manufactured surfaces.

The mild steel 1.0122 surfaces show significant influence of the overlap rate. A path overlap of 15 % leads to an increased surface roughness Sa, while the surface roughness then decreases with growing path overlap. Hence, the lowest surface roughness for these experiments is achieved with a path overlap of 80 %. The spatial wavelengths show that the micro- and meso-roughness decrease to similar levels below 0.25 μm depending on the overlap. Regarding the long wavelength surface features, there is a much more significant dependency on the path overlap. For these wavelengths, the waviness was reduced using a path overlap of 80 %, while path overlaps of 15 % and 38 % lead to significant increases of the high spatial wavelengths.

The results of the laser polished LPBF surfaces show a reduced surface roughness S_a at both 80.5 % and 90 % path overlaps compared to the as-built surface. The examination of the different spatial wavelength sections has shown that the micro- and meso-roughness as well as the waviness are reduced compared to the initial surface depending on the overlap.

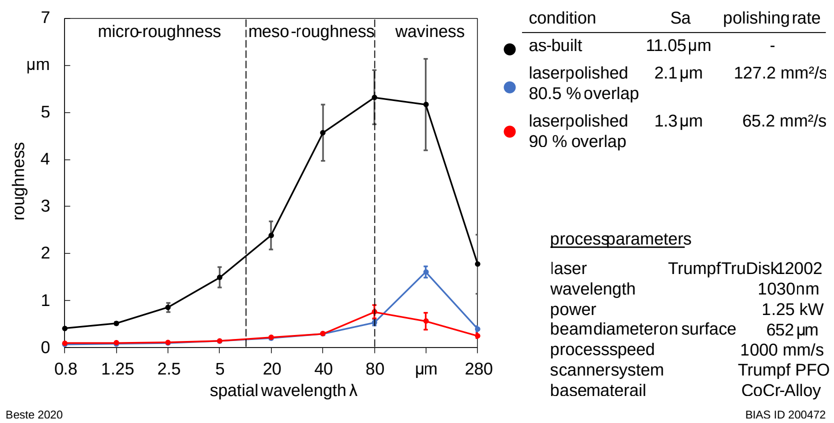

Fig. 2 Roughness as functions of the spatial wavelength λ of LPBF manufactured CoCr-component surfaces in the as-built- and laser- polished condition with different path overlaps

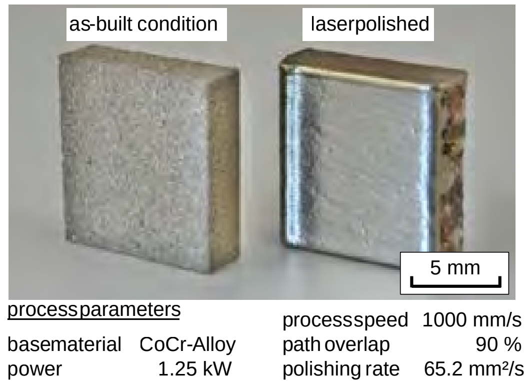

Fig. 3 Two cuboids of CoCr-alloy (Stellite-21) produced via LPBF; The cuboid on the left side is in the as-built condition, the cuboid on the right side was laser-polished

For both polishing rates, the micro and meso-roughness are reduced to 0.1 µm, while the waviness can be reduced to 1.6 µm at a polishing rate of 127.2 mm²/s and up to 0.76 µm for a polishing rate of 65.2 mm²/s. An image of an as-built and a polished LPBF-cuboid made of CoCr-alloy is shown in Fig. 3.

The results show that a high path overlap can lead to a reduction in waviness on rolled surfaces and on the surfaces of components based on LPBF. In combination with high process speeds, the polishing rate can be increased while the resulting waviness due to the melt pool dynamics can be limited.

Overall, it is shown that the long wavelength surface features created during the laser polishing process by high process speeds can be limited by a high path overlap (90 %) in such a way that not only the micro- and meso-roughness but also the waviness of LPBF-components can be reduced at high polishing rates. The evaluated scan strategies give the opportunity to perform subsequent treatment of LPBF-surfaces via laser polishing in a high mm²/s range.

*

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Laser Structuring of PVD Multilayer Systems

Enhancement of tribological properties by generation of dimple arrays

Andreas Stephen and Tim Radel

The selective laser structuring of the layer system TiN/a-C: H:Ti/MoS_2:Ti:C developed for tribological applications, including in the aviation industry, by PVD synthesis can be achieved precisely with depth deviations of less than 0.2 µm almost without any burrs or melt residues.

In the aviation industry, supported by European as well as numerous national initiatives, there is an effort to reduce emissions in aviation significantly to achieve extensive climate neutrality. There are various approaches to this, ranging from a weight reduction through lightweight construction, to a reduction in air resistance through the "hybrid laminar flow control" technology, to an increase in the efficiency of the engine technology. The latter is based on an increase in the bypass ratio in jet engines, the so-called UHBR technology (ultrahigh bypass ratio), which leads to a significantly better efficiency and thus a reduction in emissions. This concept requires a reduction gear between the fan and the turbine to be able to reduce the fan speed, since the speed of sound must not be exceeded, and thus to enable the implementation of a larger fan diameter. These reduction gears are exposed to extreme loads due to strong friction caused by high local contact pressures when the lubrication is temporarily interrupted. A surface treatment in the form of a structured multilayer system to reduce the risk of wear and to improve the load-bearing capacity of the gear box parts is therefore pursued as an approach.

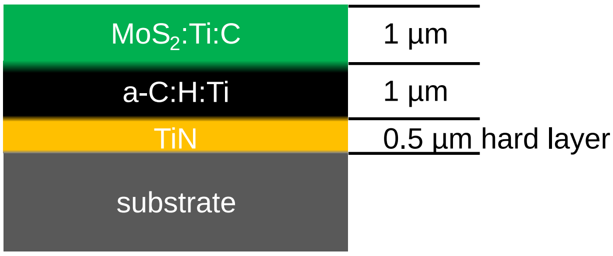

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Fig. 1 Tribological layer system to reduce wear and friction (Layer development and synthesis by Leibniz-IWT, Bremen)

Procedure

Structured multilayer systems, as low-friction and low-wear surfaces, provide a way of increasing the load-bearing capacity of the gear box parts. A suitable laser system and the process control suitable for the layer system must be developed for laser structuring. The individual layers of the system must be able to be removed selectively. PVD-synthesized TiN/a-C:H:Ti/MoS_2:Ti:C was used as a multilayer system with the necessary tribological properties (Fig. 1). The surface structuring by means of laser processing then serves to form lubrication pockets during operation of the engine, which leads to a further reduction in friction and wear on the highly stressed gear wheel flanks.

Experimental

An ultrashort pulse laser with a wavelength of 1030 nm was used as the laser beam source for structuring the multilayer systems. The laser used (Trumpf TruMicro 5050) has a pulse length of less than 10 ps with a maximum output power of 50 W and a pulse repetition rate of 200 kHz. The laser beam was guided over the workpiece by a Galvano scanner with a focus diameter of 45 µm. The laser processing was performed without protective gas supply.

Results

A defined diameter of the cavities could be set using a circular irradiation strategy, as shown, for example, applying a diameter of 80 µm (Fig. 2). By choosing a suitable pulse energy and pulse repetition rate, the ablation could be set in such a way that the MoS_2:Ti:C and a-C:H:Ti layers are removed (depth of 2 µm) and the TiN layer is retained on the substrate. The remainder of the TiN layer serves to protect the hardened steel substrate underneath from corrosion. The depth can be reproducibly set with an absolute deviation of less than 0.2 µm. The evenness of the cavity is ± 0.1 µm. Burr formation or melt residue cannot be observed.

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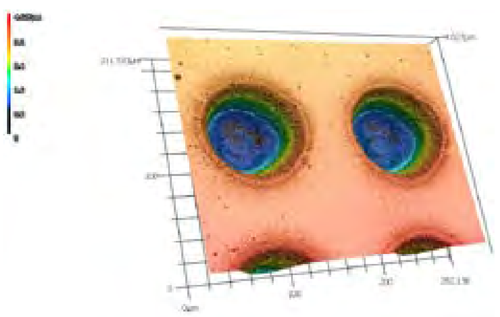

Pulse energy	5 µJ
Repetition rate	50 kHz
Scanning speed	250 mm/s
Overlap	87.5%
Scans	5

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Fig. 2 Laser confocal microscope image of a structured multilayer system of TiN / a-C: H: Ti / MoS2: Ti: C

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Implementation of a Synchronized Multi-method Process Observation in Deep Penetration Laser Welding

Ronald Pordzik and Peer Woizeschke

To understand or even control the process of deep penetration laser welding, it is essential to gain insight into the physical behavior of the highly dynamic system comprising the vapor capillary and the melt pool. This paper introduces a synchronized multi-method approach for process monitoring including the measurement of the wall temperature and the depth of the vapor capillary as well as the characterization of the process stability by means of fluctuating keyhole opening and spatter occurrence.

Deep penetration laser welding is a joining process that can produce high-quality welds with a small heat-affected zone due to the high aspect ratio of the weld [1]. This high aspect ratio is achieved through the formation of the so-called vapor capillary, which is a long, needle-shaped cavity in the melt pool surface at the approximate position of the laser beam. It is created by the recoil pressure of the laser-induced material evaporation, which leads to the local displacement of the melt and thus successively causes the formation of the vapor capillary. Within this capillary, which is filled with metal vapor and partly with ambient gases, multiple reflections of the laser radiation on the capillary walls lead to an increased absorption along the entire depth of the cavity, so that a corresponding heat input by the laser is also achieved deep below the material surface [2]. However, this system, consisting of melt pool and vapor capillary, is highly dynamic [3], and thus a quasi-stationary equilibrium does not occur on the capillary walls at any time during the process.

The dynamics of the system are characterized by fluctuations on very short time scales, requiring the use of high-speed measurements to fully map the essential characteristics of the process. Since various physical phenomena are involved and there are interfaces

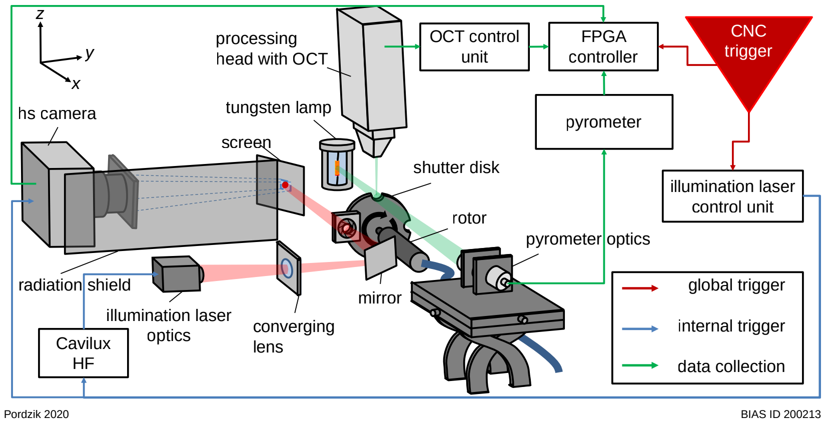

Fig. 1 Schematic of the experimental setup for the synchronization of the measuring devices

between different material phases, the process can only be comprehensively investigated by combining several measurement methods. The temperature distribution at the capillary wall is considered a central parameter for the process behavior and can be analyzed pyrometrically with the novel test setup and sample design presented here. These measurements are supplemented by high-speed images and depth measurements of the vapor capillary by means of optical coherence tomography (OCT). This enables the correlation of the determined temporal courses of the wall temperature with the fluctuations of the capillary depth, changes of the capillary opening, and process phenomena like blow-outs or splashes. The most accurate temporal allocation of the different measurements' places high demands on the synchronicity between the measurement signals. It is not sufficient to simply sample the signals synchronously to achieve this, since the internal runtimes of the signal processing can already lead to a significant time shift. The synchronization

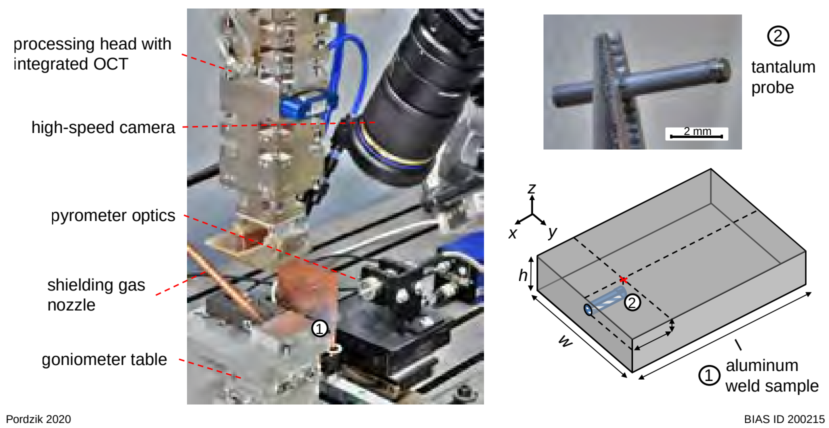

Fig. 2 Experimental setup for measuring the temperature in the vicinity of the capillary wall including a schematic of the weld sample design

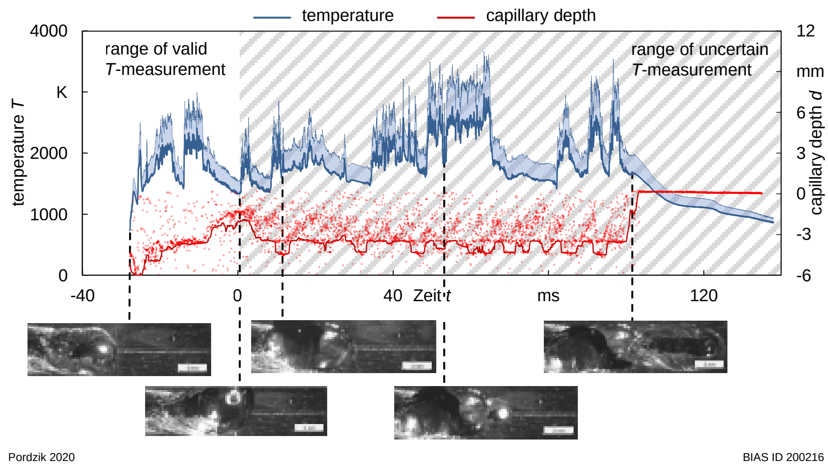

Fig. 3 Result of the synchronized process observation with measurement of the capillary wall temperature, capillary depth, and high-speed images

must therefore be realized by means of an event which, by its nature, can be detected by all measuring instruments involved and is simultaneous in all its measurable properties. The shorter the generated event, the more precisely the measurement signals can be synchronized. The experimental realization of the setup can be seen in Fig. 1. A rotating disk with semicircular notches simultaneously opens the beam path of the pyrometer and the illumination laser. For the pyrometer, the measurable signal consists of the thermal radiation of a tungsten lamp, while the high-speed camera detects the projection of the illumination laser spot on a screen. The measuring spot of the OCT is positioned on the edge of the rotating disk. The detectable event is the change in the depth of the edge of the disk relative to the detector due to the notches opened towards the edge. The accuracy of the synchronicity can be varied by the rotation speed of the disk. At maximum rotational speed, a maximum accuracy of δt_{min} = 40 µs can be achieved for the given dimensions of the disk aperture, which is less than the exposure time of a high-speed exposure.

The synchronized measurement setup was used for process observation during laser beam deep penetration welding. The pyrometric measurements of the capillary wall temperatures were in the center of the performed investigations. To perform these measurements, a tantalum tube, which was closed on one side by a tantalum foil, was inserted through a hole in the front of the weld specimen, thus forming a high-melting measuring channel (see Fig. 2). The radiation measurement by the pyrometer was carried out on the inside of the foil, which served as a temperature screen and, thus, as a grey radiator, mapping the process temperatures on the outside of the tantalum probe. By drilling holes at various depths below the sample surface, it was possible to record an axial temperature profile in several measurements. Since the capillary depth is subject to strong temporal fluctuations, the correlation between temperature and depth determined in this way is not absolute, and thus the experimental setup needed to be supplemented by an additional measurement of the welding depth by OCT. The OCT measurement was performed paraxially to the processing laser in the capillary opening, delivering the maximum detected measuring depth as a result. In addition, high speed recordings were made transverse to the welding direction to assess the process stability. The test setup is depicted in Fig. 2 and shows the arrangement of the measuring instruments around the weld sample. The experiments were carried out at a welding speed of v_{weld} = 50 mm/s, using a laser power of P = 5 kW. The drill holes for the tantalum probes were located at a depth of d = 4 mm below the sample surface.

The measurements, as shown in Fig. 3, exhibited fluctuations of the capillary depth between 3 mm and 6 mm. The filtering of the OCT signal was previously calibrated by means of metallographic cross sections of the weld penetration. In the area of the front wall of the vapor capillary, temperatures of T_{max} = 2640 ... 2960 K were measured, thereby supporting the widespread assumption in the literature that the melt overheats in the vicinity of the capillary wall [4]. The calculation of the temperature values from the pyrometer signal as well as the evaluation of the error influences were performed according to Pordzik et al. [5].

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Laser Brazing with Wire Oscillation

A new approach for increasing the optical seam edge quality

Thorsten Mattulat and Peer Woizeschke

The technology of laser brazing is frequently used to produce seams with the highest optical requirements, making them good enough to remain visible in in areas accessible to the customer. To increase these optical qualities, external wire oscillation was imposed on a conventional constant wire feed, offering a feasible method for homogenizing the wetting process and increasing the straightness of the seam edges. The technology is easy to integrate into existing systems, thereby increasing the quality of laser brazed seams also on an industrial scale. The following presents an in-depth insight into the effects of external wire oscillation.

In laser brazing in automotive production, a laser beam melts a filler wire that is continuously fed into the process zone. Hereby, beam diameters greater than the wire diameter are used to simultaneously preheat the substrate. Seams are created through the relative movement between the processing optics and the substrate. The process is predominantly used to connect zinc-coated car body parts in areas visible to the customer using seams made of a copper-based filler material. As these seams are often not reworked before painting, high optical seam qualities are required in addition to the requirements of strength and tightness. However, this requirement is frequently not fulfilled, especially in the case of hot-dip galvanized material and conventional process control. We have developed the novel approach of additional filler wire oscillation to increase the optical seam quality. The oscillation of the wire is intended to influence the movement of the melt pool and the wetting progress, thereby increasing the straightness of the seam edges. A "High Dynamic Drive" (HDD) wire feed unit from the company Dinse GmbH was used to superimpose a wire oscillation onto the constant wire feed rate. This enabled the impressing of a longitudinal oscillation via a dynamic change of the feed direction by the wire motor. Using this novel wire feed unit, brazing tests were carried out on hot-dip galvanized material.

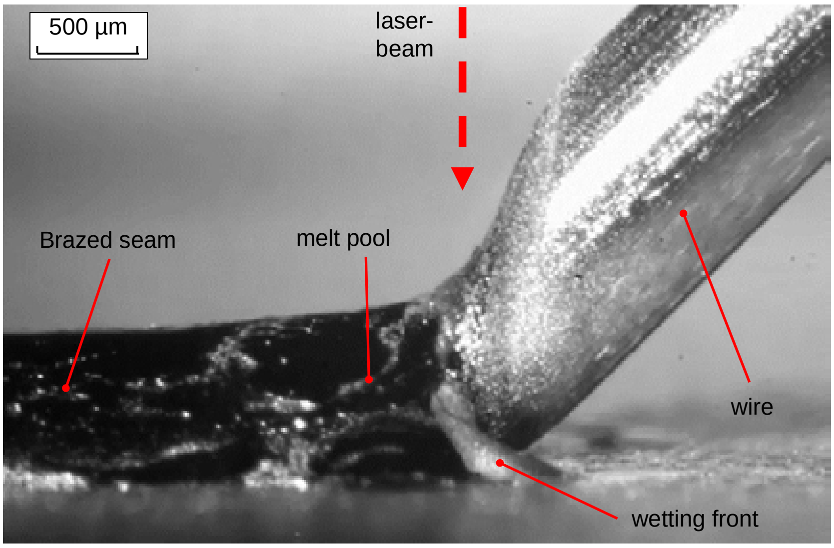

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Fig. 1 High-speed process recording during laser brazing to visualize the wetting progression.

Under conventional process control, the wetting process during laser brazing is cyclic, with the wetting first taking place beside the wire in the preheated areas. The process was recorded laterally with a high-speed camera to analyze the wetting behavior more closely. In these recordings, the wetting progress can be seen as the progression of wetting fronts (see Fig. 1). At a constant wire feed, melt pool constrictions are created in the area of the wetting fronts, which collapse from a critical size and cause an abrupt and stepwise wetting progress. By imposing wire oscillation on the brazing process, this wetting behavior can be significantly influenced. The resulting effects were described in detail in [1]. It was shown that wire oscillation can impose a frequency on the wetting progress that matches the frequency of the wire oscillation while also influencing the step size of the wetting progress. If the amplitude of the wire oscillation is comparatively high, the step size of the wetting progress can be increased compared to the step size by constriction collapses. This results in an optical seam edge quality defect in each oscillation cycle, leading to wavy seam edges. However, with reduced wire amplitude, the wetting progress per cycle can also be reduced. For this purpose, frequency and amplitude must be coordinated. For a process velocity of 3 m/min, for example, the combination of the highest adjustable frequency of 250 Hz and an amplitude of 0.11 mm was shown to be suitable to significantly reduce the wetting progress. Suitable combinations are characterized by the fact that the step size and the frequency are sufficient to keep the wetting process in a constant position while the process progresses consistently. This reduction of the step size per cycle homogenizes the wetting process during laser brazing, directly affecting the achievable optical seam edge quality. A direct comparison between two seam edges – on the one hand without oscillation and on the other hand with oscillation and a reduced step size per oscillation cycle – is shown in Fig. 2. Here, the oscillation was able to significantly reduce the wavy parts of the seam. Finally, it was concluded that while the abrupt progression

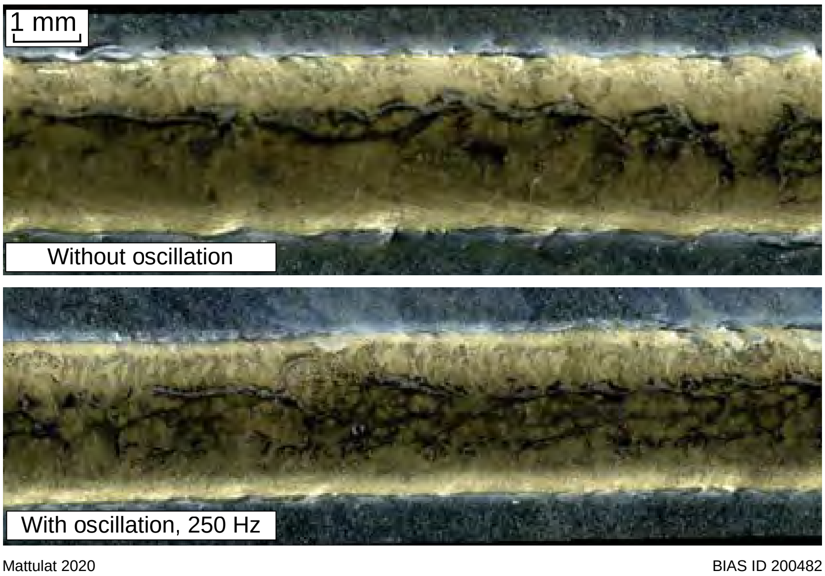

Fig. 2 Seam edge comparison of laser brazed seams on hot dip galvanized material with and without wire oscillation.

of the wetting process can cause a defect in the seam edge, this can be effectively prevented by forcing a small-step wetting progress.

The investigations have shown that the currently highest achievable frequency of 250 Hz is most suited to increasing the seam edge quality. An evaluation of the seam edge roughness, analogous to the root mean square roughness value of a line roughness measurement, showed a maximum reduction of the seam edge roughness by 26% compared to the initial state. A further increase of the seam edge quality is conceivable through an increase in the oscillation frequency, which is currently limited by the wire feed unit. At higher oscillation frequencies, a lower wetting progress per oscillation cycle would be sufficient to keep the wetting process constant relative to the process zone, further homogenizing the wetting process.

The presented solution for increasing the optical seam edge quality is particularly relevant for the users of laser brazing as well as technology manufacturers, such as the manufacturers of wire feed units and processing optics, which are often SMEs and could develop and sell new products adapted to laser brazing with wire oscillation. The simple integration into existing production lines in particular makes laser brazing with wire oscillation innovative, whereby existing laser brazing systems can be shifted to brazing with wire oscillation without structural changes. Only the conventional wire feed unit needs to be replaced by a wire feed unit that can impose an oscillation on the wire via the feed motor. Furthermore, the phase position of the oscillation is not relevant to the brazing process, so no additional communication between the wire feed unit and laser system is necessary.

*

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Laser Keyhole Brazing

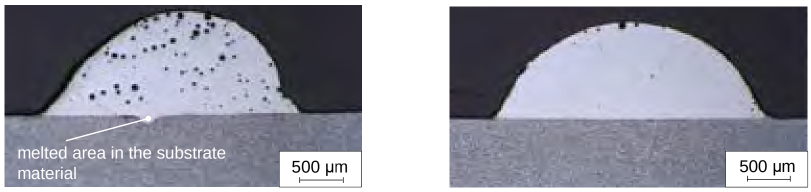
Energy-efficient brazing using the deep penetration effect in combination with two-dimensional beam oscillation

Insa Henze and Peer Woizeschke

Laser beam brazing is one way of producing seams with high visual quality. Conventional methods are based on melting the brazing material using the simple Fresnel absorption of the laser beam on its surface. Conventional copper and aluminum-based brazing materials reflect a high percentage of the laser beam, leading to decreased process efficiency as only a low proportion of the laser beam is absorbed and contributes to the process.

It is known from laser beam welding that the absorption, and thus the efficiency, of the welding process can be increased by using the so-called deep penetration effect [1]. For this purpose, small beam diameters are used, which lead to a high intensity. If a material-dependent threshold value is exceeded, a local vaporization of the material occurs, resulting in the formation of a vapor capillary (called a keyhole) in which the laser beam is absorbed and reflected multiple times. This increases the absorption and hence, the process efficiency; see e.g. [2] on the approach of keyhole brazing. Due to the formation of the vapor capillary, the energy is introduced much deeper into the material in keyhole processes than in processes with simple absorption on the workpiece surface. The depth of the resulting melt pool is significantly deeper than the width and, therefore, does not seem suitable for melting a brazing material with a round cross-sectional shape. Hence, the simple transfer of the deep penetration effect to laser beam brazing would lead to an insufficient melting of the brazing material or to melted areas in the substrate material (see Fig. 1, left). Instead, the energy must be distributed over the width of the brazing material. This can be achieved by oscillating the laser beam transversely to the brazing direction by using scanning optics, as is used, for example, to increase the gap-bridging ability or in buttonhole welding [3]. This widens the melt pool and increases the local movement speed, or rather shortens the local dwell time, of the laser beam. The latter reduces the melt pool depth compared to processes without oscillation at otherwise constant laser power and brazing speed.

without oscillation: with oscillation:



brazing parameters:	
laser	IPG YLR 1000 SM
scanoptic	SCANLAB WelDYNA (2D)
focal diameter	34 µm
laser power	470 W
brazing speed	1.0 m/min
wire material	AlSi12 (Ø 1.2 mm)

substrate	DC 01 ZE 25/25
shielding gas	Ar
wire speed	1.8 m/min
oscillation:	
oscillation frequency	200 Hz
oscillation width	1.2 mm
oscillation strategy	line

Henze 2020 BIAS ID 201057

Fig. 1 Microsections of bead-on-plate seams brazed with keyhole formation without oscillation (left) and with superimposed linear oscillation of the laser beam transverse to the brazing direction.

Another important aspect of brazing is the wetting process. Preheating the substrate favors wetting [4]. In conventional processes, this is realized through the direct irradiation of the substrate by the laser spot, whose diameter is selected to be significantly larger than the wire diameter. This is not possible when brazing with the deep penetration effect because the focused laser beam would melt the substrate material due to the high intensity. Preheating must, therefore, be realized via heat conduction through the molten brazing material.

By combining the keyhole brazing process with beam oscillation, a bead-on-plate brazing test (brazing material application on a flat substrate) with a complete melting of the brazing material and without melting in the substrate material was successfully realized (see Fig. 1, right). For this purpose, an AlSi12 brazing material was used with galvanized steel as the substrate material. Temperature measurements showed that the temperatures in the molten pool were well above the melting temperature of the solder material (580 °C) at over 1400 °C. Both one-dimensional linear and two-dimensional circular oscillation strategies were used [5].

The oscillation strategy influences the geometrical expansion of the oscillation and the effective trajectory length of the laser beam pathway. This influences the movement path and the movement speed of the laser beam, and thus the local interaction time between the laser beam and the material as well as the temperature distribution in the melt pool and at the interface. The latter is important regarding both unwanted melting in the substrate and the wetting process. Therefore, knowledge of the influence of the oscillation parameters on the temperature field is essential to controlling the process. Measuring the temperature distribution at the interface is only possible to a limited extent, if at all. However, it is possible to measure the temperature distribution on the surface of the molten pool to indicate the temperature distribution both within it and at the interface [6]. For the considered process, it is thus assumed that a more homogeneous temperature distribution on the surface correlates with a more homogeneous temperature distribution at the interface. For the determination of the temperature distribution on the molten pool surface, non-contact measuring systems based on a measure-

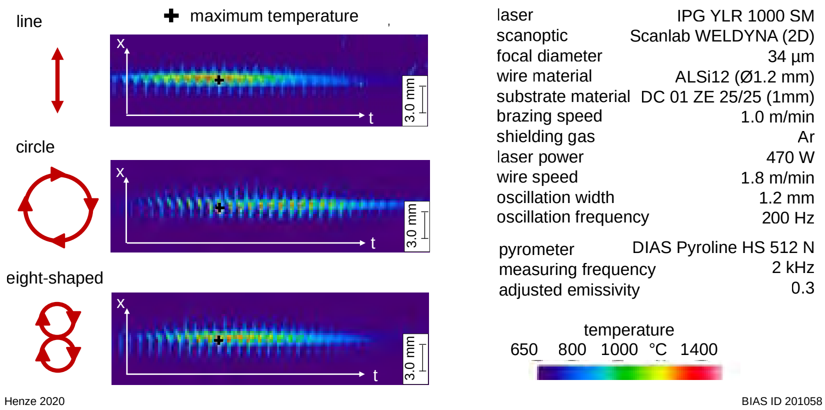


Fig. 2 Examples of temperature-time measurements using the line pyrometer across the width of the molten pool when passing through the process for different oscillation strategies.)

ment of the infrared radiation emitted by the surface are particularly suitable as they do not influence the process and allow high measuring rates. To be able to consider the molten pool surface completely, a line pyrometer was positioned transversely to the brazing direction. The pyrometer's position was fixed, while the brazing optic – and hence the brazing process – was moved at brazing speed in the brazing direction. Thus, the local temperature-time curve across the cross-section of the molten pool could be recorded (see Fig. 2). Using these measurements, the homogeneity of the temperature field and its temporal course were evaluated and the different beam strategies were compared with each other.

It was shown that compared to tests without oscillation, the beam oscillation widened the melt pool and precluded the melting of the substrate material. Circular oscillation strategies led to a further homogenization of the temperature field. This is important, especially regarding the use of the process for material combinations of brazing and substrate materials with only slight differences in terms of melting temperature, since a uniform temperature distribution at the interface is crucial for successful brazing.

*

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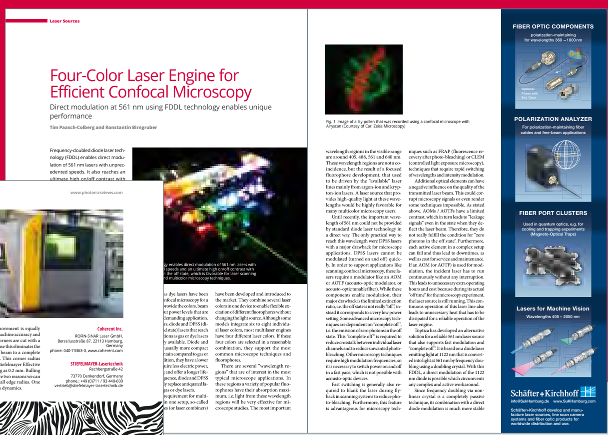

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