Progress in Laser Additive Manufacturing Equipment and Applications

Andreas Wank, Christian Schmengler, Alexander Hitzek, Annika Krause, Melissa Mülln, GTV Verschleiss-Schutz GmbH, Luckenbach / D

Keywords: Laser cladding, powder feed, laser power control, adaptive handling systems, blue laser, cladding feedstock

Laser additive manufacturing is already used in numerous application fields. However, the general capability of these processes that permit precise tailoring of heat transfer to powder feedstock and local workpiece surface areas, is not yet exploited. Among the factors that will boost exploitation of laser additive manufacturing processes capabilities are powder feeders that control powder feed rate directly and provide warnings in case of impermissible deviations. Digital image analyses tools permit closed-loop control of laser power to compensate changes in workpiece temperature, control of cladding head movement to compensate thermally induced changes of workpiece shape and monitoring of powder streams exiting powder nozzles to detect impermissible process states. Use of novel laser sources with shorter wavelength or higher power levels in combination with adapted process parameters will help to minimize production costs. And development of novel feedstock materials will help to cope with actual demands concerning sustainability and environmental friendliness.

1 Introduction

Laser additive manufacturing including laser cladding and DED-LB (directed energy deposition - laser beam) are used more and more due to continuously decreasing prices of laser sources and technological advantages like precise control of local heat transfer to workpiece surfaces and powder feedstock. While the number of applications increases and the respective market grows, there is more and more investment in development of components and tools that permit better exploitation of the full potential of laser additive manufacturing technologies. Progress in these fields as well as novel feedstock materials for new application fields developed by GTV Verschleiss-Schutz GmbH, Luckenbach, Germany, are presented in this paper.

Powder feeders are key components impacting achievable process stability and reproducibility. Scale powder feeders do not only permit convenient setting of a desired powder feed rate, but also contribute strongly to ensuring constant quality of workpieces in mass production.

Process control tools based on digital camera image analyses or pyrometry permit closed-loop control of laser beam power to achieve constant weld penetration and cladding quality despite change of workpiece temperature. Digital camera image analyses also permit offline characterization of the powder flow exiting powder nozzles and accordant evaluation of the nozzles wear state as well as online monitoring of powder flow distribution and stability. Finally digital camera image analyses and laser triangulation sensors are applied for detection of actual workpiece edge position permitting near-net-shape material deposition despite need to compensate e.g. concentricity tolerances and thermally induced expansion or shrinkage of workpieces.

Costs of laser claddings decrease as prices of laser sources decline and increase of available beam power permits exploitation of reduced production time. However, minimum coating costs will only be achieved, if claddings are produced with minimum thickness and thickness variation resulting in minimized consumption of powder and machining effort. Cladding processes at high welding speed and high overlap of beads are suitable to reach these goals.

For cladding of noble metals use of at least some contribution of blue laser radiation permits significant improvement of both cladding quality and deposition efficiency.

Novel powder materials are needed in various applications to support environmental protection. Traditional corrosion and wear protective coatings are mostly based on nickel or cobalt. For many applications alternatives can be realized with materials based on iron or aluminium using adapted hard phases for reinforcement.

2 Powder feeders

Disk type powder feeders represent the default choice in laser cladding and DED-LB machinery due to high stability of powder feed rate even for long term operation and their capability to feed powders with various composition, shape and size fractions covering a very wide range of powder feed rates. GTV powder feeders type PF permit setting of powder feed rates between roughly 0.1 - 500 g/min and powder feeder hoppers hold volumes of up to 8 l.

In the base version feeder disk rotation speed is controlled and the corresponding powder feed rate needs to be determined by weighing of powder that is fed into a storage vessel in a defined time period [1]. Then feeder disk rotation speed needs to be adjusted to achieve a desired powder feed rate. Suitability of the set feeder disk rotation speed needs to be checked regularly. Machinery including such powder feeders serves multiple applications successfully. However, scale powder feeders that operate with closed-loop control of a set powder feed rate based on continuous monitoring of hopper weight reduction and automatic adjustment of feeder disk rotation speed can even meet increasing demands concerning reproducibility in laser additive mass production.

If powder is fed with constant feeder disk rotation speed scattering of powder feed rate (measured with high time resolution using a precision scale unit equal to scale units that monitor weight of hoppers for the receiving vessel) can be even slightly lower compared to operation of scale powder feeders in closed-loop control mode (fig. 1). However, feeder disk rotation is typically set with one decimal place. So, adjustment starting from 1.0 or 5.0 rpm by one step will result in change of powder feed rate by 10% or 2% respectively with accordant effect on the mean powder feed rate value. In extensive test series with gas atomized AISI 316L powder with size fractions +20 -53 µm and +53 -150 µm average powder feed rate always differed less than 1% from the set value in closed-loop control mode for feed time of one hour. For constant feeder disk rotation speed deviation of mean powder feed rate from the desired value could even exceed 4%. In both operation modes standard deviation of high time resolution powder feed rate data ranged from 1 - 2% for +20 -53 µm size fraction and from 1 - 3% for +53 -150 µm size fraction.

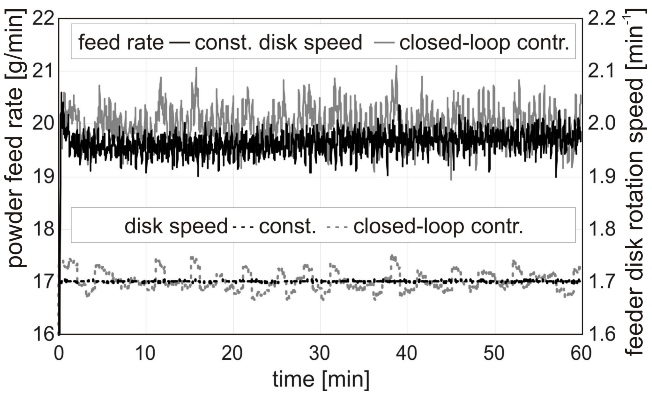

Figure 1: Feeder disk rotation speed and powder feed rate for feeding AISI 316L, +20 -53 µm, inert gas atomized powder in constant feeder disk rotation and constant powder feed rate mode; steel disk, 11x0.6 mm groove

There can be a relatively slow drift of powder feed rate in constant feeder disk rotation speed mode due to change of apparent density of powder filling the disk groove e.g. due to change of powder filling level and according change of pressure imposed by the contained powder mass, but there can also be sudden change e.g. due to wear of disks, spreaders or exhausters (fig. 2).

While conventional powder feeders will not even provide information concerning change of powder feed rate, scale powder feeders will react fast and compensate for it by adjustment of feeder disk rotation speed. Depending on the required stability of powder feed rate in specific applications the reaction time of scale powder feeders might even prevent production of faulty parts. In any case recording of actual powder feed rate data is a key factor permitting certification of demanded process stability for production of safety relevant workpieces.

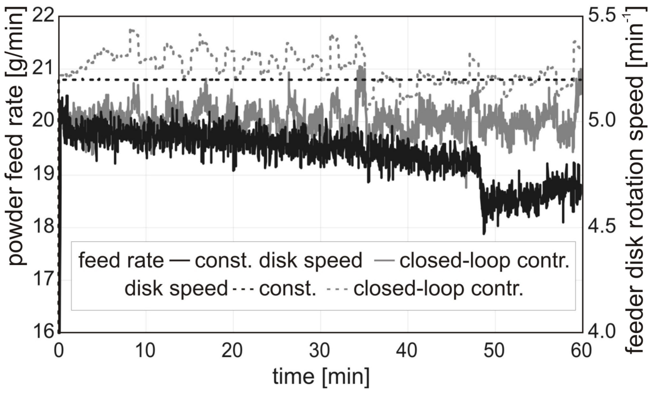

Figure 2: Feeder disk rotation speed and powder feed rate for feeding AISI 316L, +53 -150 µm, inert gas atomized powder in constant feeder disk rotation and constant powder feed rate mode; anodized aluminium disk, 5x0.6 mm groove

Also, scale powder feeders can contribute to detection of impermissible impurities in powder feedstock like polymer pieces from powder bottles or bags, because these typically result in change of filling level of the feeder disk groove. But even scale powder feeders cannot compensate for inhomogeneous filling of feeder disk grooves, because feed lines are generally too sluggish in reaction.

3 Process monitoring and control tools

Laser cladding offers the possibility of unsurpassed precision of local heat transfer to powder feedstock on its way into the melt pool and to workpiece surfaces, because laser power can be adjusted extremely fast. Therefore, exceptionally low dilution with base materials without compromising metallurgical bonding, small heat affected zones and minimum distortion can be achieved, if the right process parameters are applied.

The full potential of the laser cladding process capability to deposit optimum quality coatings on workpieces that show considerable change of temperature during the process can only be exploited, if laser power will be adjusted accordingly. There are different approaches for laser power adjustment. There are complex tools based on thermography cameras that provide space resolved temperature information that can be used for closed-loop control of laser power [2]. Typically, cladding centre operators are not able to define suitable criteria for laser power control cycles themselves. Therefore, systems have been developed that include laser power control cycles e.g. based on use of constant bead width as control criterion [3].

GTV offers solutions for closed-loop laser power control based on pyrometry or analyses of digital images recorded by cameras that are installed in the optical path anyway for alignment of laser beam and powder nozzle and for visual melt pool inspection. GTV LPowC uses emission intensity of the melt pool as criterion to adjust laser power. The capability to ascertain constant weld penetration, cladding

thickness, microstructure and hardness has been proven at the example of cladding of thin-walled tubes with different types of cladding materials [4]. The tool is only applicable, if melt pool geometry does not change, e.g. because workpiece edges will also be clad. Contrary, fast pyrometry permits achieving the same result without dependency on melt pool geometry. Discrete coaxial six-stream powder nozzles type GTV PN6625 that are frequently used for conventional and high speed cladding as well as DED-LB processes are available with dedicated bores for pyrometer analyses. Thereby necessity of re-calibration that is needed, if pyrometers are installed in the optical path of a cladding head and protective glasses or lenses with coatings that provide special transmissive properties are replaced, can be avoided. The focus of the pyrometer coincides with the powder nozzle axis in the optimal working distance of 25 mm. Laser power evolution for a constant melt pool temperature of 1,500 °C during cladding of Stellite®6 on a thin-walled AISI 316L tube is shown in fig. 3.
Closed-loop laser power control tools generally only permit keeping cladding characteristics constant, but pre-investigations correlating cladding properties with sensor readings and definition of optimum process conditions cannot be avoided.

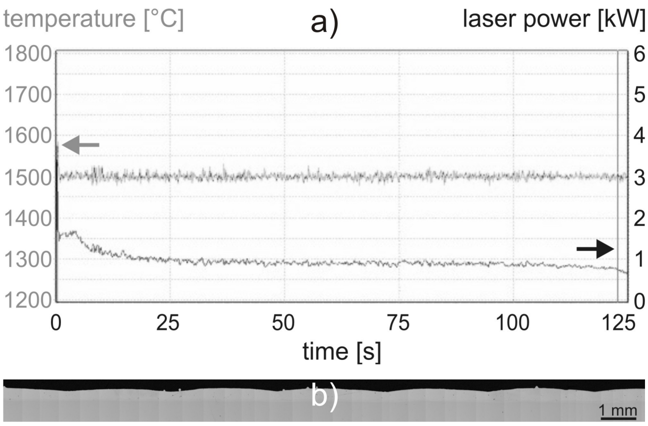

Figure 3: a) Fast pyrometry based closed-loop laser power (black) control for constant melt pool temperature (grey); b) constant quality of a Stellite©6 cladding deposited on a thin-walled AISI 316L tube

Analyses of images from cameras that are installed in the optical path of cladding heads also represent a key technology for near-net-shape cladding of extrusion screw flights despite undefined temperature distribution and accordingly undefined screw length and position of flight edges. Accordant cladding centres include axes for fast compensation of deviations from an optimum distance between workpiece edges and powder nozzle centre detected by GTV LPosC (fig. 4). Additional compensation axes permit reaction to distortion of extrusion screws and move the cladding head with constant distance between powder nozzle tip and eccentric screw surface movement detected by laser triangulation sensors.

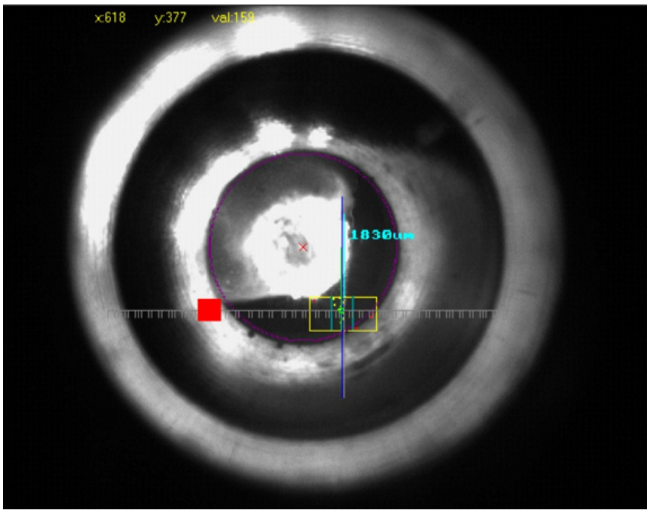

Figure 4: Online measurement of powder nozzle centre distance to screw flight edge by GTV LPosC; digital image analysis of laser illuminated screw flight edge within rectangular area of interest in the vicinity of the melt pool

Finally, GTV uses digital image analyses for online and offline characterization of powder jets exiting powder nozzles. For online monitoring during cladding processes a sheet laser illuminates particles in a plane between nozzle tip and workpiece surface and a camera installed in the optical path of the cladding head records images that will be analysed in areas of interest around individual jets exiting bores of discrete nozzles (fig. 5) or in several overlapping areas of interest for evaluation of homogeneity of powder flow exiting annular gap nozzles. The monitoring tool permits setting of upper and lower limit values around an optimum process value and error messages will be generated, if the limit values are violated. Accordingly, the tool can detect e.g. damage or blocking of powder feed hoses, blocking of individual injectors or uneven distribution of powder density due to wear of powder nozzles or misaligned or worn distributors.

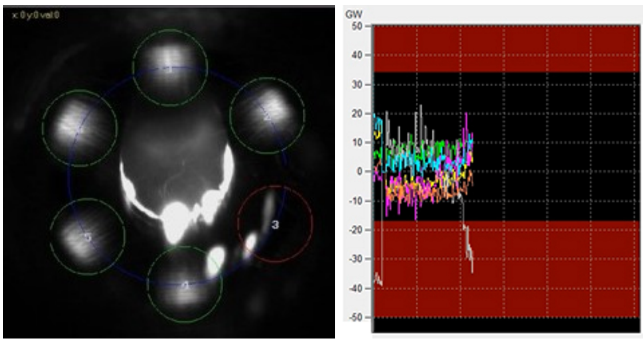

Figure 5: Online monitoring of laser illuminated powder jets exiting a six-stream powder nozzle GTV PN6625 during a cladding process with automatic detection of reduced powder flow through injector no. 3

Particle density distribution of powder jets exiting nozzles are determined by moving the powder nozzle through an illuminating sheet laser with constant speed, which provides a matrix of space resolved data that are analysed automatically concerning different criteria (fig. 6). For discrete nozzles individual jets exiting nozzle injectors will be identified and deviations from an average value will be calculated for several planes with defined short distances (h_1, h_2, …, h_n) to the nozzle tip. Deviations of particle densities are useful for evaluation of powder distributors. In case of annular gap nozzles homogeneity of particle density data will permit an overall evaluation of powder distribution and internal nozzle geometry.

The tool for offline characterization of powder jets exiting nozzles also automatically determines the distance from the nozzle tip, where powder jets converge to one united jet, the powder focus diameter and its distance to the nozzle tip as well as the powder jet diameter at working distance. These data are useful for optimization of working distance in correlation with carrier gas and nozzle gas flow rates taking into consideration a desired bead width. After correlation of powder focus diameter and cladding quality the offline characterization tool can also be used to decide, if a nozzle or injectors need to be replaced to ascertain required cladding quality features.

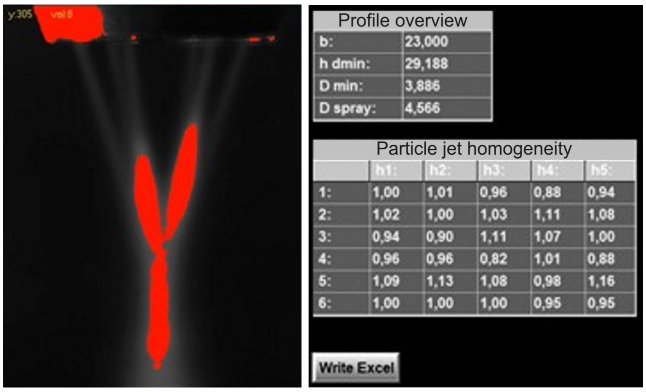

Figure 6: Offline particle density distribution analysis of illuminated powder jets exiting a six-stream powder nozzle GTV PN6625 (18 mm nozzle diameter at exit plane) with automatic calculation of characteristics

4 Process development

In contrast to alternative cladding technologies that are limited e.g. by stability of transferred arcs laser cladding permits use of very high welding speed, i.e. > 10 m/min. That is a key factor enabling production of thin claddings at high coverage rate and resulting in an economic alternative to electroplating or thermal spraying in several application fields. Powder costs will be minimized, if claddings with minimum thickness and thickness variation are deposited at maximum deposition efficiency. It is well known from PTA cladding that thickness variation can be minimized by applying strong overlap of beads [5], which also results in low weld penetration and accordingly low dilution with base material [6].

Capability of laser cladding to produce coatings with less than 100 µm thickness at welding speed of up to 30 m/min has already been reported in the early 2000´s [7]. Later, cladding at high welding speed and allegedly required process conditions with laser beam focus above the workpiece surface was advertised under the name EHLA. But conventional process conditions with laser beam and powder focus both coinciding with workpiece surfaces permit production of claddings with the same characteristics [8]. GTV can offer solutions based on use of six-stream powder nozzle type PN6625, 5 mm laser spot diameter and laser beam power up to 22 kW that is capable of production of roughly 100 µm thick AISI 316L stainless steel claddings at coverage rates of 7.2 m^2/h and 90% deposition efficiency. Also, roughly 250 µm topcoats consisting of a stainless steel matrix and fused tungsten carbides as reinforcing phase can be produced at coverage rates of 6.0 m^2/h and 85% deposition efficiency. Thin laser claddings show high potential for corrosion protective applications in print and paper industries, for hydraulic pistons and low emission brake disks.

Thin laser claddings also represent advantageous alternatives to thermally sprayed bond coats for ceramic topcoats. Thereby, the intrinsic advantages of thermal spraying and cladding technologies are combined. While thermal spraying permits production of pure ceramic coatings without macro crack formation, laser clad bond coats require neither pre-treatment of workpiece surfaces, e.g. by grit blasting, nor sealing of the coating to exclude undercorrosion due to penetration by corrosive media. The safe corrosion protective function of thin laser claddings that act as bond coats for thermally sprayed oxide ceramic coatings has been proven in publicly funded research projects [9] and capability of such compound coatings to withstand grinding, polishing and laser engraving processes has been demonstrated, too (fig. 7).

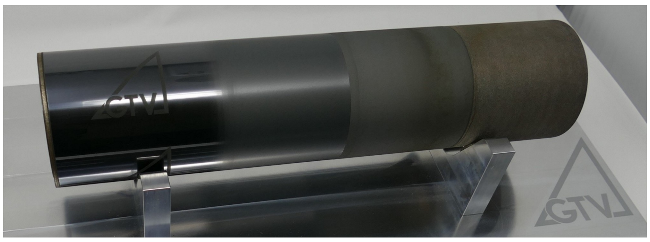

Figure 7: Anilox roll demonstrator with thin laser cladding bond coat and subsequently deposited Cr_2O_3 plasma spray coating in as sprayed, ground and polished + laser engraved state (from right to left)

These days typically laser sources with wavelength of about 1 µm are applied in laser cladding applications. Noble metals like copper and silver absorb only a small portion of photons in that wavelength range and require a relatively strong heat flux to permit formation of a melt pool due to their high thermal conductivity. Recently blue lasers with power of up to 2 kW have become available and even higher power levels will be developed. In the meantime, hybrid cladding heads uniting IR and blue laser beams permit use of higher overall power levels and have successfully been used for cladding of silver on steel and pure copper substrates [10] (fig. 8). According claddings show high potential for corrosion protection applications in chemical industries and to create low electrical (contact) resistance or high antimicrobial activity surfaces. Also, cladding of pure copper with bronze for improved resistance against tribological load is possible at particularly high efficiency using the hybrid cladding approach (fig. 8).

Figure 8: Silver claddings on mild steel (a)) and pure copper (b)) and aluminium bronze cladding on pure copper (c)) produced with a hybrid cladding process combining IR and blue laser radiation

5 Feedstock development

Internationally rising concerns related to environmental friendliness also cause pressure on coating industries. For example, electroplated hard chromium coatings have already been replaced in numerous applications and costs of coatings in the remaining applications have increased significantly due to extensive measures for occupational health. But permissible exposure limits of e.g. cobalt and nickel, which are key elements in traditional thermal spray and cladding materials for corrosion and wear protection, are reduced more and more, too. Besides exposure of coating machinery operators also exposure of the public needs to be considered, if wear debris will be released into the environment.

For example, brakes of road and rail vehicles represent an application field of major concern, because large volumes of wear debris are released. In urban areas the contribution of brake dust to driving-related particulate emissions is about 15%. In case of e.g. subway stations wear debris of brakes even accumulates in confined spaces. Brake discs like Bosch Buderus iDisc that feature a nickel-based matrix hardmetal coating permit reduction of fine dust emission by up to 90%. However, there are concerns that toxicity of that debris might be even more critical despite the reduced number of particles.

Actual research and development of protective coatings focusses on iron-based alloys. Ideally these materials would only contain cobalt, nickel and copper at inevitable impurity levels. Despite good experience with HVOF sprayed coatings on iDiscs most companies favour laser claddings for the brake disk application because of metallurgical bonding to the substrate material and possibility to achieve much higher deposition efficiencies.

Ferritic stainless steels show high potential as environmentally friendly material candidates for cladding of brake disks, although their resistance against corrosive attack by salt water is limited. Their rather low wear resistance can be improved significantly by embedding of hard phases like carbides. While WC/FeCr (GTV 80.72.1) and Cr_3C_2/FeCr (GTV 80.82.1) cermet powders with ferritic stainless matrix are useful for HVOF spraying of wear protective and environmentally friendly coatings, they are not ideal for laser cladding, because these carbides show high tendency to form brittle mixed carbides after dissolution in iron-based alloy matrices. Contrary, vanadium, niobium and titanium carbides precipitate completely without formation of brittle mixed carbides, if they are dissolved in iron-based alloy matrices. Therefore, using NbC/FeCr 80/20 (GTV 81.71.8) or TiC/FeCr 70/30 (GTV 81.61.8) crack free claddings containing roughly 30 vol.-% of carbides in stainless steel matrices can be deposited without pre-heating of grey cast iron substrates (fig. 9). Such claddings show a microhardness of 500 - 600 HV0.3 and form cracks neither during grinding nor in dyno tests except for the so-called crack formation tests, when being tested with adapted brake pads [11,12].

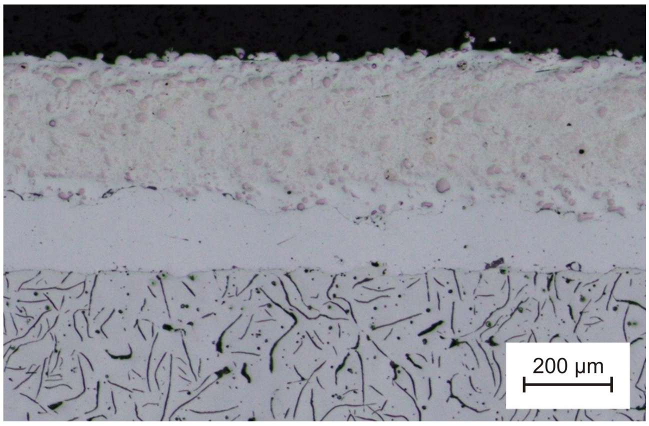

Figure 9: 300 µm NbC / stainless steel 70/30 top layer on a 150 µm stainless steel layer deposited by laser cladding on grey cast iron

NbC shows outstanding stability due to niobium’s high affinity to carbon. Therefore, NbC is suitable even for reinforcement of aluminium alloys. Laser dispersion of NbC in cast aluminium alloys permits formation of low porosity, crack free layers with microhardness exceeding 500 HV0.3 (fig. 10) maintaining the good corrosion resistance of the aluminium alloy matrix. Formation of brittle, needle shaped aluminium carbides is avoided securely. Such surface layers show high potential to realize even heavy-duty aluminium brake disk [13].

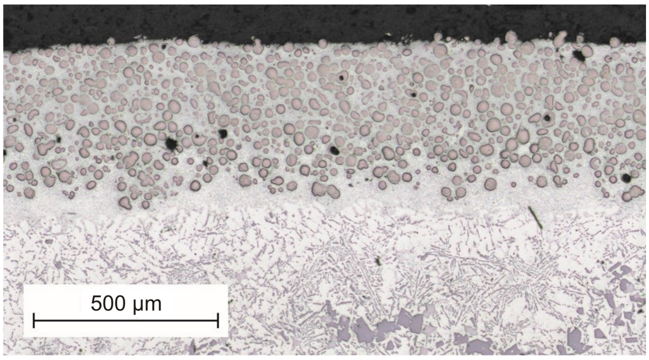

Figure 10: 300 µm NbC reinforced aluminium layer on a cast aluminium alloy substrate

6 Summary and Outlook

Exploitation of the full potential of laser additive manufacturing processes requires consideration of multiple influencing factors including technologies that secure a constant and well defined powder feed rate, process monitoring and control tools that help adjusting heat transfer to powder particles and local workpiece surface areas in an optimal way and to detect impermissible deviations of powder flow characteristics on their way between powder nozzle exit plane and workpiece surface, suitable hardware and process conditions to minimize production costs as well as use of adapted laser sources and cladding materials, also with respect to environmental concerns. Continuous development in all these fields will help laser additive manufacturing to expand into even more application fields and to become a key factor for production of near-net-shape products that cannot be realized with any other production process. Finally, combination of laser cladding and thermal spraying will permit production of surfaces that feature characteristics that could not be achieved by use of only one coating technology.

8 Literature

[1] N.N.: Code of practice DVS 2322: Determination of powder feed rate, 09/2017, pp. 1-11

[2] Bonss, S., M. Seifert, J. Hannweber, U. Karsunke, S. Kühn, D. Pögen, E. Beyer: Precise contact-free temperature measurement is the formula for reliable laser driven manufacturing processes. Proceedings 9th Int. Conf. Photonic Techn. LANE 2016, pp. 1-9

[3] Ramirez, A.B.: CLAMIR precisely controls advanced laser manufacturing processes. Laser Focus World, January 2019, pp. 99-100

[4] Wank, A., F. Beck, C. Schmengler, J. Zierhut, K. Kloiber: Closed-loop control tools for automated laser cladding processes. Proc. Int. Thermal Spray Conf. 2016, May 10th-12th, 2016, Shanghai, P.R. China, pp. 1-6

[5] Schreiber, F., J. Wilden: Laser-Like-Plasma-Pulver-Auftragschweißen LLP - Eine Alternative zum Laser-Pulver-Auftragschweißen. Proc. 11th Fachtagung Verschleißschutz von Bauteilen durch Auftragschweißen, Halle, Germany, June 15th-16th, 2016, pp. 14-17

[6] Yaakob, K.I., M. Ishak, S.R.A. Idris: The effect of pulse welding parameters on weld geometry of boron steel using low power fibre laser. Journal of Mechanical Engineering and Sciences, 11 (2017) 3, pp. 2895-2905

[7] Partes, K., C. Theiler, T. Seefeld, F. Vollertsen: Laser cladding powered by diode lasers at high processing speed. Proceedings 2nd Intl. WLT-Conference on Lasers in Manufacturing 2003, Munich, June 2003

[8] Schmengler, C., A. Hitzek, A. Wank: Capability of High Speed Laser Process with Iron-based Alloys. Proc. Int. Thermal Spray Conf. 2019, May 26th-29th, 2019, Yokohama, Japan, pp. 1-7

[9] Bobzin, K., et al.: Combination of a laser deposition welded corrosion protection coating and a thermally sprayed wear protection coating. Thermal Spray Bulletin, 13 (2020) 2, pp. 114-121

[10] Wank, A., A. Hitzek, C. Schmengler, T. Molitor, S. Ocylok: Capability of blue lasers for cladding of noble metals. Thermal Spray Bulletin, 14 (2021) 1, pp. 32-39

[11] Rettig, M., et al.: Carbidic Brake Rotor Surface Coating Applied by High-Performance Laser-Cladding. Proceedings of EuroBrake 2020, EB2020-MDS-025, pp. 1-8

[12] EP3620546A3, Brake disc and method for producing the same. Patent pending

[13] Rettig, M.: Aluminium Brake Disc. Proceedings of EuroBrake 2020, EB2020-MDS-010, pp. 1-8