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High Speed Micro Cladding Using a High-Power Single-Mode Continuous-Wave Fiber Laser and a Polygon Scanning System

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Abstract

High speed micro cladding is a new field of research at the Laserinstitut Hochschule Mittweida (LHM). So far, the investigations have been focused on high rate micro cladding with high power short pulse lasers and fast galvanometer scanner systems. Thereby, a high build-up rate of more than 3,500 mm^3/h and a structural resolution of 50 µm have been achieved [1, 2]. Laser micro processing e.g. welding and cutting by applying high brilliance laser radiation of continuous wave (cw) lasers in combination with ultrafast beam deflection systems has been successfully applied at LHM [3, 4]. Therefore, the current investigations deal with the potential of high speed micro cladding of µm-sized metal powder using a cw laser. For the experiments, a cw fiber laser with an output power up to 3 kW and a polygon scanning system for fast laser beam deflection with a scan speed up to 500 m/s are used. Furthermore, to switch the laser irradiation during the scan line, an acousto-optic modulator with a maximum frequency up to 2 MHz is applied. Generated micro-walls and the results of the rapid surface coating with layer thicknesses in the micron range are presented depending on the various laser parameters. Also, the influence of process limits of the high speed micro cladding are shown and discussed.

Keywords: Micro Cladding, High Speed, Coating, Surface Functionalization, Surface Treatment and Cladding, Additive Manufacturing

1. Introduction

Micro Cladding rank among the generative production processes. The procedure is mostly used with cw lasers and executed by relative motion realized using axes or robots. Focusing is achieved with a fixed optic. A melt pool is generated on the workpiece surface into which the powder reaching the surface is melted. This produces a material deposition. To generate and maintain the melt pool in the interaction zone, high energies per unit of greater than 10 J/cm are needed. This has the disadvantage that the substrate and the structure that is built up are thermally loaded. Additionally the processing speeds remain small, at less than 10 mm/s [5-9].

The particularity of the variant of the procedure developed at LHM is the use of a short-pulse fiber laser in combination with a rapid galvanometer scanner [10-13]. This allows application of high scan speeds (> 1 m/s) and low energies per unit (< 0.1 J/cm). For the use of rapid beam deflection, a new procedure variant was developed in order to be able to realize the material deposition there, too [12, 13]. Due to the high scan speeds, the powder stream cannot be fed along in the same way as in classical laser cladding. Instead, using coaxial or flat spray nozzles and a square or rectangular powder spot is produced on the workpiece surface in which the processing occurred. By using high pulse peak intensities (greater than 10^8 W/cm³), a targeted microstructuring in the form of regular cavities was introduced into the structures that are to be generated (Fig. 1a). The cavities serve to store powder. By irradiating the filled cavity (Fig. 1c) with high intensities and sufficiently high pulse energies or fluences, enamel margins are formed around the cavity (Fig. 1d). This caused the cavities to grow in height continuously with the increasing number of irradiations. Another condition for generating regular cavities was the geometric spacing of pulses, which had to lie in the range of the focus diameter. Additionally, a geometric repeatability of the laser pulses had to be assured from one scan to the next.

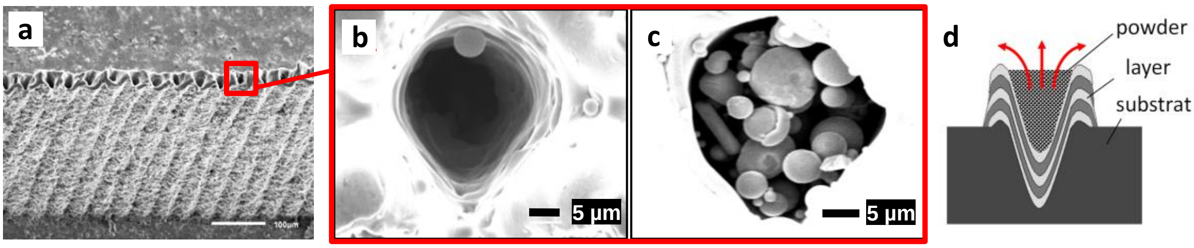

Fig. 1: Description of the micro cladding proceeding at LHM. SEM-pictures: (a) Micro wall with cavities on the structure surface;
(b) Empty cavity after ultrasonic cleaning; (c) Powder filled cavity before ultrasonic cleaning;
(d) Schematic illustration of the building process, layer = enamel margins after a laser pulse.

Building on the results, the procedure at LHM was transitioned to a high rate process [1, 2]. By an upscaling of the laser output power (from 14 to 200 W), the pulse repetition rate (from 50 to 200 kHz), and the scan speed (from 2 to 15 m/s) it was possible to achieve a build-up rate of more than 3,500 mm³/h. The structural resolution achieved currently lies at 40 µm.

In order to achieve a further increase of the build-up rate as well as to identify the physical and technical limits, the ongoing investigations deal with the application of even higher laser output. For this purpose a polygon scanner system, a cw high power fiber laser and an acoustic-optic modulator were used. This process draws on the experiences of the LHM in high-speed micro machining (welding, cutting and structuring) [3, 4]. The studies on micro cladding using ultrafast beam deflection presented in this paper deal with the options for surface coating as well as the generation of linear structures. The first results in this are presented and discussed.

Possible applications of the generation of linear structures lie in the surface structuring for flow reduction, microstructures with undercuts on turbine blades in order to stability the layers, micro-heating elements, or the repair of micro-components [5-9]. Applications for rapid surface coatings are seen in the area of wear and slip protection coatings [7, 14].

2. Experimental Setup

To realize high speed scanning, a polygonal mirror scanner with a maximum scan speed of 500 m/s developed at LHM was used. The lateral scanning transverse to the polygon scanner was realized with a galvanometer mirror. This also enables a two-dimensional processing. In the experiments, a high brilliant single mode fiber laser YLR-3000 SM (IPG) was applied. The maximum cw laser output of the random linear polarized laser radiation was 3 kW with a times-diffraction-limit-factor of $M^2 < 1.2$. Significant parameters of the laser machining system are summarized in table 1.

Table 1. Significant parameters of the laser system

focal length [mm]	255	167
focal spot size ($d_{0,86\%}$) [µm]	38	26
peak intensity (3 kW) [10^8 W/cm²]	5.29	11.3
maximum scan speed [m/s]	500	300

During the scanning motion the laser beam was switched by means of acoustic-optical modulators (AOM). The maximum frequency was 2 MHz with a minimum pulse duration of 500 ns. This allows the realization of a quasi-pulsed regime as in earlier studies with a short-pulsed fiber laser and therefore also a comparison to these studies. An austenitic CrNiMo - Steel (1.4404) was used for the linear structures; in the investigations of the surface coating by contrast, a nickel super alloy (Inconel 625) was used. Both powders had an average particle diameter of approximately 6 µm and a mostly spherical particle form. The substrate material used was stainless steel (1.4301). The powder-gas mixture was distributed at the processing site by a flat spray nozzle developed in-house of 20 or 40 mm width. The stream is effected using a powder feeder (CP2) by Thermico. The following feeder parameters proved the most suitable: Carrier gas flow of Argon at 13 l/min and powder mass flow at approximately 20 g/min. The feeding parameters were not varied during the experiment series. The experimental structure shall be schematically illustrated in Fig. 2a.

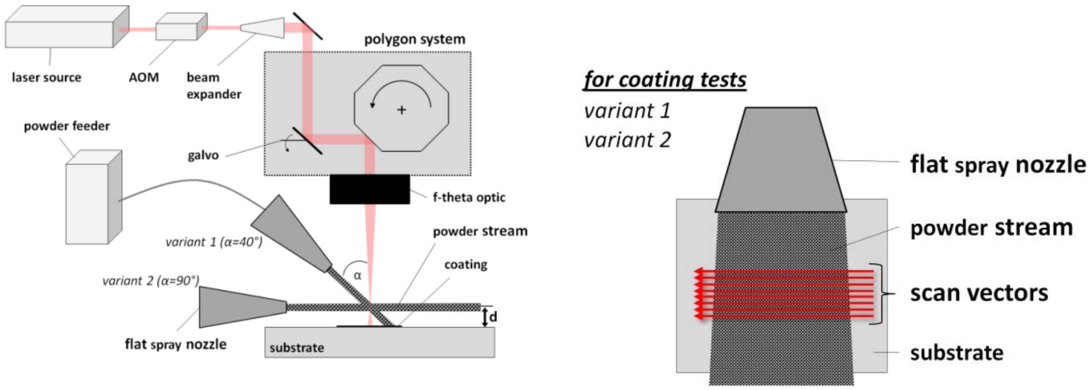

Fig. 2. Schematic illustration: (right) Experimental setup; (left) Scanning regime for coating tests.

In order to investigate the high speed micro cladding for linear structures, variant 1 (α = 40°) was exclusively used with substrate position d = 0 mm. Thereby the processing took place in the focus. For the coating experiments, variants 1 and 2 were used at different substrate positions (d). Here the laser beam focus was always in the middle of the powder stream. For the coating experiments a range of 10 mm transverse to the polygon scan direction was scanned (Fig. 2b). The line distance was selected such that a closed layer was created. At a focal length of f = 255 mm, the line distance was 40 µm and 33 µm at a focal length of f = 167 mm. In future experiments this should be realized by an integrated X- or Y-axis.

3. Results and Discussions

3.1 Generation of Linear Structures

The experiments began with a cw-laser radiation without additional modulation. The scan speed was at maximum 200 m/s, the laser output was varied from 0.5 to 2 kW. The build-up rates achieved by this were however very small. When using lower laser outputs or intensities there was only an adhesion of loose powder onto the workpiece surface. With increasing intensity however indentations form with laterally elevated enamel margins along the scan line. It turned out however that a continuous indentation is unsuitable for powder storage. For this reason the following investigations were carried out with modulated cw-laser radiation (clocked mode). Therefor a high-performance AOM was integrated into the beam path. By using a quasi-pulsed processing, it was possible to observe a creation of microstructures similar to those achieved with the short-pulsed laser (pulsed mode). The optic used for these experiments had a focal length of 255 mm with a focus diameter (86% power inclusion) of 38 µm. This made it possible to achieve approximately the same intensities as when using the short-pulsed laser. The scan speed and intensity were varied. The lengthening of pulses had to be taken into consideration for the experiments in clocked mode. At a scan speed of 100 m/s and a pulse duration of 500 ns, the geometric pulse lengthening was already 50 µm. In order to form regular cavities a defined geometric pulse distance had to be set. This resulted from the focus diameter plus the pulse lengthening and was adjusted by the pulse frequency. The repeat accuracy of the impact points of the laser pulses from scan to scan was given. Affected by the conditions for the geometric pulse distance and the maximum frequency of the AOM of 2 MHz, there was a maximum scan speed of 100 m/s. At higher scan speeds, there was a pulse separation and pillar formation was observed (Fig. 3). The build-up rate has dropped by half compared to the micro-walls. This was already determined in the former experiments in pulsed mode.

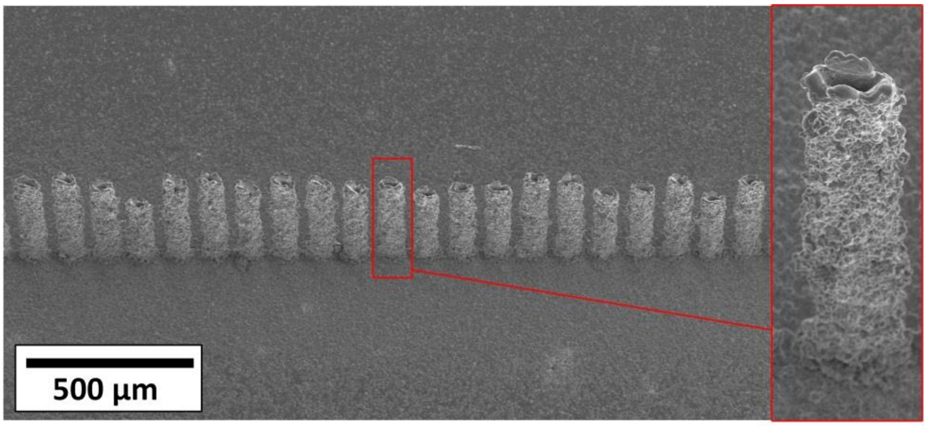

Fig. 3: SEM photograph of micro pillars with a scan speed of 200 m/s, pulse distance 100 µm.

The highest build-up rate could be observed at a scan speed of 100 m/s, a frequency of 1.5 MHz, and a pulse duration of 500 ns. The geometric pulse distance was at 66 µm. In Fig. 4 the results with the highest build-up rates in clocked mode compared to the pulsed mode are shown.

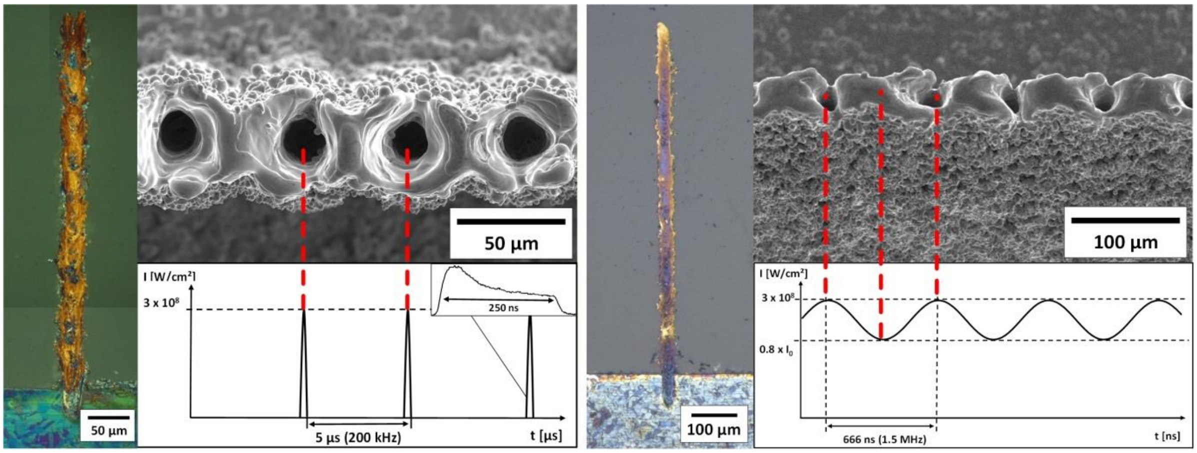

Fig. 4: Comparison of the best results at short pulsed mode and clocked mode. SEM-photograph of the micro cavity and appertaining time pulses; etched cross-section polish.

Since the high-performance AOM had a rise and fall time of 500 ns, the output or intensity at a frequency of 1.5 MHz did not drop off completely but instead was modulated between 100% and 80%. Fig. 4 shows that lengthening the pulses to 66 µm and reducing the intensity between the pulses or cavities brought about enamel agglomeration. This appeared not to influence the uniformity of the height, but did lead to a reduction of the cavity diameters and thereby led to reduced powder storage. In comparing these results with the pulsed mode, a great deviation in the layer thickness per scan was observed (Tab. 2). This is due to the geometric pulse lengthening and the resulting worsened powder storage. When comparing the build-up rate it was still possible to achieve an increased elevation by applying a higher output.

Table 2. Comparison of short pulsed mode and clocked mode; process and building parameter.

	pulsed mode	clocked mode
peak intensity (3 kW) [10^8 W/cm²]	2.7	2
scan speed [m/s]	11	100
wall thickness [µm]	60	40
layer thickness per scan [µm]	0.7	0.25
build-up rate (laser time) [mm³/h]	1386	3600
build-up rate (process time) [mm³/h]	1054	1800

When observing the etched cross-section polish (Fig. 4) it was not possible to identify any oxidation as well as in pulsed mode. The color etching was done following Lichtenegger and Bloech. Color areas demonstrate differences in the concentration in the chemical composition. Grey areas on the other hand point out an oxidation. The first results of high speed micro cladding using cw laser radiation and AOM demonstrate impressively the potential of the innovative process variant. Enlarging the cavity diameter to increase the storage effectiveness is a part of ongoing studies.

3.2 Studies on Surface Coating

For the studies of rapid surface coating, the work was done again without additional modulation. To generate layers an effect was exploited that was already investigated in previous studies [11]. It arises if powder particles are irradiated at high intensity. Due to evaporation close to the surface and the resulting recoil effect, the particles are deflected in the direction of the laser beam. Due to the ultrafast beam deflection, a powder particle can be considered as static during the irradiation. With the flat stream nozzle and the feed parameters used, it was possible to estimate a particle speed at the nozzle outlet of approximately 15 m/s. This resulted in a dwell time of maximum 1 µs at a minimally applied scan speed of 50 m/s and a focus diameter of a maximum of 50 µm. This in turn resulted in a maximum completed particle path during the interaction period with the laser beam of 5.4 µm. The recoil effect should be illustrated in Fig. 5. The focus level was in the middle of the powder stream. Based on the plasma formation the focus level of the laser beam could be easily recognized. Particle deflection occurred in this range. Above this area powder particles were already heated up. The intensity at that position was however not sufficient to produce evaporation near the surface. Underneath the plasma area the particle deflection in the direction of the laser beam was clearly visible. Coating was realized by placing the substrate underneath the focus level (Fig. 5).

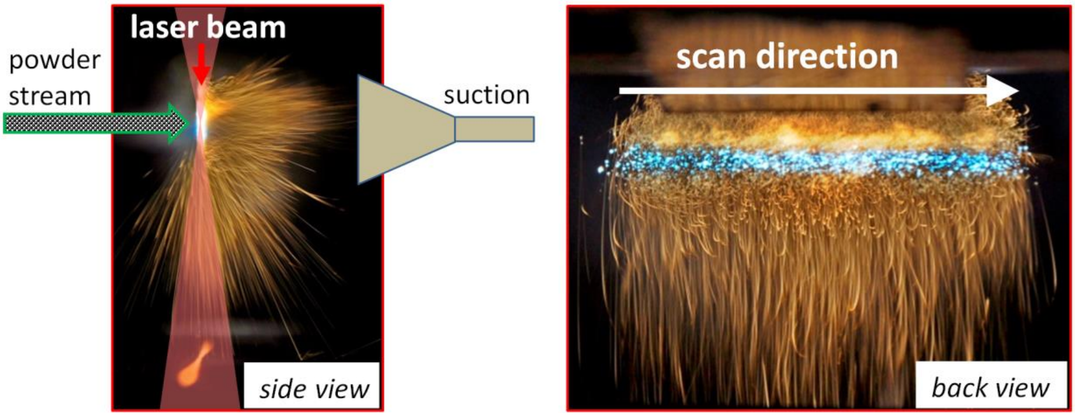

Fig. 5: Digital SLR camera photographs of the recoil effect (exposure time was 1/320 s = 3 ms, time per one scan line approx. 1 ms)

For these investigations, the substrate position, the scan speed, the intensity, and the number of irradiations were varied. In addition, two different focus diameters and nozzle angles were used. Fig. 6 should clarify the influence of the process parameters based on SEM-pictures. It was possible to determine that the coating rates depended essentially on the intensity and the substrate position. If the intensity was too low, the particles got a little or no recoil. They were not melted into the substrate surface (Fig. 6a, f). With increasing intensity, the particle melting could be clearly observed (Fig. 6b-e). Based on EDX measurements, it was possible to determine that particles already adhering to the substrate surface were melted into the layer by additional irradiation. For this reason the particles from previous irradiations could no longer be identified or could hardly be identified in the SEM photographs. Additionally, it was possible to determine that the ideal substrate position for effective coating was between 2 and 3 mm underneath the focus level (Tab. 3). If the distance to the focus level was too small, this caused in an ablation of the substrate material because of the high intensities. If however the distance was too great, the particles cooled down too much in the motion. Additionally, the intensity on the substrate surface was too low to generate temperatures at which already adhering particles could be melted. The roughness increased noticeably with the increase of the distance to the substrate.

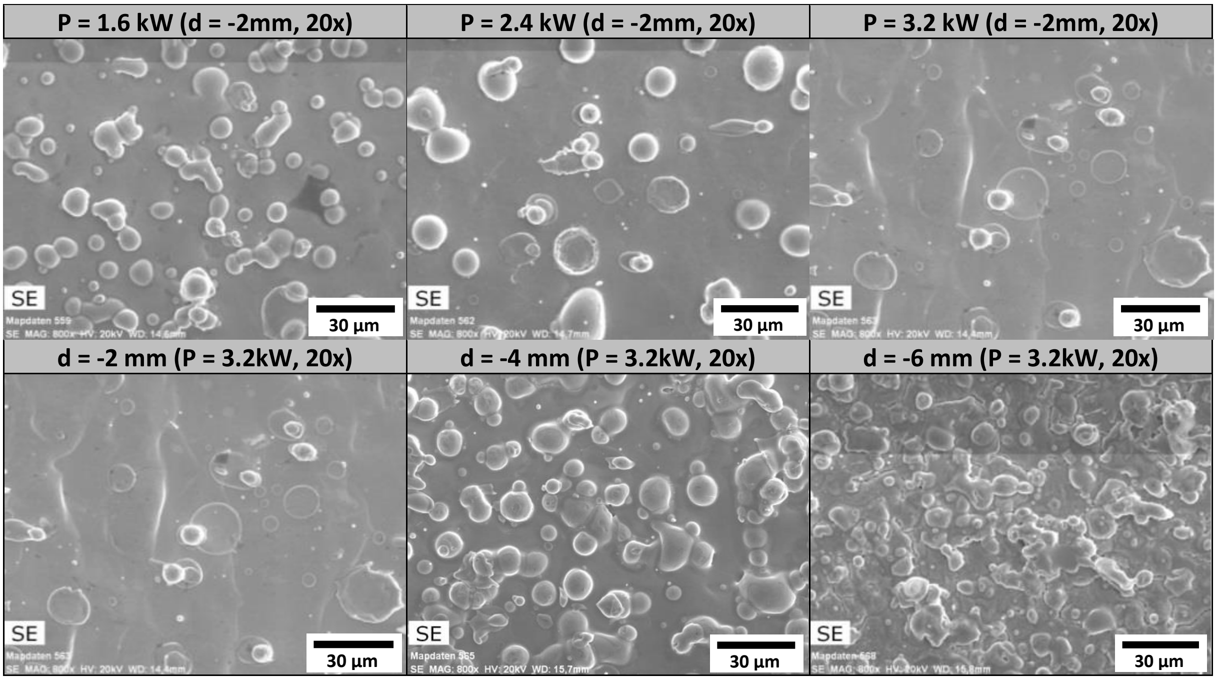

Fig. 6: SEM photographs by different laser power and substrate distances. (P = laser power, d = substrate distance to laser focus, 20 irradiations)

To generate a closed layer, a minimum number of passes were necessary. This was depending on process parameters between 10 and 30. The layer thickness increased with additional passes. By varying the scan speed it was possible to identify an optimal scan speed of 250 m/s. At higher speeds and as a result of lower dwell times the coating efficiency dropped clearly.

In Tab. 3, the chemical compositions of the layers that has been created are listed depending on the substrate position and the selected nozzle angle as well as the focal length. The measurement was made using EDX. To this end an area of 150 x 120 µm^2 (see image size Fig. 6) was selected in the coating created. The spectrum achieved thus constitutes an average value for the surface. Based on the measured average values and the mapping image (cf. Fig. 7) it was possible to record the mixture with the substrate material as well as the distribution. When observing the influence of the selected focus diameter or the focal length, it was not possible to identify any significant difference. It seemed in this that the higher intensity with the shorter focal length compensated for the larger interaction cross-section with the longer focal length. The minimum coating result was to be recorded at a substrate position in the focus level. As already mentioned, this already resulted here in an ablation of the substrate material. The comparison of the nozzle angles shows, that a higher coating efficiency could be achieved at an angle of 40°. Based on the particle stream in the direction of the substrate, it was possible for more particles to be melted into the layer. However this increased the roughness and the layers had in part a lower density.

Tab. 3: Chemical composition by variation of substrate position, focal length and nozzle angle; (grey line = best result, last line = Chemical composition of Inconel @ alloy 625).

focal length [mm]	nozzle angle	substrate position [mm]	chemical composition [%]								
			nickel	iron	chromium	molybdenum	niobium	silicon	manganese	carbon	oxygen
167	40°	0	24.0	49.8	17.2	3.6	1.3	0.2	1.3	2.7	0.0
		-2	52.5	11.4	19.4	8.8	3.0	0.4	1.0	3.5	0.0
		-4	48.6	11.3	23.5	6.0	3.9	0.3	1.1	3.4	1.8
		-6	35.9	12.1	29.6	5.7	5.6	0.4	1.2	5.0	4.6
167	90°	0	18.2	54.7	18.1	2.1	0.7	0.4	1.8	4.1	0.0
		-2	44.7	16.3	21.7	6.4	4.9	0.1	0.7	3.3	1.8
		-4	27.8	39.1	19.8	3.9	2.6	0.3	1.4	3.5	1.7
		-6	31.1	37.1	19.3	4.1	1.9	0.3	1.4	4.3	0.4
255	90°	0	35.2	33.2	18.7	5.5	1.8	0.4	1.4	3.7	0.0
		-2	46.0	12.2	22.4	7.0	6.2	0.2	0.8	3.3	1.9
		-4	33.5	22.4	26.1	5.3	4.4	0.4	1.4	3.2	3.2
		-6	38.1	22.5	22.7	6.5	3.8	0.4	1.1	2.9	1.9
167	40°	-3; 3.2 kW; 10x	56.9	5.3	20.5	9.1	3.6	0.3	0.5	3.7	0.1
		Inconel @ alloy 625 :	≥ 58	≤ 5	20 - 23	8 - 10	3 - 4	0.5	0.5	0.03 - 0.1	-

Proceeding from these investigations, the coating result with the highest coating efficiency is also listed in Tab. 3 (penultimate line). Compared with the composition of the powder material Inconel 625, a good agreement could be recorded. With an average layer thickness of 5 µm there was a coating rate of 242 cm²/h. The results are comparable to the values as they are known from the literature [14].

Fig. 7 shows a selection of different pictures and measurements of the best coating results. Based on the cross-section polish in Fig. 7b, c the area of mixture of the substrate surface and the coating is clearly visible.

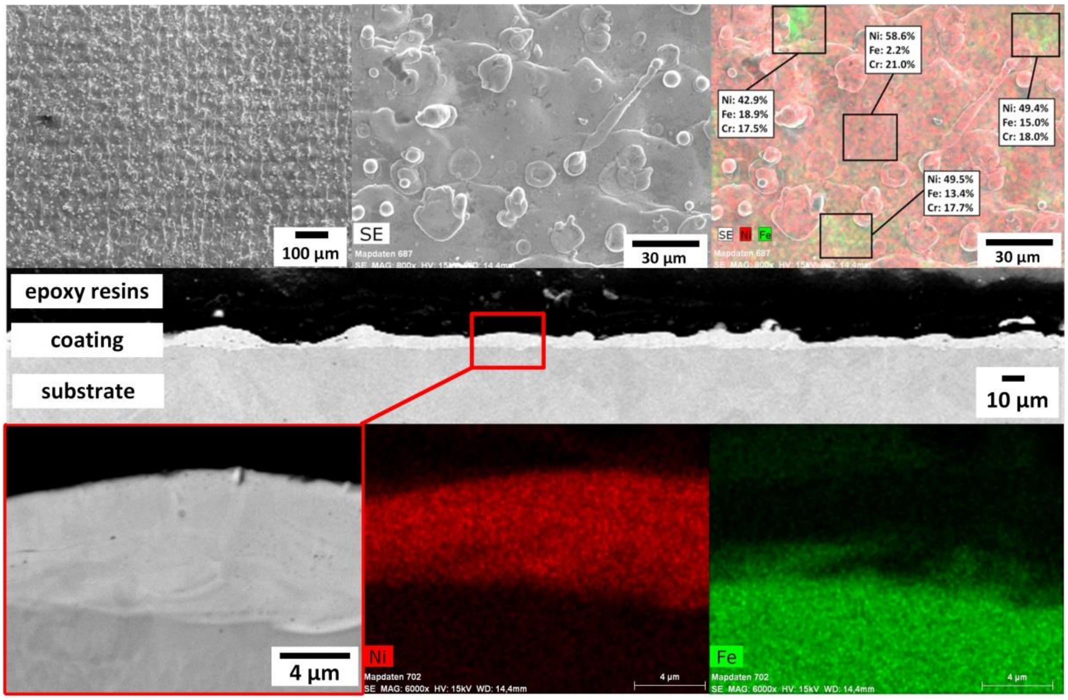

Fig. 7: (upper row) Top view SEM photographs by the best result and a mapping image; (middle row) Cross-section polish; (lower row) detail view SEM photographs and appertaining mapping images of the cross-section polish.

4. Outlook

In future experiments, a high-power fiber laser with 10 kW output should be used. In the surface coatings, it would be possible, at the same intensities, to use greater focus diameters as well as larger line spacings. Coating rates up to 1000 cm²/min would be conceivable.

By using larger focus diameters, it would be possible to increase the build-up rate of the linear structures. Through the resulting increased cavity diameters, more powder could be stored, which would lead to an increase in layer thickness per scan.

Due to the explosive risk because of the high powder through-put and the high price of the very fine powder, the process in future experiments will be carried out entirely in a protective gas environment with powder recapture using a cyclone separator.

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