Closed-loop control tools for automated laser cladding processes

A. Wank, F. Beck, C. Schmengler, GTV Verschleiss-Schutz GmbH, Luckenbach / D,
J. Zierhut, K. Kloiber, Zierhut Messtechnik GmbH, München / D

As costs of laser sources have decreased strongly laser cladding and laser additive manufacturing have become fast-growing technologies due to the inherent advantages like high precision of material deposition, flexibility concerning achievable coating thickness and deposition rates, metallurgical bonding to substrate materials, low porosity and fine microstructure deposits, relatively low heat transfer to substrates and aptitude for process automation. However, there is a multitude of applications that require closed-loop control tools in order to permit complete process automation. For example change of component temperature during the cladding process, e.g. for cladding of small wall thickness components, results in need of tools to adjust laser power. And in order to fill cavities like grooves precisely despite distortion and thermal expansion of components to be clad edge recognition systems for adjustment of laser head movement are needed. GTV Verschleiss-Schutz GmbH and Zierhut Messtechnik GmbH jointly developed LPowC (Laser Power Control) and LPosC (Laser Positioning Control) systems based on digital image analyses to address these needs. Both tools are based on intelligent cameras that evaluate recordings from the cladding zone through the optical path of the laser optics. While LPowC controls local emission by the laser cladding process, LPosC detects distances between edges on component surfaces and laser spot as a base for positioning correction. Exemplary cladding of thin wall tubes with different iron, nickel and cobalt based alloys with automatic adjustment of laser power and the effect on local microstructure of the deposits are presented as well as evaluation of filling of grooves on shafts that undergo strong cooling during the cladding process.

1 Introduction

Laser additive manufacturing including laser cladding is used in more and more applications due to technological advantages on the one hand and steadily decreasing prices of laser sources [1-2] on the other hand. Laser cladding offers unsurpassed reproducibility and precision of position as well as heat transfer to component surfaces and powder feedstock. This results in exceptionally low dilution with base material without compromising metallurgical bonding, small heat affected zones and distortion as well as low porosity and homogeneous, fine grained micro-structure of deposited layers.

Automation of laser cladding process is relatively easy due to typical high degree of electronic control of quality relevant process parameters like laser power, carrier and laser process gas flow rates as well as powder feed rate and handling system positions. However, full process automation sometimes does not work for control of absolute handling system positioning only. Instead precise control of actual relative positioning of powder nozzle and component surface is needed and must even cover disturbance variables like thermally induced expansion and / or component distortion that can even vary during the cladding process. Cladding of extrusion screw threads or turbine blade leading edges are examples of such jobs. Additionally typical repair jobs involve machining of damaged areas and material needs to be deposited between the edges of the machined surface area.

Also, change of component temperature during a cladding job e.g. due to small wall thickness of a component to be coated can require adaptation of laser power in order to avoid scattering of dilution with base material, coating thickness and / or microstructure.

CCD cameras are standard tools for alignment of laser beam and coaxial feed powder nozzles. But digital analyses of their images also permits determination of in-flight particle velocity [3], laser power closed-loop control [4-6] and laser cladding head positioning adaptation. The latter two features are combined in a single camera system that was jointly developed by GTV Verschleiss-Schutz GmbH and Zierhut Messtechnik GmbH. This paper describes the contained tools laser power control LPowC and laser positioning control LPosC tools both concerning their function principle and capability in use.

2 Laser Cladding Process Control Tools

2.1 LPOwC

The laser power control tool LPowC uses two analysis areas within camera images that need to be defined by the user, **Fig. 1**. The total intensity of the bigger area is used to monitor reflections from the inner surface of the powder nozzle as a means to detect impermissible pollution of the cladding head optics. If a pre-defined threshold is exceeded the respective digital signal from the interface box can be used to either shut down the laser source automatically or at least to display an error message on a control panel.

The total intensity continuously recorded within the smaller circle is used as control factor to compensate for substrate temperature change by laser power adaptation. However, LPowC cannot replace process parameter optimization. Users first need to carry out cladding tests and define optimal starting parameters including according intensity measured by LPowC at specified camera settings (exposure time and amplification).

Then users need to set minimum and maximum values around the optimal target intensity in order to receive digital signals from the interface box to initiate laser power modification in a suitable control loop. According adjustable control loops are implemented in

GTV laser cladding centre PLC programs, but can also be realized by users themselves. GTV software permits customized damping of control cycles based on number of images for averaged intensity calculation, power adaptation step and reaction time.

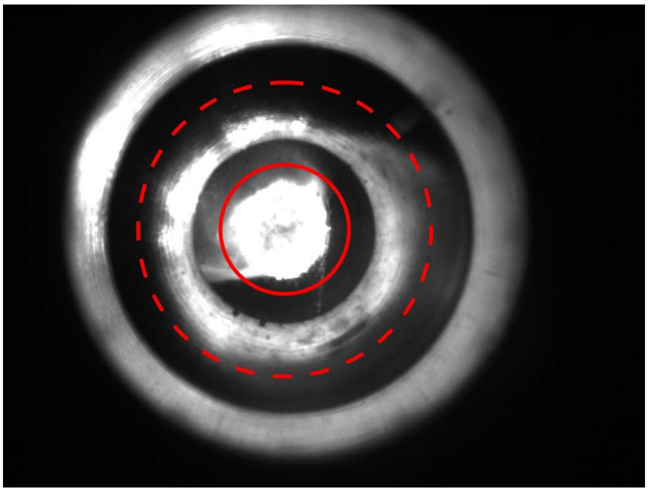

Fig. 1. Exemplary laser cladding process image with display of two observation areas; continuous line circle: image area used for process control, dashed line circle: image area for process safety check

2.2 LPosC

The laser positioning control tool LPosC detects both the actual position of laser beam centre as well as component edges and thereby permits adjustment of cladding head movement programs, **Fig. 2**. Laser beam centre point is defined by centre point of the circle formed by the powder nozzle internal bore edges on recorded images. LPosC permits considering laser beam centre position as constant or calculates it from recorded images continuously.
For actual edge detection a region of interest is specified by a rectangle with edge length ratio 2:1 (marked in yellow in **Fig. 2**). Within this area the user needs to define minimal grey scale gradients as well as their maximum length and maximum grey scale values for the system to calculate a line representing the component edge from recorded images. The software contains error correction that includes maximum permissible distance to previously detected edges as well as maximum permissible deviations from previously calculated line gradients to avoid faulty line detection and accordingly faulty cladding head movement correction. If natural emission of the cladding process is too low additional illumination e.g. by special (triggered) lasers can be applied. Such artificial illumination does not influence the general function of the edge detection software.
LPosC software by itself is not capable of defining optimal distances between component edges and laser beam centres. Optimum needs to be determined in pre-tests and depends on material combination and edge geometry as well as demands concerning permissible melting of the component edge and required metallurgical bonding degree, etc.. If the calculated distance between laser beam centre and component edge differs from a set distance more than a set value position correction in the required direction is initiated by an according digital signal to the master PLC.

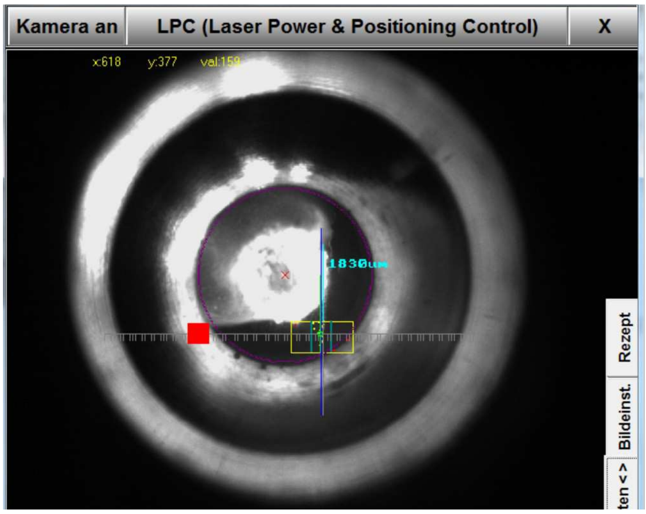

Fig. 2. Exemplary laser cladding process image with laser beam centre point too close to substrate edge as displayed by LPosC; red square indicates shift of reversal point in an oscillating head movement process to left side

3 Experimental

3.1 LPOwC tests on thin walled tubes

Three different kinds of materials are clad on 316L (1.4404) stainless steel tube with 28 mm outer diameter and 1.2 mm wall thickness on 70 mm length up to tube edges. Besides iron based hard alloy FeCrV15 (GTV 31.40.10, gas atomized, +63 -180 µm) and NiBSi 22 HRC alloy (GTV 80.10.1, water atomized, +20 -53 µm) also Stellite® 6 (GTV 31.06.10, gas atomized, +63 -150 µm) is clad. Chemical compositions of powders and cladding parameters are listed in **Table 1** and **2** respectively.

Table 1. Chemical composition of used powders

powder	31.40.10	80.10.1	31.06.10
Fe	base	0.15	1.1
Ni	-	base	1.4
Co	-	0.02	base
C	4.49	0.02	1.0
B	-	1.7	-
Si	1.18	2.76	1.2
Mn	0.97	-	-
Cr	14.5	0.1	28.4
Mo	1.13	-	-
V	15.0	-	-
W	-	-	4.4

In all three cladding tests Laserline LDF 6000-100 laser source, 80 mm collimation and 250 mm focussing length and powder nozzle GTV PN6625 with two 1-3 GTV powder splitters have been used.

Table 2. Cladding process parameters

coating	31.40.10	80.10.1	31.06.10
Fibre diameter	1,500	1,000	1,000
laser power (initial)	900	1,200	900
process gas Ar	25 l/min	25 l/min	25 l/min
carrier gas Ar	2 x 2.5 l/min	2 x 2.5 l/min	2 x 2.5 l/min
surface speed	0.5 m/min	1.2 m/min	0.8 m/min
offset / rotation	1.0 mm	1.0 mm	1.5 mm
layers	1	1	1

Laser power is recorded during the process, cross sections of claddings are prepared along the whole tube axis length and analysed metallographically by optical microscopy. Weld penetration and cladding thickness distribution are evaluated as well as hardness evolution.

3.2 LPOsC tests

Tests are carried out on tool steel X40CrMoV5-1 (1.2344) with the above mentioned powder GTV 31.40.10 as cladding material. The above mentioned laser source, optics, fibre, powder nozzle and splitters have been used. Groove depth and width are varied between 0.5 - 2.0 mm and 5 - 50 mm respectively.

4 Results

4.1 LPOwC tests on thin walled tubes

The evolution of laser power in accordance with the automatic LPosC control for the three tested cladding processes is shown in **Fig. 3**. While the combination of chosen starting laser power and working area emission ranges for FeCrV15 and NiBSi result in strong decrease of laser power after completion of the first turn of the tube, there is a slight increase of laser power in case of Stellite® 6.

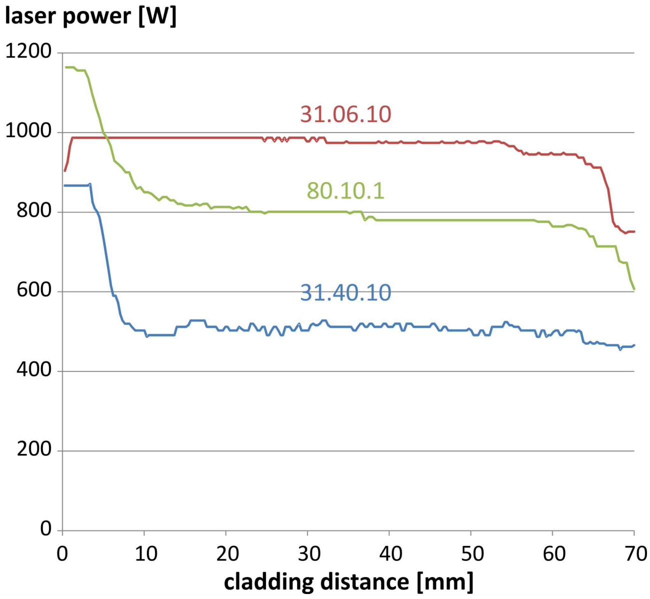

Fig. 3. Laser power evolution during cladding tests with automatic power control by LPowC

Heat accumulation at the tube edge causes automatic reduction of laser power for all three tested materials. However, extent of power reduction is only small in case of FeCrV15.

Optical micrographs of claddings at the start, centre and end of the produced specimens are shown in **Figs. 4** (FeCrV15) and **5** (NiBSi). Both interface between base and clad material and cladding microstructure are homogeneous along the whole covered cladding length. While FeCrV15 claddings consist of very fine vanadium carbides dispersed in a chromium rich iron based matrix, NiBSi and Stellite®6 claddings show dendritic microstructure. All three claddings show low porosity level with small pore size typical for state-of-the-art laser cladding processes.

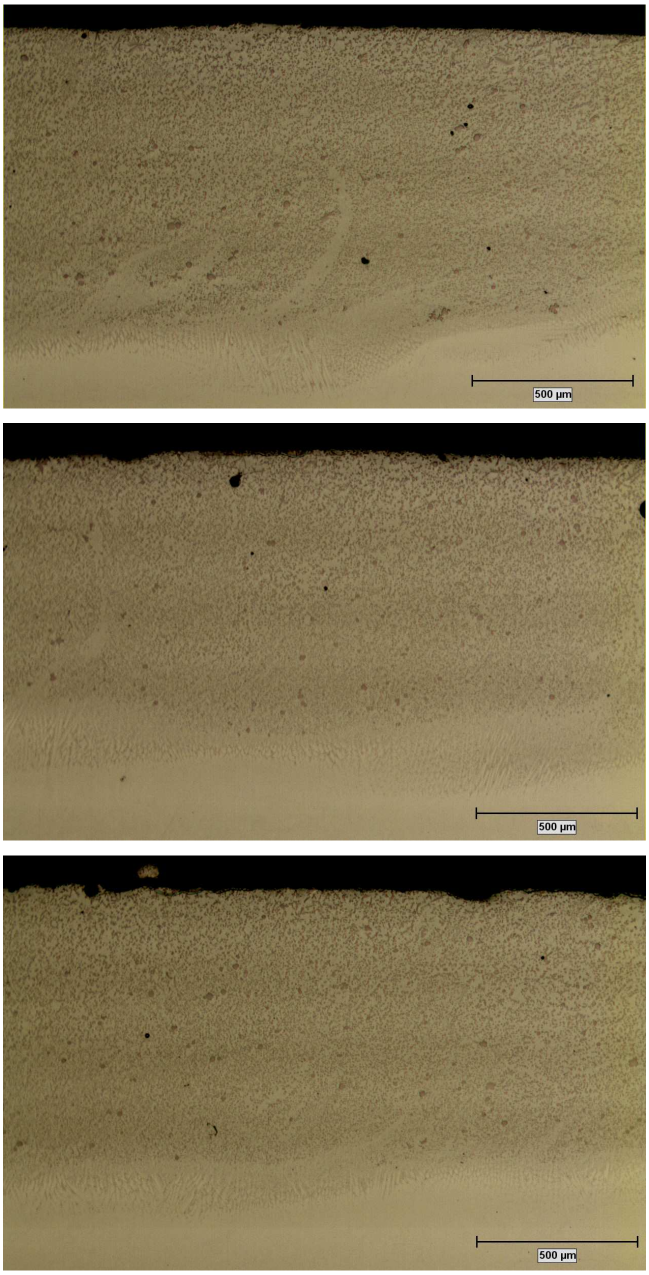

Fig. 4. Optical micrographs of FeCrV15 cladding after 5 mm (top), 35 mm (middle) and 65 mm (bottom) distance

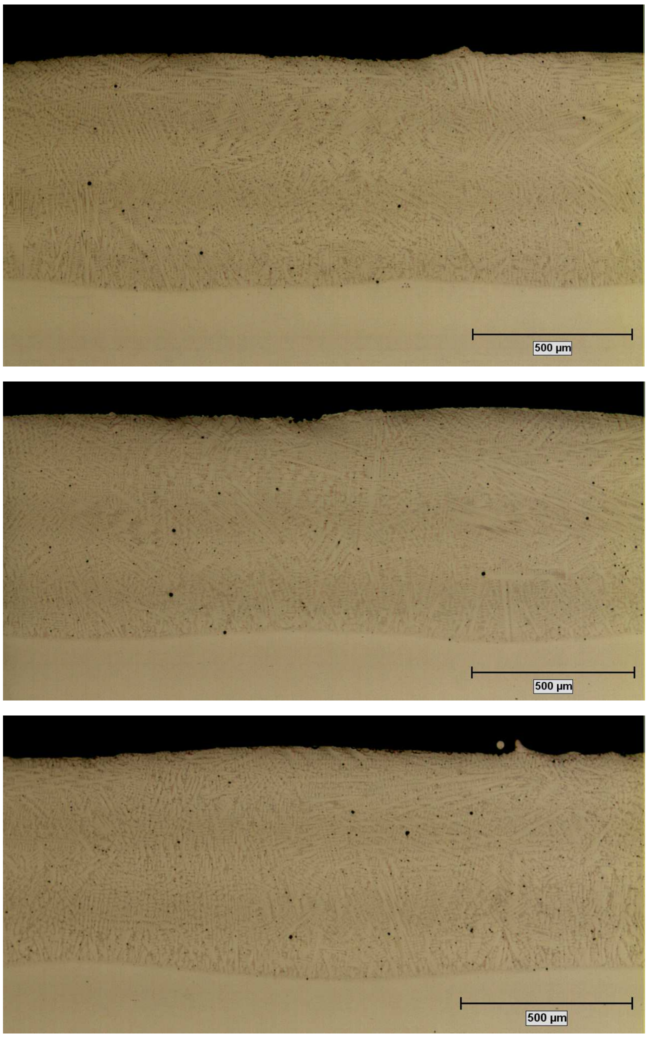

Fig. 5. Optical micrographs of NiBSi cladding after 5 mm (top), 35 mm (middle) and 65 mm (bottom) distance

The overall thickness of FeCrV15 and Stellite®6 clad 316L tubes decreases slightly along the tube axis, while the NiBSi clad tube shows perfectly constant thickness (**Fig. 6**). For FeCrV15 and Stellite®6 thicknesses decrease from 2,200 µm to 2,050 µm and from 2,050 µm to 1,950 µm respectively.

Cladding thicknesses are almost constant along the tube axis for all three kinds of cladding materials. In case of NiBSi overall and cladding thickness amount to 1,688 µm (σ: 19 µm) and 666 µm (σ: 40 µm) respectively. Accordingly weld penetration is about 180 µm, which means about 25% dilution of NiBSi coating with base material.

In the range between 5 - 65 mm cladding distance cladding thicknesses of FeCrV15 and Stellite®6 amount to about 1,050 µm and 1,500 µm respectively. So, weld penetration and base material dilution amount to 100 µm and 10% respectively for FeCrV15 and to 650 µm and 45% respectively for Stellite®6.

In contrast to FeCrV15 and NiBSi claddings that show constant cladding thickness up to the tube edge the Stellite®6 cladding shows decreasing cladding thickness as a consequence of decreased laser power towards the tube edge.

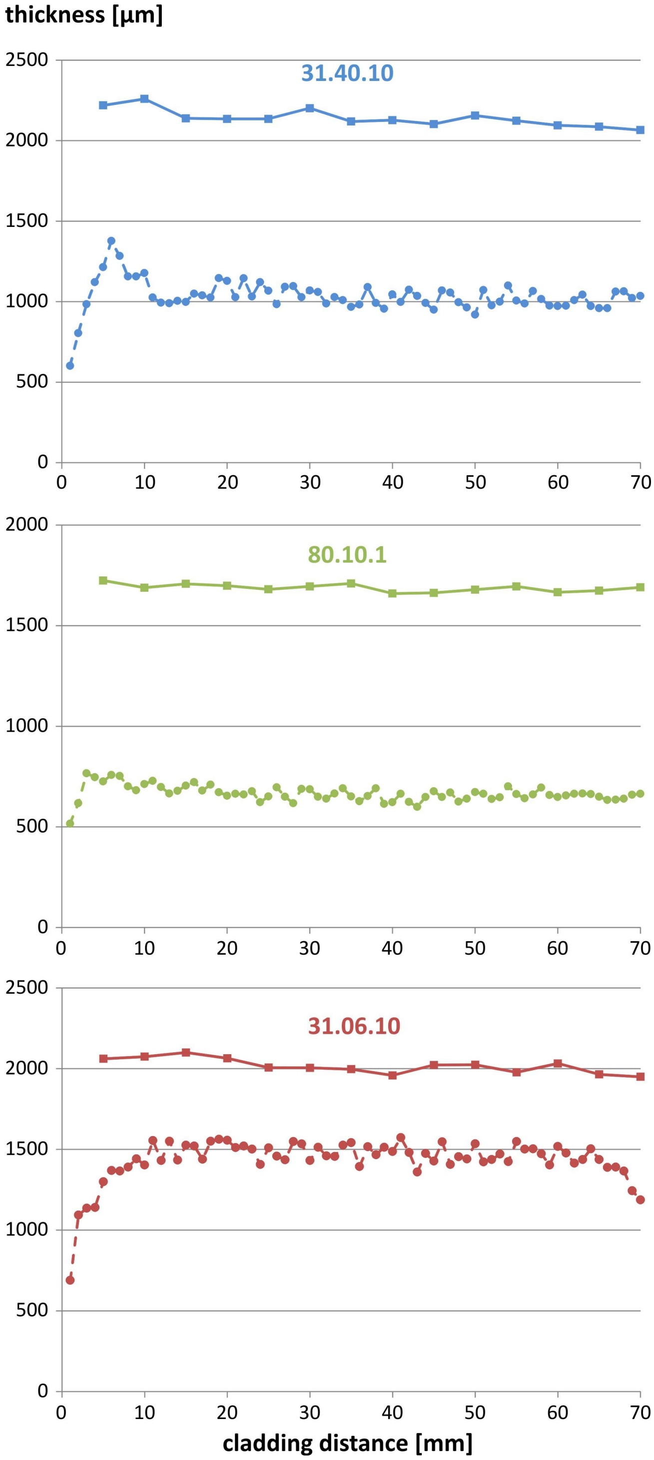

Fig. 6. Total thickness of clad tubes (continuous lines) and cladding thickness (dashed lines) along the tube axis

Despite decreased cooling rate as a consequence of increasing base material temperature during the cladding process microhardness along the tube axis remains basically constant for all three types of claddings (**Fig. 7**). Microhardness of FeCrV, NiBSi and Stellite®6 coatings amounts to 789 HV.3 (σ: 43 HV0.3), 307 HV.3 (σ: 6 HV0.3) and 308 HV.3 (σ: 13 HV0.3) respectively. Especially the NiBSi cladding shows outstanding small microhardness deviations.

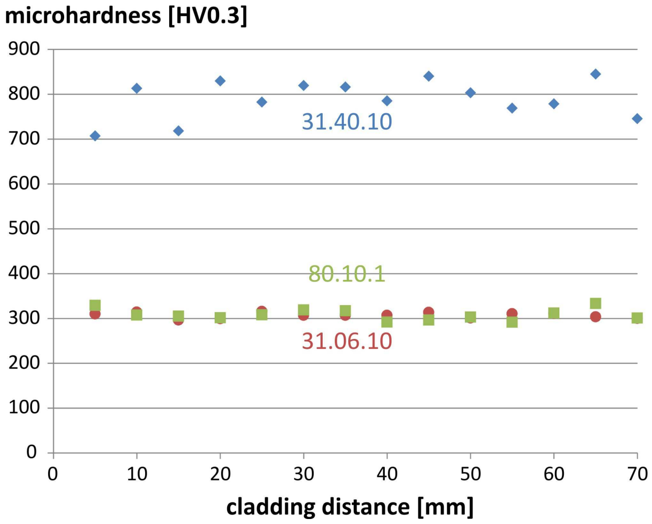

Fig. 7. Microhardness distribution of claddings along the tube axes

4.2 LPOsC tests

Besides laser power, oscillation width and speed, traverse velocity, powder feed rate and cladding head inclination to the workpiece need to be adjusted to groove geometries in order to achieve claddings that fill grooves with perfect bonding along the whole interface between base material and cladding. **Figs. 8** and **9** contain images of an exemplary 8 mm wide FeCrV15 cladding that has been deposited inside a groove with 2 mm depth and 45° inclined edges. Laser cladding head inclination to the workpiece surface was kept constant at 90°. 3,000 W laser power, 5.33 mm/s traverse speed and 10 mm oscillation width have been applied. Less than 0.2 mm had to be ground in order to achieve a cladding smooth surface at the same height like the surrounding workpiece surface.

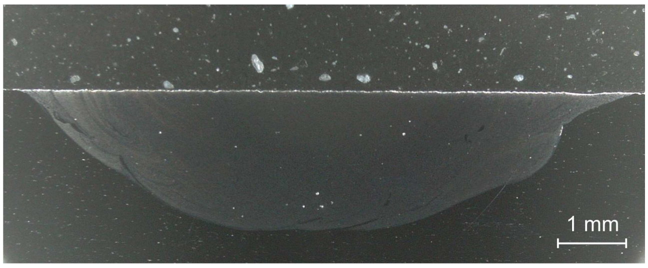

Fig. 8. Overview image of a FeCrV15 cladding that has been produced by oscillating laser cladding head movement inside a groove with 45° edges after grinding

The applied process strategy results in considerable dilution of cladding material with base material at the 45° inclined outer regions and rounded transition to the groove bottom plane. Cladding microhardness amounts to 650 HV0.3 with 20 HV0.3 standard deviation. As typical of state-of-the-art laser claddings only low porosity with small pore size (i.e. < 20 µm) is observed in cladding cross sections.

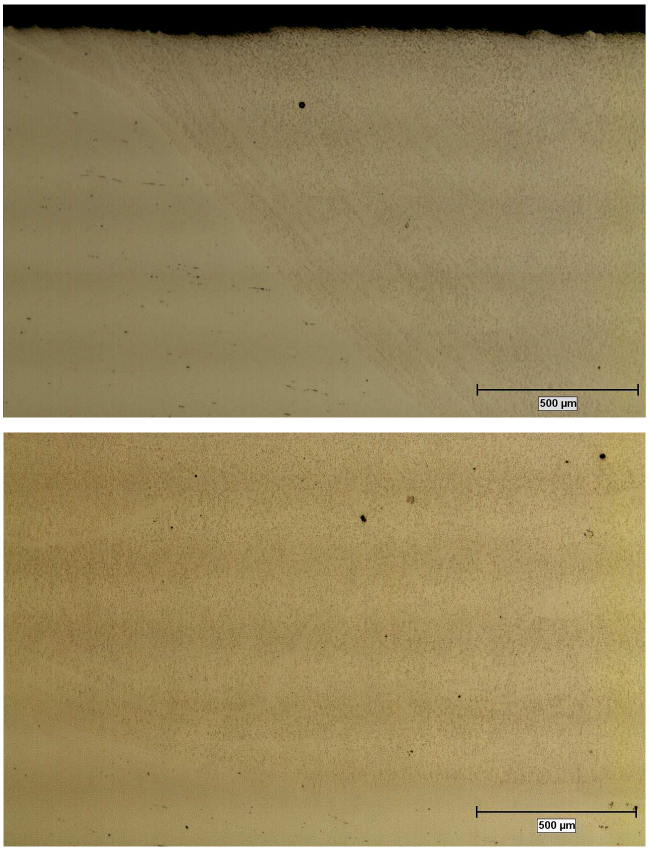

Fig. 9. Optical micrographs of a FeCrV15 cladding that has been produced by oscillating laser cladding head movement; top: groove edge, bottom: groove centre

5 Discussion

Generally, for all types of claddings produced with automatic laser power adjustment tool LPowC good homogeneity of thickness and weld penetration has been achieved even for the demanding application of relatively thick cladding of thin walled tubes. Dilution of the produced Stellite®6 specimen is certainly by far too high for typical industrial applications. Nevertheless this specimen also proves capability of LPowC to maintain cladding quality constant even in case of a process with extremely strong dilution with base material.

Despite strong increase of base material temperature in the cladding zone and accordingly decreased cooling rate all claddings show constant microstructure and even microhardness along the whole cladding distance. Low microhardness of Stellite®6 claddings must be attributed to strong dilution with the 316L base material and is not typical of Stellite®6 laser claddings.

The presented tests of the laser positioning tool LPosC are not very demanding concerning groove edge detection and positioning correction, because workpiece and groove geometry were not complex and no thermally induced workpiece expansion or shrinkage and distortion needed to be compensated.

FeCrV15 claddings inside grooves show significantly lower microhardness compared to claddings on 316L steel tubes. That can be attributed to lower content of vanadium carbides as a consequence of stronger dilution of cladding material with base material.

6 Summary and Perspectives

The high potential of closed-loop laser power control tool LPowC and laser cladding head positioning adaptation tool LPosC for complicated laser cladding tasks is confirmed. Iron, nickel and cobalt based alloys have been clad on thin walled tubes and use of LPowC permits production of claddings with homogeneous thickness, weld penetration and even microstructure as well as microhardness. LPowC still requires process parameter optimization prior to automatic process control with the aim to keep desired cladding properties constant despite workpiece temperature change. If parameters that cause excessive weld penetration and dilution with base material are chosen, the according disadvantageous cladding characteristics will also be kept constant automatically.

LPosC is capable of detecting groove edges and adjust laser cladding head positioning. Subsequent to the here presented tests the tool has successfully been applied for control of cladding processes on extrusion screws that are pre-heated prior to cladding and that show continuously changing width and inclination of screw surfaces to be clad with respect to screw axis as well as considerable distortion. Depending on the specific job demands it is necessary to combine LPosC with powerful (triggered) illumination devices or to adjust LPosC settings for different screw areas to be clad by area dedicated LPosC recipes that will be activated by an external master PLC. Thereby it is possible to use CAM data for groove machining in order to transform these automatically into CAM data for laser cladding.

LPowC and LPosC are valuable tools for automation of laser cladding processes with high complexity. Their further adaptation to specific jobs will certainly expand the field of laser cladding applications even more.

7 Literature

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