Capability of High Speed Laser Process with Iron-based Alloys

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Abstract

High speed laser cladding processes combine the benefits of conventional laser cladding with the high surface coverage rates of thermal spraying. Gas-tight thin layers (< 200 µm) with metallurgical bonding to substrates and high deposition efficiency (> 80%) as well as high coverage rate (> 1.0 m²/h) characterize these processes. However, the high-speed variant of laser cladding is still in its infancy. There are limitations of the applicable material spectrum due to increased susceptibility to cracking as a consequence of extremely high cooling rates and narrow process parameter windows result in challenges for process development. This study aims for clarification of the applicability of high speed laser cladding processes for production of iron-based alloy coatings, in particular 22% Cr 5% Ni duplex steel, FeCrV17 and FeCrNiB.

Process parameters are optimized for production of ~150 µm thick claddings on mild steel using different laser power levels, surface speeds and preheating temperatures. Then, optimized claddings are produced on cylindrical substrates with different diameters to investigate dependency on component geometry.

Duplex steel shows robust processability in high speed laser cladding processes. In contrast, crack free FeCrV17 hard facing alloy claddings can only be produced on small shaft diameters using preheating. FeCrNiB cannot be applied crack free by high speed laser cladding in the limits of this study.

Introduction

Laser cladding is an additive manufacturing process in which powder or wire feedstock is melted by a laser beam and solidifies into layers. Layer thickness of 0.3 to 3.0 mm can be achieved with perfect metallurgical bonding to substrates. Repair of worn parts and improvement of tribological properties or corrosion resistance of components are among the main applications. Especially in the last decade laser cladding is utilized more and more. On the one hand, laser sources have become cheaper and on the other hand, coatings with high quality, low dilution and high deposition efficiency can be produced precisely with high reproducibility. However, in contrast to thermal spraying the laser cladding process with coverage rates from 0.06 to 0.3 m²/h is rather slow and therefore comparatively uneconomical for coating of components with large surface areas.

The high speed laser cladding process (HSLC) is a development based on conventional laser cladding and was designed especially for the coating of rotationally-symmetric components and for production of 25 to 250 µm thick layers [1, 2]. With this method, process speeds can be increased by a factor of 10 or more. Essential differences compared to the conventional laser cladding process are significantly higher surface speeds (up to 200 m/min) and smaller track offsets. The basic idea is to heat up powder particles close to their melting point before they enter the melt pool. Due to the high surface speeds and accordingly high cooling rates melt pools with very low penetration and small heat affected zones are produced. Strong dilution between substrate and coating material can be avoided easily. So, even the first deposited layer has almost the same chemical composition as the feedstock material.

Currently, different HSLC processes are described and applied. On the one hand a patented method is characterized by fully molten feedstock entering the melt pool, surface velocities exceeding 20 m/min and a maximum of 60% of the total laser power interacting with the melt pool [3]. Thereby laser foci are set above the formed melt pools. Other HSLC processes work with only partially molten feedstock entering the melt pool, laser foci set below the surface of the melt pool and / or > 60% of the total laser power interacting with the melt pool [4].

HSLC processes aim for production of thin claddings that require no or only minimum post machining. This goal is achieved most effectively by use of relatively fine powders and application of high overlaps. While in conventional laser cladding processes powders with size between 45 and 200 µm are preferred, size between 5 and 63 µm permits manufacturing of claddings with smoother surfaces. Conventional laser cladding is typically carried out with 15-35% overlap creating considerable waviness [5] and accordingly large machining effort, while overlaps exceeding 50% in HSLC processes minimize waviness.

High laser power density is essential in HSLC processes to obtain high coverage rates. This is realized by using small laser spot diameters or high laser powers. However, combining small laser spot sizes and high overlap rates results in only small track offsets. In such case, high coverage rates require accordingly high surface speed (Eq. 1). Alternatively, high coverage rates can also be achieved with larger track offset, which is possible using bigger laser spot diameter and higher laser power. This is particularly advantageous for materials with strong crack susceptibility at the extremely high cooling rates due to high surface speeds.

$$\dot{A}_{CR} = v_{surface} * s_{track} \qquad \text{(Eq. 1)}$$

$\dot{A}_{CR}$: coverage rate $v_{surface}$: surface speed s_{track}: track offset

Because of the novelty of HSLC processes, only few investigations have been published so far. At present, not all materials used in conventional laser cladding have been investigated concerning their suitability for the HSLC process. In this study, the capability of iron-based alloys duplex steel (1.4462), FeCrNiB and FeCrV17 is investigated. The influence of cladding parameters and workpiece dimensions are studied.

Experimental

Experiments were carried out with a high power diode laser source LDF 6000-60 (Laserline GmbH, Mühlheim-Kärlich, Germany). This laser generates a laser power up to 6000 W and operates with the wavelengths of 980, 1020 and 1060 nm. The fiber coupled laser beam was focused onto the component surfaces with a spot diameter of 3.1 mm. Quasi-coaxial powder nozzle PN6625 (GTV Verschleiss-Schutz GmbH, Luckenbach, Germany) with 1.5 mm ID injectors was used with powder conveyed to the nozzle via two powder feed lines. Each line used 2.5 l/min argon as carrier gas flow rate. Laser and powder foci coincided at the powder nozzle optimum working distance of 25 mm. The melt pool was protected with an argon shield gas with flow rate of 20 l/min.

Three kinds of iron-based alloy powders from GTV Verschleiss-Schutz GmbH, Luckenbach, Germany, were investigated: Duplex steel (1.4462, GTV 80.97.1), FeCrNiB (GTV 82.02.1C) and FeCrV17 (GTV 80.49.1). Particle size distributions (PSD) of the powders were measured by laser scattering analyses using Quantachrome CILAS 920. The powders PSD and chemical compositions are listed in Table 1. All three powders show good corrosion resistance, but differ strongly in hardness, toughness and weldability. Cold drawn AISI 1010 seamless steel tubes with outer diameter of 98 mm, wall thickness of 9 mm and length of 100 mm were used as substrates in machined state. Different laser power levels, surface speeds, track offsets, powder feed rates and preheating temperatures were applied to produce ~150 µm thick claddings. The optimized parameters were applied for cladding on different hot-rolled S355 cylindrical shafts with diameters of 10, 20, 30, 40, 50, 75, 100, 125 and 150 mm to investigate the dependency on component geometry.

Table 1: Particle size distribution and chemical composition of applied iron-based alloys.

powder	**80.97.1**	**82.02.1C**	**80.49.1**
material	duplex steel	FeCrNiB	FeCrV17
d_{10} [µm]	30.41	25.00	32.49
d_{50} [µm]	44.01	34.73	44.80
d_{90} [µm]	62.69	50.32	62.82
Fe [wt.-%]	base	base	base
B [wt.-%]	-	3.41	-
C [wt.-%]	0.03	0.6	3.8
Cr [wt.-%]	22.0	32.8	12.7
Ni [wt.-%]	5.7	12.1	-
V [wt.-%]	-	-	16.6
others [wt.-%]	5.65	-	3.84

Cross sections of HSLC specimens were prepared and analysed by optical microscope (Olympus BX53M, OLYMPUS, Japan). Layer thickness and bead width, penetration depth as well as the waviness of surfaces were measured and metallurgical bonding, porosity, dilution and microcracks were assessed. Vickers hardness (HV0.3) was measured according to standard DIN EN ISO 6507-1 with a microhardness tester FM-300C (Future-Tech Corp., Japan). Average values and standard deviations of 10 measurement were determined.

Results and Discussion

Duplex Steel

Firstly, the suitability of duplex steel for HSLC processes was examined. For this purpose, process parameter limits were identified. Single beads were deposited on E235+C tube specimens with increasing surface speeds using the maximum accessible laser power of 6.0 kW and a powder feed rate of 30 g/min. The topography of the single beads is shown in Fig. 1.

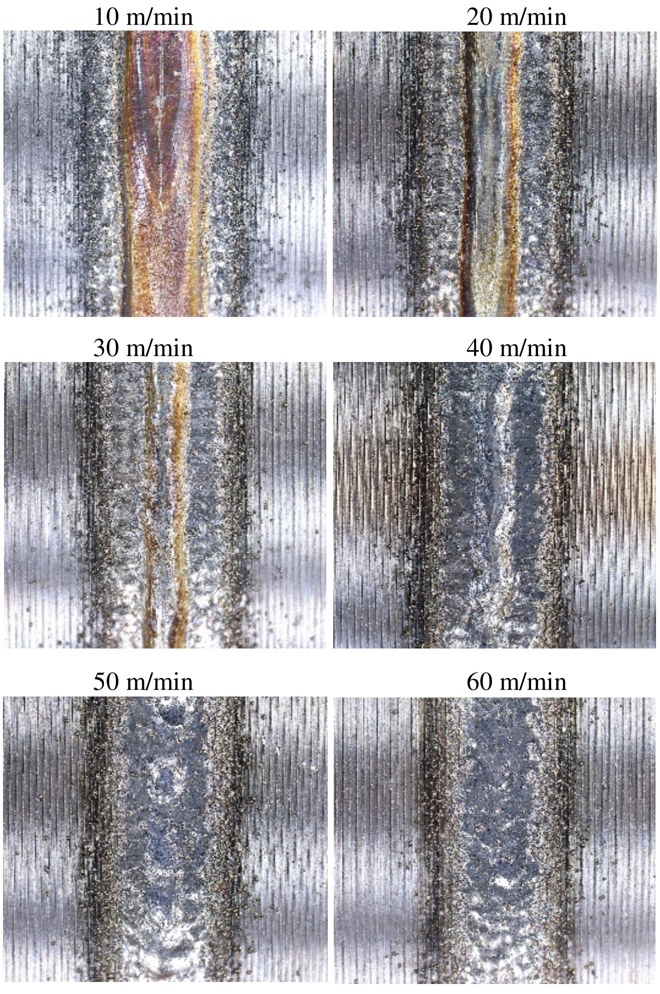

Figure 1: Topography of duplex steel single beads depending on surface speed.

All single beads are crack free and without any delamination. The beads differ strongly in their appearance. While material buildup is particularly high in the center at surface speeds of 10 to 30 m/min, beads flatten out at higher surface speeds (Fig. 1). However, there is increasing lack of material on the bead fringes for surface speeds exceeding 40 m/min and no coherent layer is formed there. Bead width and thickness decrease significantly from 2.91 to 1.50 mm and from 214 to 25 µm respectively, if the surface speed is increased from 10 to 60 m/min. Simultaneously, penetration depth and dilution with the base material are reduced due to decreasing heat input at increased surface speeds. The provided energy does not permit formation of a sufficiently large melt pool. This effect is reinforced by the circular shape of the laser beam. During the cladding head movement, the heat input in the center of the track is significantly higher than in the fringe regions due to longer exposure to the laser beam.

In a next step, applicable ranges of powder feed rate and laser power were identified. The limits of powder feed rates were examined by single bead investigations. The powder feed rate was increased in increments of 10 g/min for each surface speed while keeping laser power constant at 6.0 kW. The dependency of cladding thickness on powder feed rate is shown in Fig. 2.

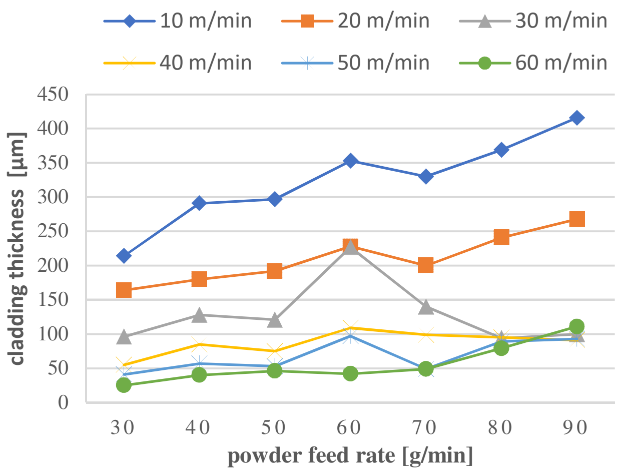

Figure 2: Cladding thickness depending on powder feed rate at different surface speeds.

The cladding thickness increases with powder feed rate. However, for 30 m/min surface speed no consistent trend is observed. This is due to a bead geometry change, which is also observed (less clearly) for other surface speeds. With increasing powder feed rate beads are built up more and more uniform without central elevation. Simultaneously clad width decreases. Even for powder feed rates of 90 g/min beads are crack free and without delamination in the range of tested surface speeds.

In a next step, required laser powers for different surface speeds were determined. For this, 150 µm thick claddings were produced with a width of 15 mm. Laser power was reduced gradually from 6.0 down to 1.0 kW. The required track offsets and powder feed rates for production of 150 µm thick claddings were chosen based on previous findings in the single bead deposition tests.

At a surface speed of 10 m/min a laser power exceeding 3.0 kW is required to produce crater free claddings (Fig. 3). However, using laser power of 5.0 kW or more results in significantly increased weld penetration and waviness of cladding surfaces. With increasing surface speed, the laser power needs to be increased, too, to avoid formation of craters. At 20 m/min at least 4.0 kW, and at 30 - 50 m/min at least 6.0 kW laser power are needed. For even higher surface speeds the available maximum laser power of 6.0 kW does not permit production of useful claddings. Further experiments with different preheating temperatures show that defects can be avoided at a preheating temperature of 250 °C.

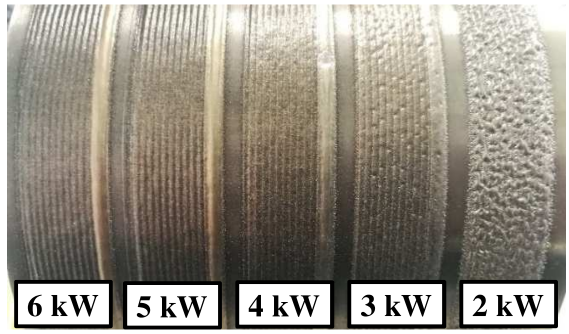

Figure 3: Variation of laser power for cladding of duplex steel on a E235+C tube substrate at a surface speed of 10 m/min.

With the obtained knowledge, additional tests were carried out to optimize coverage rates. For this purpose, the track offset was increased gradually for each surface speed. In order to keep the waviness as low as possible and to obtain the desired coating thickness of 150 µm, powder feed rate and laser power were adjusted accordingly. All other parameters were kept constant. The ranges of the investigated process parameters are listed in Table 2.

Table 2: Applied process parameter ranges for optimization of coverage rates for duplex steel.

surface speed [m/min]	**laser power [kW]**	**track offset [mm]**	**powder feed rate [g/min]**	**preheat temp. [°C]**
10	3.2 - 3.7	1.0 - 1.4	20 - 34	20 - 250
20	4.2 - 4.9	0.6 - 1.0	28 - 44	20 - 250
30	5.1 - 6.0	0.5 - 1.0	30 - 60	20 - 250
40	5.5 - 6.0	0.4 - 0.6	34 - 48	20 - 250
50	6.0	0.3 - 0.6	34 - 55	20 - 250
60	6.0	0.3 - 0.5	38 - 58	250

The optimized process parameters are listed in Table 3. Cross section images and average microhardness of respective claddings are shown in Fig. 4. With increasing surface speeds, coverage rates increase and waviness decreases. The highest coverage rate of 1.5 m²/h is achieved at a surface speed of 50 m/min.

Table 3: Process parameter of optimization process for high coverage rates with duplex steel.

surface speed [m/min]	laser power [kW]	track offset [mm]	powder feed rate [g/min]	preheat temp. [°C]
10	3.3	1.2	30	20
20	4.4	0.8	34	20
30	5.8	0.7	44	20
40	6.0	0.6	48	20
50	6.0	0.5	55	20
60	6.0	0.4	50	250

Despite optimized laser powers and powder feed rates, the waviness of claddings increases with increasing track offsets. Tests to increase the applicable track offset along with preheating of the tube specimens do not result in reduced waviness of claddings.

Small craters are observed on some surfaces of the duplex steel claddings. Such craters show a depth between 20 to 70 µm and occur irregularly. Their density decreases with increasing surface speed and can also be reduced by applying smaller track offsets and lower powder feed rates.

All produced duplex steel claddings are crack free and show an average microhardness close to 400 HV0.3 (SD 20 HV0.3), while conventional laser claddings show about 340 HV0.3 microhardness. Porosity, bonding faults and dilution with the substrate are negligibly small for all layers. Surface waviness decreases with increasing surface speed. The heat flow direction causes formation of a microstructure with grains of the two austenite and ferrite phases oriented perpendicular to the substrate surface (Fig. 5).

In a last step, dependency on component geometry was investigated. The process parameter set permitting the highest coverage rate of 1.5 m²/h was applied for cladding S355 cylindrical shafts with a width of 90 mm (Fig. 6). All coatings are crack free and do not differ in their porosity, hardness and waviness. However, for shaft diameters exceeding 100 mm crater defects occur with increasing density.

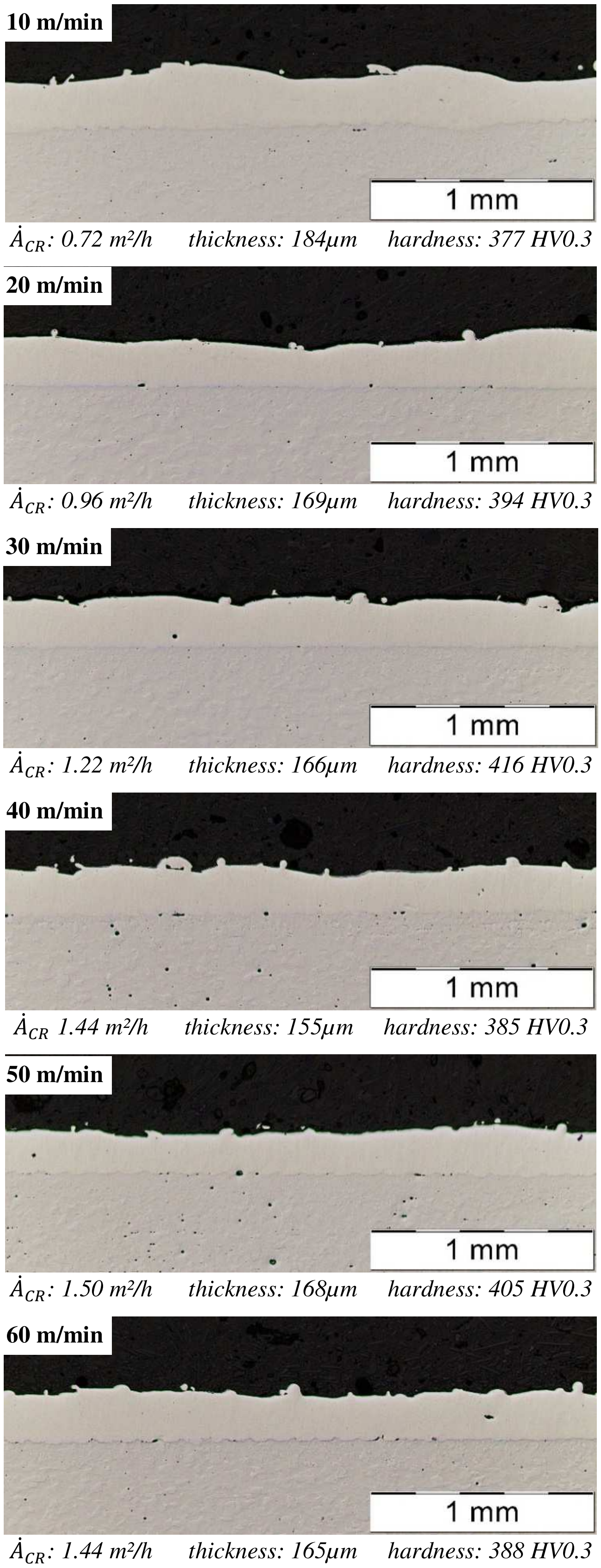

Figure 4: Cross section images and microhardness of duplex steel claddings optimized concerning coverage rate.

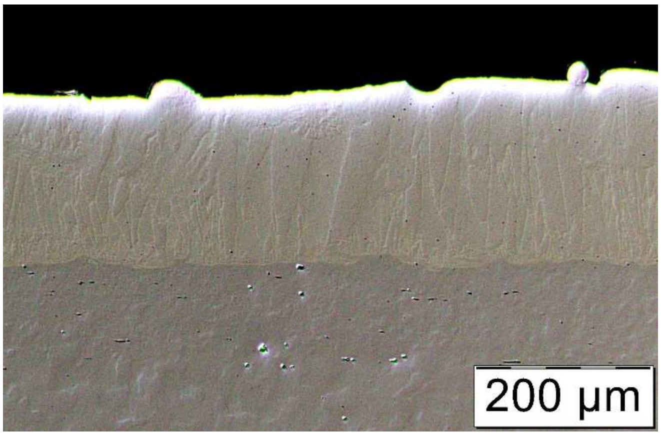

Figure 5: Two-phase microstructure of a duplex steel cladding with austenite and ferrite grains oriented perpendicular to the substrate surface.

Figure 6: Duplex steel claddings on a S355 shaft substrate with sections showing diameters of 150, 125 and 100 mm.

FeCrNiB

The capability of HLSC processes for hard facing alloy FeCrNiB was investigated using the same approach as for duplex steel. Single beads were cladded on E235+C tube specimen with increasing surface speeds. In contrast to duplex steel, FeCrNiB cannot be applied crack free without preheating. Cracks occur at the fringes of the clad seam (Fig. 7). Additionally, transverse cracks are formed for surface speeds exceeding 20 m/min.

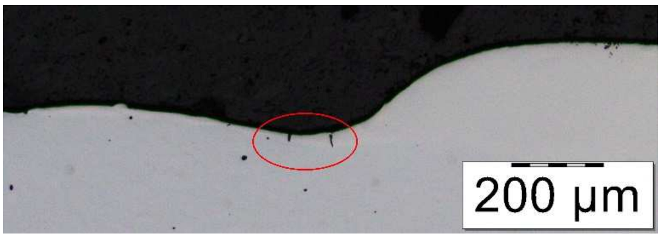

Figure 7: Cross section image of a single FeCrNiB bead on a E235+C tube substrate deposited at a surface speed of 20 m/min with crack nuclei at the fringes.

The preheating temperature of the tube substrate was gradually increased up to 300 °C. This permits the production of crack free claddings for a maximum surface speed of 20 m/min. Bead width and thickness decrease with increasing surface speed. In order to deduce the limits of powder feed rates, single beads were deposited at increasing powder feed rates on substrates preheated to a temperature of 300 °C. Crack free beads can be realized at powder feed rates up to 60 g/min for a surface speed of 10 m/min and up to 50 g/min for 20 m/min surface speed.

The limits of applicable laser power were also determined on preheated E235+C tubes. Macrocracks have been observed in all tests at 20 m/min surface speed. Only for 10 m/min surface speed coatings are crack free. In contrast to duplex steel, no formation of craters is observed. All cross sections show deep weld penetration and strong dilution with the base material. Also, a high surface waviness has been observed (Fig. 8). As a result of the strong dilution with the substrate, an average microhardness of only 550 HV0.3 (SD 35 HV0.3) has been measured in areas close to the base material. Close to the surface, claddings show a dendritic microstructure and the average microhardness amounts to 700 HV0.3 (SD 38 HV0.3).

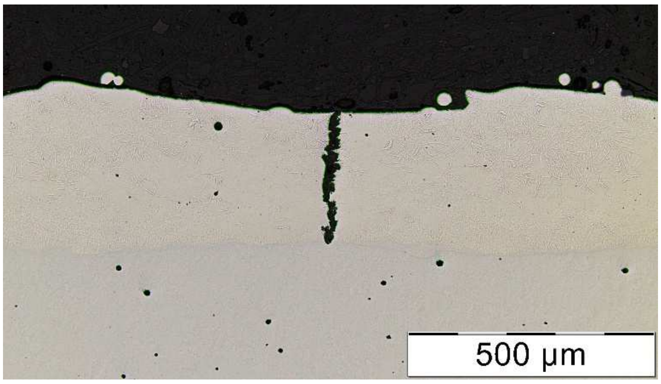

Figure 8: Cross section image of a FeCrNiB cladding on a E235+C tube substrate produced at a surface speed of 10 m/min and preheating temperature of 300 °C.

With the aim to achieve acceptable coating quality investigations with laser power between 2.2 and 2.8 kW and preheating temperature between 150 and 450 °C were carried out. Penetration depth and waviness of coatings are decreased significantly compared to previous tests, but no crack free claddings can be produced. The microstructure contains high shares of dendritic phases. As there is no indication that FeCrNiB could be produced crack free by means of HSLC, tests were stopped.

FeCrV17

The hard facing alloy FeCrV17 was studied in the same way as the previous materials. All single beads can be applied crack free without preheating for maximum surface speeds of 30 m/min. In contrast to duplex steel and FeCrNiB, FeCrV17 claddings show a uniform lenticular cross sectional area without central elevation, which is beneficial for manufacturing of claddings with smooth surface. Width and thickness of deposited beads decrease with increasing surface speed.

For surface speeds up to 30 m/min, a maximum applicable powder feed rate of 70 g/min has been determined. Thereby, tube specimens need to be preheated up to 200 °C for surface speeds of 20 and 30 m/min. Otherwise, cracks occur even at a powder feed rate of only 40 g/min. Preheating results in a shift from previously observed flat bead shape towards material accumulation in the bead center as also observed for duplex steel and FeCrNiB.

Required laser power levels depending on surface speed were evaluated on preheated E235+C tubes. For a surface speed of 10 m/min a laser power range between 3.0 and 4.0 kW is applicable. In contrast to the previous tests concerning powder feed rate influence, no crack free claddings can be produced without preheating. For 20 m/min surface speed an optimum laser power range between 3.5 and 4.5 kW with a preheating temperature of 200 °C has been determined. At a preheating temperature of 100 °C stress cracks cannot be avoided. On the other hand, substrate temperatures of 300 °C or more cause formation of large pores. Despite only moderate dilution with base material, microcracks are formed in the interface between the substrate and the cladding (Fig. 9). No crack free claddings can be produced at surface speeds of at least 30 m/min.

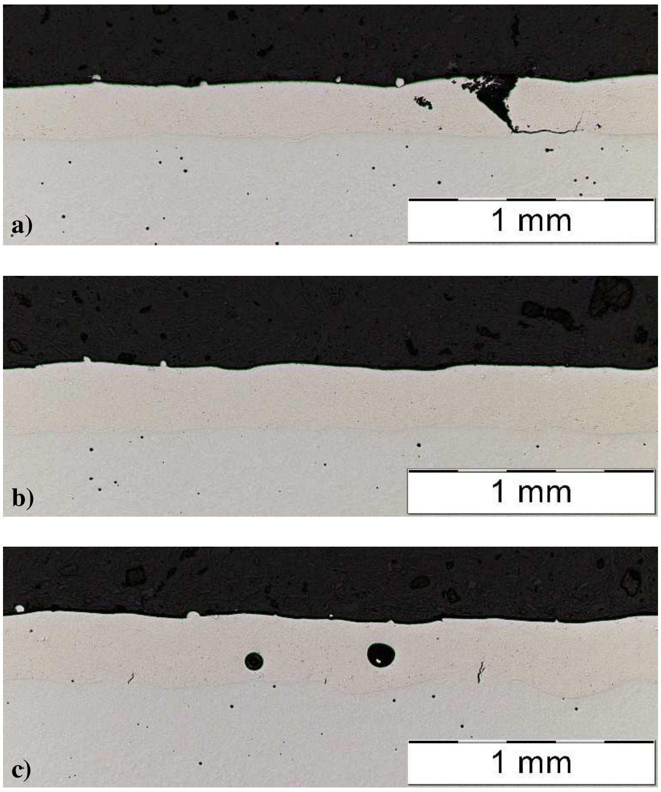

Figure 9: Cross section images of FeCrV17 claddings on a E235+C tube substrate produced at a surface speed of 20 m/min and preheating temperature of (a) 100 °C, (b) 200 °C and (c) 300 °C.

Process parameters are optimized concerning maximum coverage rate for surface speeds of 10 and 20 m/min. The tube substrates were preheated up to 200 °C. With a laser power of 2.7 kW and a powder feed rate of 25 g/min 150 µm thick cladding can be produced at a surface speed of 10 m/min. With a track offset of 1.2 mm a coverage rate of 0.72 m²/h has been obtained. The highest coverage rate of 0.96 m²/h can be achieved with a surface speed of 20 m/min and a track offset of 0.8 mm. Using a laser power of 3.8 kW and a powder feed rate of 32 g/min claddings with a smooth surface and a negligibly small weld penetration have been produced. FeCrV17 claddings show a homogeneous distribution of fine vanadium carbides with an average size of 1-2 µm. All identified pores are smaller than 40 µm and their content is significantly lower than 1%. Cladding properties for optimized coverage rates are listed in Table 4.

Table 4: Results of processes optimized concerning maximum coverage rate using FeCrV17 feedstock.

surface speed [m/min]	**coverage rate [m²/h]**	**coating thickness [µm]**	**coating hardness [HV0.3]**
10	0.72	189	761
20	0.96	168	720

The parameter set for the highest coverage rate was tested on S355 shafts with different diameter. Stress cracks perpendicular to the cladding direction occur for shaft diameters of 100 mm and more. In comparison to the previous tests, cross section images show significantly increased dilution with the base material. Exceeding critical degrees of dilution results in crack formation in the interface between the cladding and the substrate (Fig. 10). Only for 10 mm shaft diameter, no crack has been observed. In addition, there is a slightly increased surface waviness compared to previous investigations on E235+C tube substrates. Nevertheless, a minimum coating thickness of 150 µm can be achieved. A homogeneous microstructure with evenly distributed vanadium carbides is observed in all samples. All claddings show an average microhardness of 720 HV0.3.

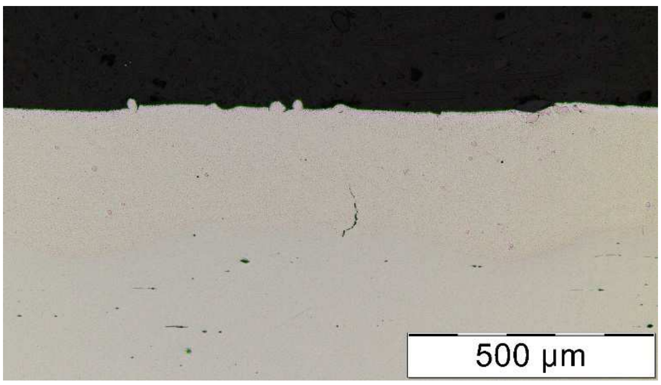

Figure 10: Cross section of a FeCrV17 cladding on a S355 tube substrate with 75 mm diameter produced at a surface speed of 20 m/min.

Summary and Conclusions

The applicability of high speed laser cladding processes for production of duplex steel (1.4462), FeCrNiB and FeCrV17 is studied. Process parameter limits have been identified, parameters have been optimized concerning maximum coverage rates and validated concerning their transferability to different component geometries of mild steel substrates.

Duplex steel (1.4462) shows excellent suitability for HSLC processes. A coverage rate of 1.5 m²/h can be achieved for 150 µm thick claddings at a laser power of 6.0 kW and powder feed rate of 55 g/min. The claddings show a microhardness of 400 HV0.3. Porosity and dilution with the substrate are negligibly small. A good reproducibility can be confirmed. There is a little dependency on component geometry that needs to be taken into consideration for transfer of parameter sets from one workpiece to the other.

In contrast to duplex steel, FeCrNiB cannot be applied crack free by means of HSLC processes in the limits of this study. Due to the high residual stresses, the claddings crack even at a surface speed of only 10 m/min despite preheating temperature of 450 °C.

FeCrV17 shows limited suitability for HSLC processes. Crack free and low porosity coatings can only be produced in case of strict heat management. On the one hand, too low preheating temperature results in stress cracks. On the other hand, excessive preheating temperature and / or laser power cause the formation of large pores and cracks in the bonding zone. A maximum surface speed of 30 m/min, a maximum preheating temperature of 300 °C and a maximum powder feed rate of 70 g/min have been determined in the limits of these investigations. Coverage rates of 0.96 m²/h for 150 µm thick, crack free claddings can be achieved using a preheating temperature of 200 °C and 3.8 kW laser power. Claddings show a homogeneous distribution of 1-2 µm sized vanadium carbides, a porosity < 1% and a microhardness of 720 HV0.3.

Perspectives

Further investigations aim for determination of HSLC process limits for critical base materials like heat treatable steels and grey cast iron. In addition, HSLC processes are optimized for production of gas tight bond coats for thermally sprayed ceramic coatings offering improved corrosion resistance without application of sealers.

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