Investigation of deposition welding in vertical and horizontal position with a coaxial laser wire welding head

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Abstract
Deposition welding of components using the laser metal deposition (LMD) process is a proven method of creating 3D structures. It is used for the manufacturing of components, the repair of machine parts and for cladding. Up to now, claddings have mainly been investigated in the flat welding position. Some investigations on deposition welding in vertical orientation are available with different processes. For the cladding of large components, welding in the vertical direction offers advantages. So far, there are no investigations on the LMD process with coaxial wire feeding when welding in vertical direction. Therefore, in this study, the influence of the welding direction, i.e., vertical down and vertical up weld seams, and the influence of the welding speed are investigated. Single weld seams, claddings and a wall are welded. A stable welding process could be achieved for a welding speed parameter window of 100 to 1000 mm/min. The results show that there is a statistical correlation between the welding direction and the waviness of the weld seams. Vertical up weld seams have a lower waviness. Another influence on the waviness is the welding speed. As the welding speed decreases, the waviness increases. The weld seam geometry is strongly dependent on the welding direction. With vertical down weld seams, the width and height of the weld seam vary depending on the distance welded. This can be attributed to the influence of the gravitational force. Vertical up weld seams, on the other hand, have a more uniform shape.

Keywords LMD-W · Horizontal position · Vertical up · Vertical down · Out-of-position welding · Cladding

1 Introduction
Additive manufacturing is a processing technique in which a component can be created from 3D data without subtractive material removal from a block of material. It is possible to clad miniaturized as well as large surfaces two-dimensionally by a welding process as well as to produce three-dimensional components. The technology is used in various application areas such as aerospace, medical technology, petrochemistry, automotive and mechanical engineering. In general, the technology is used for prototyping, production of components, machine parts repairing and for functional claddings [1, 2].

In most cases a flat position is used for the deposition welding process. In other welding positions, there is a risk that, due to the gravitational force, the molten metal will separate from the substrate and drip off [3].

A widely used process is laser metal deposition (LMD). Although a large number of studies can be found on the LMD process in flat position, the effects that occur during deposition welding in vertical orientation (horizontal (PC), vertical up (PF) and vertical down (PG) position) are little known.

2 State of the art
2.1 Laser metal deposition
The application of claddings can be divided into two main functions. Firstly, to improve surface-dependent properties such as abrasion resistance, erosion resistance and corrosion resistance, and secondly, to improve bulk-dependent properties such as hardness and strength, which is also known as hardfacing [4]. Laser cladding is used to provide a protective layer on the base material with properties such as wear protection, self-lubrication, corrosion resistance, high
temperature oxidation resistance and to some extent fatigue resistance to protect component areas from mechanical, chemical and tribological stress. For the application of the claddings, which have a thickness from 0.5 mm to several millimeters, various processes are known. These processes are for example laser metal deposition with powder (LMD-P), laser metal deposition with hot or cold wire (LMD-W), laser induction cladding (LIC), gas metal arc welding (GMAW), laser assisted GMAW (LA-GMAW) and plasma transferred arc (PTA) welding [2, 4–7].

For laser cladding with wire two possibilities of wire feeding are used - coaxial and lateral feeding. Coaxial heads with centric wire feeding have advantages over processes where the wire is fed laterally, such as the independence of the welding direction, the alignment of the laser beam to the wire and a reduced number of parameters to be controlled. These features are important to produce a high quality cladding [8].

Leyens and Beyer state that after the melt pool has solidified, there is a good metallurgical bond between the deposited material and the substrate. Due to the locally applied energy of the laser beam, only a small area of the substrate is melted, which leads to low dilution between substrate and cladding material. For this reason, the properties are usually very good from the first layer [1].

Verma and Das have stated that applying a protective cladding does not change the microstructure of the base material, as a new surface layer with a different composition is applied to the base material. Furthermore, the applied layer is usually harder than the base material [9].

An advantage of laser cladding is that a wide range of materials is available as cladding material. For example, steel, aluminum and titanium as well as stellite, nickel-based superalloys and shape memory alloys can be used [7].

### 2.2 Welding in vertical and horizontal position

Paul et al. investigated analytically and experimentally the laser additive manufacturing on vertical surfaces. The experiments were carried out with the cladding material AISI 304 stainless steel in powder form on a substrate of the same material. They used a LMD process with a fiber laser with a maximum power of 2 kW and a lateral powder feed. For the experiments, horizontal seams were welded onto a vertically oriented substrate. The laser power was varied in the range of 800 to 1600 W, the welding speed in the range of 200 to 1000 mm/min, and the powder feed rate in the range of 3 to 18 g/min. The evaluation was performed based on width and height of the deposited weld seams. The analytical and experimental results based on the analysis of the cross sections of the weld seams revealed a displacement of the deposited material in the direction of gravity. For a welding speed lower than 200 mm/min, clear asymmetric bulges of the deposited material were observed. For welding speeds above 400 mm/min, the displacement was very small. If the welding speed of 700 mm/min is exceeded, the displacements were insignificant. At constant welding speed, higher powder feed rates led to a higher weld seam, which led to a higher displacement of the weld seam in the direction of gravity. At constant laser power and powder feed rate, the displacements were explained by the fact that the interaction time of the material to remain in the molten state decreases with increasing speed. As a result, the flow of the molten material is counteracted by a higher effective viscosity. The influence of the laser power was determined via a calculated parameter, the laser energy per unit traverse length. The influence of the powder feed rate is expressed via the parameter powder fed per unit traverse length. With high laser energy unit per traverse length and low powder fed per unit traverse length, there is a risk that the filler material will evaporate. In the opposite case, the filler material may not generate a bond and a non-continuous seam may be applied. For this reason, there is a parameter window in which a balance between the parameters leads to a continuous weld seam. The threshold value for this case for the laser power is the parameter laser energy per unit traverse length, which is calculated via the quotient of the laser power and the welding speed, of approximately 96 J/mm. The threshold value for the powder feed rate is the parameter powder fed unit traverse length, which is calculated by the quotient of the powder feed rate and the welding speed, of approximately 0.006 g/mm [10].

Chen et al. studied the effects of welding positions on droplet transfer in CO2-laser metal active gas hybrid welding. The welding torch was placed under 30° laterally in the forehand position and the laser beam was placed in the neutral position with respect to the substrate. The laser beam spot is positioned in front of the base point of the arc, so that there is a trailing orientation. The welding positions studied were flat position, horizontal position welding in vertical orientation and vertical up position welding. The materials used were G3Si1 with a diameter of 1.2 mm as wire material and S355J0 as substrate. The experiments were performed using a CO2-laser with a maximum power of 3.0 kW and a 500 A arc welding machine. During the respective welding positions, the experimental parameters were kept constant. The evaluation of the droplet size was performed with a high speed camera. The parameters laser power of 2800 W and stickout length of 15 mm are constant for all welding positions. For the horizontal position, a welding speed of 400 mm/min, a current of 180 A and a voltage of 30 V was used. In the vertical position, the laser beam was placed at 800 mm/min with a current of 150 A and a voltage of 15 V. The impact point of the droplets was mainly dependent on gravity and the electromagnetic force. For the horizontal position, there were three locations where the droplets can impact, which depend on the droplet size. Droplets with large diameter fell down due to their higher mass and gravity. Droplets with medium diameter impacted under the weld
3 Aims and perspective

The state of the art shows that investigations have already been carried out for deposition welding in the vertical direction with lateral wire feed into the process zone. For welding in vertical direction with a laser processing head, where the wire is fed coaxially to the collimated beam, no investigations are available. In the study by Gu and Li, important parameters affecting the weld geometry, such as welding speed and wire feed rate, were kept constant. Similarly, the power density and laser energy per unit length were not varied. In this paper the influence of gravitational force on weld formation at different weld cross-sectional areas and laser energies per unit length is investigated using a LMD cold wire process. The following questions have to be answered in this study:

- How does the welding position and direction influence the seam geometry?
- Does the welding position and direction have an influence on the surface finish of the claddings?
- What influence does the welding speed have on the seam geometry?
- Can 3D structures be created in the vertical direction and what problems are encountered?
- How does the coaxial experiment setup influence the quality of the weld?
- What is a possible process parameter window for welding with coaxial wire feed in vertical welding direction?

4 Materials and methods

In this work, LMD-W in the three welding positions horizontal, vertical up and vertical down is investigated. It is investigated whether a stable welding process from the point of view of seam connection, process control without wire burnback can be achieved in these welding positions. The geometry of the weld seams is analyzed and the influence of the welding position on the geometry is determined.

4.1 Experimental setup

The LZH MK-II coaxial welding head, developed and built at the Laser Zentrum Hannover e.V., is used for the welding experiments. In this welding head, the laser beam is split into four partial beams below the focusing lens with a pyramid, deflected by mirrors and recombined in one spot [15]. Figure 1 shows the beam guidance in the coaxial setup for welding in a vertical orientation. The gravitational vector is marked with the symbol $g$.

A diode laser from the company Laserline GmbH with a maximum power of 3.0 kW is used as the laser beam source. The fiber has a core diameter of 400 µm with a numerical aperture of 0.22. The laser beam source emits the radiation in continuous wave mode with the wavelengths of 1020 ± 15 nm and 1060 ± 15 nm. A collimator with a focal
length of 100 mm and a focusing lens with a 300 mm focal length are chosen for the experiment. The wire feed unit DIX FED100, manufactured by Dinse GmbH, was used. Welding tests are performed with a LMD cold wire process. All welding parameters are kept constant during the experiment except for welding direction and welding speed. Since the shielding gas represents another parameter whose influence on the welding result would have to be investigated, welding was carried out in ambient air. For this reason, the number of variables taken into account in the evaluation was minimized. An overview of the process parameters is given in Table 1.

Figure 2 shows the experimental setup with the welding head mounted horizontally on the Z-axis of the three-axis system. A flat steel is used as a substrate with a thickness of 10 mm and a length and width of 300 mm and 240 mm. Clamping devices hold the substrate in place on the X-Y axis. Before welding the substrate was sandblasted and cleaned with ethanol. The filler wire has a diameter of 1.0 mm.

4.2 Materials

Mild steel S355J2 is used as a base material for the investigations. The martensitic chrom-silica steel X45CrSi9-3 is used as cladding material. Table 2 shows the chemical composition of both materials.

4.3 Single weld seams

To investigate welding in vertical and horizontal positions, individual weld seams are welded to the substrate at different welding speeds. Experiments are carried out with constant parameters for wire feed rate $v_W$ and laser output power $P_L$. In addition, the investigation is performed without shielding gas supply. For vertical welding, the welding speed $v_S$ is varied between 1000 mm/min and 100 mm/min in 50 mm/min steps. For each speed, one vertical down and one vertical up weld seam with a length of 50 mm is welded. The single weld seams in the vertical direction are shown in Fig. 3.

The welding speed decreases from the left to the right side of the picture. The first welded seam of a parameter set is the vertical down seam and the second is the vertical up seam.

4.4 Claddings

In addition to the single weld seams a cladding of six adjacent weld seams is welded bidirectional in the vertical up and vertical down direction with a welding speed of $v_S = 1000$ mm/min (see Fig. 4). The cladding is welded in a meandering pattern with a 1.5 mm offset between the vertical down and vertical up direction.

Another cladding of five adjacent weld seams is welded unidirectional with a welding speed of $v_S = 1000$ mm/min in horizontal welding direction in vertical orientation. The distance between the welded individual seams is 1.5 mm. The cladding is shown in Fig. 5.
4.5 3D structure

A wall consisting of 30 layers, which are welded unidirectional in horizontal direction, is manufactured as well (see Fig. 6). The wall has a length of 50 mm and the height offset of each layer is 0.6 mm.

4.6 3D data acquisition

The weld seam surface data is determined by measurement with the laser scanning microscope VK-X 1100, manufactured by Keyence GmbH. The seams and claddings are measured with the Focus Variation measuring mode. The measuring accuracy of the laser scanning microscope for the height measurement is (± 0.2 + measured height in m/100) µm. The resolution is specified as 0.5 nm. For each welded seam and each cladding, the surface is measured. Figure 7 shows the 3D data of the first vertical down weld seam welded at a welding speed of 1000 mm/min.

Based on the measured surface data of the weld seams, the width, height and cross-sectional area of each weld seam are determined at three locations of the weld seam. In addition, the waviness of each weld seam along the welding direction and the angle between the weld seam surface along the welding direction and the substrate surface are measured using the software MultiFileAnalyzer by Keyence GmbH. An example of a measurement of the angle is shown in Fig. 8. The change in weld seam geometry within a weld seam is analyzed and a comparison of vertically upward and vertically downward weld seams is performed. Furthermore, the correlations of welding parameters with each other and with the weld seam geometry are checked for significance.

Cross sections are made of weld seams that are welded in a vertical down position and in a vertical up position. In addition, a cross section of the wall is made to determine the microstructure and to examine for defects. To create the cross sections the specimens are embedded, ground, polished and then etched with 3% alcoholic nitric acid (Nital).

5 Results and discussion

5.1 Single weld seam results

The stickout length has increased by 1 mm from the first weld seam to the 13th weld seam during the experiments. The influence of the stickout length can be seen in Fig. 3 at the gap in the weld seams. Before the stickout length was corrected from 9 to 8 mm, the wire burned back during welding, which is due to the fact that the displacement causes the laser radiation to hit the wire 0.5 mm above the focal point. This is likely to exceed the critical intensity that leads to wire burn back. Another adjustment of 0.5 mm was performed after the 26th weld seam back to a stickout length of 8 mm.

The waviness of the vertical up and vertical down weld seams was analyzed. The waviness is defined as uneven surfaces occurring periodically at longer intervals than

| Chemical composition in wt.% of S355J2 [13] and X45CrSi9-3 [14] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Fe              | C               | Si              | Mn              | P               | S               | Cr              | Ni              | Cu              |
| S355J2 (1.0577) | bal.            | 0.15–0.20       | < 0.30          | < 1.60          | < 0.025         | < 0.015         | < 0.20          |                 |
| X45CrSi9-3 (1.4718) | bal.            | 0.40–0.50       | 2.70–3.30       | < 0.60          | < 0.040         | < 0.030         | 8.00–10.00      | < 0.50          |

Fig. 3 Weld seams manufactured by vertical laser deposition welding with wire

Fig. 4 Cladding welded bidirectional in vertical up and vertical down direction
roughness. The deviation from an ideal surface occurs repeatedly at relatively longer intervals than the deviation depth. Roughness is divided from waviness based on a filter cutoff frequency $\lambda$. The analysis is performed with an ANOVA (analysis of variance) test with the software JMP of the company SAS Institute GmbH with a significance level $\alpha = 0.05$. Based on the recorded 3D data and the evaluation regarding the correlations between the welding direction and the waviness of the weld seam, it is evident that there is a significant correlation with a value of $p = 0.0233$. The statistical evaluation shows that vertical up welded seams have less waviness than vertical down welded seams. If the evaluation is extended to include the welding speed, it is noticeable when looking at the individual measured values for the waviness that the values for a welding speed for the vertical up welded seam are lower than for the vertical down welded seam for all cases considered. The boxplot of the evaluation is shown in Fig. 9.

Furthermore, when looking at the boxplot, it is noticeable that the waviness is dependent on the welding speed. This means that as the welding speed increases, the waviness of the surface of a weld seam decreases, whereby the correlation between the welding directions also continues to exist.

The seam height and the seam width depend on the welding direction. For vertical down welded seams, the width of the seam is in most cases smaller compared to the vertical up welded seam. The height of the seam, on the other hand, is greater in the case of the vertical down welded seam than the vertical up welded seam. If the welding speed is also taken into account, it is noticeable that the seam width and height become smaller as the welding speed increases. The previously established relationships remain valid when the welding speed is taken into account.

The measured values for the angle measured between the substrate surface and the seam in the welding direction (see Fig. 8) for all welded seams range from 0.012 to 0.463°. If the angle and the welding direction are considered there is a significant correlation between the two parameters, with a calculated value of $p = 0.0141$. This means that a smaller angle was determined for weld seams welded in vertical up than for vertical down weld seams. This observation is confirmed by considering the weld seam height as a function of the measuring position. For vertical down welded seams, the seam shape shows a greater relative difference in height from the lowest to the highest measured weld seam height than for vertical up welded seams.

The micrographs shown in Fig. 10 of a seam welded vertically down and a seam welded vertically up clearly show that the geometry differs. All measurements were performed on the micrographs shown. In two cases, the vertical down welded seam has a narrower weld seam width than the three widths of the different
sections of the vertical up welded seam. Furthermore, it is noticeable that within the vertical down welded seam, the geometry is not constant. It can be seen that the beginning of the weld seam is flat and relatively wide compared to the other examined points of the weld seam. This can be attributed to the influence of gravity on the molten pool as shown by Gu and Li. In addition, a pore is visible in the area where the weld seam is connected to the base material in the case of the vertical down welded seam in the cross section at the bottom left of the figure. The connection

**Fig. 9** Waviness of the weld seam surface in dependence of the welding direction and the welding speed

**Fig. 10** Cross sections at three different positions of weld seams welded in vertical down and vertical up direction
angles in the middle and at the end of the weld seam are steeper with a value in the range from 78 to 81° compared to the weld seam beginning with 61°. The deviations from the mean joint angle of 60° of the vertical up weld seam are similar, from which a uniform weld can be concluded. In addition to the angles of connection, the degree of dilution was determined for the individual sections of the two weld seams shown. The dilution values measured on the three micrographs for the vertical down welded seam vary in a range from 9.6 to 14.2%. For the vertical up welded seam, the range of the three measured values is between 7.8 and 9.8%.

Figure 11 shows cross sections of weld seams (a) welded at two different welding speeds $v_S$, as a vertical down weld seam and as a vertical up weld seam. In the cross sections, the weld material is labeled WM, the base material is labeled BM, and the heat-affected zone (HAZ) is labeled HAZ. In (b) a magnified view of the HAZ of the weld seam, which

![Micrographs of weld seams](image-url)
was a vertical down weld seam and welded at $v_S = 1000 \text{ mm/min}$ is shown. Figure 11c presents the vertical up weld seam, which was also welded with $v_S = 1000 \text{ mm/min}$. In both Fig. 11b and c, a martensitic microstructure is present in the weld material. The HAZ, which consists of a ferritic-martensitic microstructure, is divided into a fine-grained region and a coarse-grained region. The microstructure of the base material is ferritic-perlitic. One difference that can be seen between the welding directions is the HAZ. In the case of the vertical up weld seam, the HAZ is approx. 50 µm less deep in the base material than in the case of the vertical down weld seam. The comparison of the micrographs of the welded seams welded at $v_S = 100 \text{ mm/min}$ in subfigure (a) shows a similar effect. The HAZ is more pronounced in this case, which can be explained by the higher amount of heat introduced by the lower welding speed. The microstructure of the weld material is a martensitic one in all cases, regardless of the welding speed. For this reason, only the HAZ of the weld seams with the high welding speed is presented.

5.2 Cladding results

The surface of the cladding, which is welded in the vertical direction, does not appear uniform. This can be confirmed by the profile section shown in Fig. 12 of the measured 3D data of the cladding. The unidirectional cladding welded in the horizontal direction has a more uniform surface. Another important point is the roughness $R_z$. The roughness is determined with a cutoff wavelength, which separates the waviness from the roughness based on a defined wavelength, of $\lambda_c = 8.0 \text{ mm}$. The measurement is taken in the center of the cladding at half the travel distance of a weld seam. The vertical cladding has a roughness of $R_z_v = 257 \mu\text{m}$ and the horizontal welded cladding has a roughness of $R_z_h = 193 \mu\text{m}$. The roughness reflects the visual appearance of the cladding surfaces, with the surface of the horizontally welded cladding being perceived as more uniform. The waviness values $W_a$ of the individual claddings were determined with a cutoff of $\lambda_c = 0.8 \text{ mm}$. The vertical cladding has an average waviness of $W_a_v = 200 \mu\text{m}$ and the horizontal cladding an average waviness of $W_a_h = 269 \mu\text{m}$.

5.3 3D structure results

The unidirectionally welded wall shows a crack in the area of the first layers in the region of the respective starting points. A detailed image of the crack is shown in Fig. 13b. The crack starts at the connection of the first weld seam on the substrate and extends over several layers along the welding direction for about 1/3 of the length of the wall. The crack was audible after the application of approximately the 20th layer.

The reasons for cracking are explained by Ri-Sheng, Shao-Ni and Zi-sheng as the enormous stresses in the X-direction and in the Z-direction induced by the application of thermal energy with the welding process. The Z-direction is the deposition direction of each layer of the wall and the X-direction is along the weld seam. In addition, the shrinkage effect during the cooling process is another factor that favors crack formation, especially for tall thin-walled metal parts. Furthermore, it was found that the welding strategy and the associated path planning have a major influence on the Von Mises stresses and their principal stress components [16].

Figure 13a gives an overview of the welded wall. The white line represents the position where the specimen was separated to create the cross sections. Figure 13c shows the polished wall with the different positions of the other detail views. Subfigure (d) shows the upper area of the wall. A martensitic microstructure is present in this region. Subfigure (e) shows the polished specimen with a higher magnification level. A defect in the form of a pore can be seen in this area. Sporadic pores occur to a small extent over the course of the wall inside the weld. In subfigure (f), the area of the bond between the first applied weld seam and the base material is shown. In this case, the weld material has a martensitic structure and the base material consists of ferrite and perlite.

5.4 Discussion

As described in the state of the art, the weld seam geometry depends on the welding direction when welding in the vertical direction. Gu and Li have shown that in the case of
vertical up welded seams, a waviness occurs within the weld seam and the vertical down welded seams have a uniform shape [12]. In the experiments conducted, it was found that the vertical up welded seams show a uniform shape and the vertical down welded seams show a non-uniform shape. This is not in agreement with the results obtained by Gu and Li. In this case, the cause may be the feeding of the welding wire, which can lead to the melt pool being influenced by the lateral wire feeding under the influence of gravity, resulting in the described effects. In the experiments carried out with the coaxial wire feed, any influence of the wire feed on the melt can be almost ruled out. For this reason, it can be concluded that a much more stable process can be used by the direction-independent wire feeding, which leads to better results. Another reason for the deviations could be the different thermal conductivities of the substrates. Gu and Li used an ANSI 316L with a thermal conductivity of 15 W/(m·K) [17]. In the experiments conducted, an S355J2 with a thermal conductivity of about 40 W/(m·K) was used [18]. Gu and Li welded on a material of the same type resulting in constant heat conduction into the substrate. In the experiments with X45CrSi9-3 as filler material on an S355J2 substrate, there is a difference of about 19 W/(m·K), with the substrate conducting heat better than the filler material. As a result, the melt quickly transfers the heat to the substrate and thus has less opportunity to run due to the influence of the gravitational force. Compared to Gu and Li, who conducted the experiments with a constant welding speed of 600 mm/min, the present study showed that welding is possible within a wide process window of the welding speed in the range from 100 to 1000 mm/min [12].

6 Conclusion
In this investigation, deposition welding was successfully performed in vertical direction. The experiments were carried out using a laser head with coaxial wire feed and the laser metal deposition with wire process with a substrate of S355J2 and X45CrSi9-3 as the wire material. The influence of the welding direction, i.e., the vertical down, the vertical up, and the horizontal welding positions, and the welding speed parameter on the weld seam geometry and the weld seam surface properties were investigated. The results show that when the welding direction coincides with the direction of action of gravity, the weld seam has higher waviness with statistical significance of \( p = 0.0233 \) than when the welding direction is opposite to the direction of action of gravity. When the welding speed is added to the evaluation, greater waviness occurs in all welded seams as
the welding speed decreases. In addition, the vertical down welded seams exhibit greater waviness than the vertical up welded seams in all cases. All weld seams could be welded within the parameter window from 100 to 1000 mm/min. Furthermore, the influence of the gravitational force on the weld seam geometry was considered. It could be shown that the welding direction has an influence on the weld seam geometry for the vertical welding positions. The gravitational force causes the vertical down welded seams to have an uneven shape. The weld seam start is flat and the weld seam height increases with increasing welded length until a constant height is reached. The vertical up welded seam, on the other hand, does not show such effects and has a uniform height over almost the entire weld seam. Based on the change of the stickout length until the process could no longer be stably guided, it is evident that the stickout length has an influence on the welding result. The microstructure is identical for both welding directions, from which it can be concluded that there is no influence of the welding direction on the microstructure. The welding speed also has no influence on the microstructure. Only the size of the HAZ is dependent on the welding speed. In addition to single weld seams, claddings were welded. One bidirectionally in vertical direction and one unidirectionally in horizontal direction. The cladding welded in horizontal direction has a very uniform surface. The roughness at a cutoff of λc = 8.0 mm shows that the horizontally welded cladding with a value of Rzh = 193 µm is lower than the vertically welded cladding with Rzv = 257 µm. This can be attributed to the differences in the weld seam geometry due to the dependency on the welding direction. Furthermore, it was shown that it is possible in principle to produce a wall with 30 layers when welding in the horizontal position in the vertical direction. In this case, the occurrence of cracks in the structure is not due to the welding position. A small number of defects in the form of pores occurred in the wall, which can be attributed to the lack of shielding gas coverage.

For the application, deposition welding in vertical orientation is conceivable for large-scale components that are handled with the greatest effort, since in this case mobile process technology can be used to perform the welds on the component in a forced position and the component may not have to be disassembled. Further investigations are necessary to further develop the process for this application. Further experiments to investigate the effects of welding in the vertical direction with a processing head that feeds the wire to the process coaxially with the collimated laser beam must be undertaken. Based on the results of the welding tests, it is evident that the stickout length has an influence on the process result. For this reason, further investigations are to be carried out to determine the effects and influences of the stickout length. From the results on the surface properties for the single welds and the bidirectionally welded cladding, it is evident that differences in the weld seam geometry occur depending on whether welding is done in the vertical up or vertical down direction. In this respect, further experiments have to be carried out to investigate the deviation by a welding strategy or a variation of the welding parameters. Another focus of further work should be the examination and optimization of the degree of dilution between the cladding material and the substrate. Furthermore, investigations are required to determine the process limits in experiments to increase the application rate for which, for example, a hot wire process could be used, since no results are available on this subject to date. Even if the results in the horizontal position already show uniform surfaces, further investigation of the process parameters is required. For example, there are no findings on the influence of the welding speed on the weld seam geometry. Further investigations must be undertaken with the coaxial welding head and vertical weld seams to determine the influence of the amount of gravitational force on the weld seam geometry. The range with low gravitational force up to zero gravity is of interest for space applications. Further aspects for future investigations lie in the consideration of the influence of the wire feed rate on the waviness of the weld surface.

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Declarations

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