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Process development for laser hot-wire deposition welding with high-carbon cladding Material AISI52100

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Abstract

An increase in wear resistance and thus an increase in service life is of great importance for many components. The production of hybrid components with high-carbon steel as cladding material offers the possibility of achieving these goals. However, materials with a carbon equivalent of more than 0.65 are considered difficult to weld due to their tendency to crack. In this study, a laser hot-wire deposition welding process with bearing steel AISI 52100 as cladding material is used to investigate the influence of laser power, wire feed speed, scanning speed, overlap ratio and wire preheating as well as interactions of these parameters on process stability, the formation of cracks and pores, the cladding waviness and the dilution. Layers of eight adjacent weld seams are welded onto an austenitic stainless steel. A stable process is observed for most parameter combinations except for samples with low wire feed speed and major wire preheating.
Keywords: LMD-W; Cladding; high-carbon steel

1. Introduction

In order to improve the mechanical, physical or chemical properties in particularly stressed component areas, a cladding can be used. Improving wear resistance and the associated longer service life is a frequent objective in cladding applications. High hardness and thus also high wear resistance can be achieved by using high-carbon cladding materials. However, these materials have a high carbon equivalent value (CEV), which makes welding of these materials difficult. Steels with a CEV of more than 0.6 are considered to have very low weldability. Welding is only possible with great effort or not at all.

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When processing materials with high carbon content, various defects such as cracks and pores can occur. The high carbon content in particular is the reason for the poor weldability of steels with high CEV. The combination of the carbon with other alloying elements leads to hardening and embrittlement of the microstructure of the heat affected zone. The increased brittleness reduces ductility and the formation of material defects increases. Self-quenching during laser deposition welding further enhances this effect. The high cooling rates lead to the formation of martensite with high lattice strains. (Schulze, 2010)

Due to the difficulty in processing high-carbon steels, they have rarely been used for cladding. Coors et al. investigated hybrid thrust bearing washers which were manufactured by applying a cladding of AISI52100 to a substrate of AISI1022M by plasma transferred arc welding (Coors et al., 2020). After welding, there were large pore occurrences in the area of the later running surface. A subsequent hot forming process led to a reduction of the pore occurrence in the cladding layer and to an improvement in the microstructure. The axial bearing washers produced achieved a service life of 82 % of conventional AISI52100 mono-material bearings. The calculated Weibull curved indicated premature damage of the axial bearing washers due to pores and cavities. Behrens et al. investigated the mechanism of pore closure by hot forming in more detail (Behrens et al., 2021). For this purpose, weld seams of AISI52100 were applied to the base material AISI1015 and monomaterial specimens and hybrid specimens were taken from these for a compression test. It was shown that the pores are largely closed from a plastic strain of 0.7 in the cladding material.

Wenz et al. investigated the process stability, microstructure, and hardness during processing of a high-carbon FeCr-10V alloy by selective electron beam melting (Wenz et al., 2020). A crack-free martensitic steel with close to 2 wt% carbon was produced. The microstructure exhibited mainly narrow vanadium carbides, which provided for a high hardness of the microstructure. A completely pore-free microstructure could not be produced, but the highest density, i.e. minimal pore formation, and high process stability were found at a surface energy of 4 J/mm^2. Higher process speeds were found to have a strong negative effect on process stability.

Chang et al. carried out investigations on the generation of hypereutectic Fe-Cr-C claddings with different carbon contents using flux-cored arc welding (Chang et al., 2010). It was found that increasing the carbon content from 3.73 wt% to 4.85 wt% can increase the carbide formation from 33.8% to as high as 86.1%. Carbides significantly increase the strength and hardness of metals. Their formation is mainly favored by the alloying elements C and Cr. At high carbon contents, the significantly stronger and more wear-resistant round carbides are formed, which was confirmed by the investigations of Chang et al.

Sander et al. used a selective laser melting (SLM) process with platform preheating of 500°C to study the weldability of high-strength tool steel Fe85Cr4Mo8V2C1 with a carbon content of 1% (Sander et al., 2016). The chamber was flooded with argon and the oxygen content during the process was less than 0.2%. Two sets of parameters were found with a resulting sample density of at least 99.6%. An increased compression strength of 3,796 ± 163 MPa and a hardness of 900 ± 12 HV0.1 compared to the as-cast state was achieved. Kempen et al. used a similar setup to investigate an SLM process with M2 HSS powder with a carbon content of 0.9 %. Preheating of the baseplate was necessary to avoid cracks and delamination from the baseplate. A maximum density of 99.8% was achieved using a preheating temperature of 200°C. The hardness was increased from 57 HRC to 64 HRC by using a laser remelting process for every layer, which increases the martensitic phase, but the tendency to crack also increased. (Kempen et al., 2014) A SLM process with tool steel X110CrMoVAl8-2 was investigated by Feuerhahn et al.. A crack free sample with only small pores was manufactured. Homogenous microstructure and high hardness values of 765 HV were achieved by a subsequent heat treatment. (Feuerhahn et al., 2013)

The weldability of steels can be improved by various measures. The measures are intended to reduce or even prevent the formation of cracks or pores. As mentioned before one measure to reduce cracks is to preheat the component or baseplate. The process reduces the cooling rates thereby lowering martensite formation.

The investigations of Schaefer et al. (Schaefer et al., 2015) showed that there is a dependence of hot cracking on energy input, solidification geometry and material properties in joint welding of tempered steel. It was shown that transverse cracks, i.e. cracks that form transverse to the feed direction, are influenced by the beam quality and focus position. Shifting the focus point to a point above the workpiece surface leads to a reduction and relocation of the cracks. The large cracks in the seam root were thus avoided and significantly fewer cracks formed near the seam surface. In addition, defect-free specimens were created by increasing the laser power while maintaining the welding speed. Accordingly, by changing the focus and applied power, the formation of cracks can be significantly reduced and even completely avoided.

The formation of pores can be reduced or prevented by creating better degassing during welding. This can be achieved, for example, by reducing the welding speed. In addition, the removal of impurities from the base metal and filler metal, as well as a slight increase in the molten pool temperature, can significantly reduce pore formation. (Dilthey, 2005)

The use of high-carbon steel as a cladding material offers the possibility of achieving very high hardness values in the cladding, which is advantageous for components exposed to high mechanical loads. Previous investigations have shown that the processing of such steels is difficult due to their low weldability and that cracking and porosity are a common defect. Therefore, the influence of the process parameters of a laser hot-wire deposition welding process with bearing steel AISI52100 on process stability, pore occurrence, waviness and dilution is investigated. For this purpose, the influence of the process parameters laser power, wire feed rate, welding speed, current and weld seam overlap and their interactions on the welding result are investigated. The aim is to determine a set of parameters that enables a defect-free, stable welding process with low dilution and low waviness.

2. Material and Methods

2.1. Materials

For the experiments plates of the austenitic steel AISI316L with a thickness of 10mm are used as substrate material. Bearing steel AISI52100 is used as cladding material. The chemical compositions of both materials is shown in Table 1. Due to the high carbon content of about 1% AISI52100 is considered difficult to weld.

Table 1. Chemical composition in wt.% of AISI316L and AISI52100 (according to manufacturer data sheet)

	Fe	C	Si	Mn	P	S	Cr	Ni	Mo	N	Al	Co
AISI316L	bal.	0.022	0.516	1.583	0.037	0.0004	17.56	12.71	2.606	0.082	-	0.181
AISI52100	bal.	0.94	0.20	0.34	0.009	0.007	1.4	-	0.010	-	0.002	-

2.2. Experimental Setup

The cladding is applied by laser metal deposition welding with hot-wire. The coaxial deposition welding head MK-II, manufactured by Laser Zentrum Hannover e.V., is used for this purpose. A LDM 3000-40 cw diode laser, manufactured by Laserline, with a wavelength of 1020-1060 nm ±15nm, a fiber core diameter of 400 µm and a maximum power output of 3 kW is used as laser source. Within the welding head the laser beam is divided into four partial beams by a four-sided pyramid with a reflective coating, which is positioned below the focusing lens. The four partial beams are each redirected by a mirror and recombined at the tip of the wire. The splitting of the laser beam enables the media hoses and welding wire to be inserted into the center of the processing head. The coaxial arrangement of laser beams and wire is advantageous compared to lateral wire feeding due to independence of the process from the welding direction. Therefore, coaxial welding heads are more suitable for manufacturing of complex components.(Lammers, Budde, et al., 2020; Lammers, Hermsdorf, et al., 2020)

For feeding and heating of the wire, the wire feeding unit DIX FED 100 L and the hot current source DIX PI 270 from the company Dinse are used. The actual values of wire feed speed and current during welding are recorded and used to evaluate the process stability. A collimator with a focus length of 100 mm and a focusing lens with a focus length of 300 mm are used. The focus position is 2.5 mm below substrate surface, resulting in a spot diameter of 2.7 mm on the substrate. The substrate is inserted into a clamping device and fixed via four pneumatic clamps. The wire diameter is 1 mm.

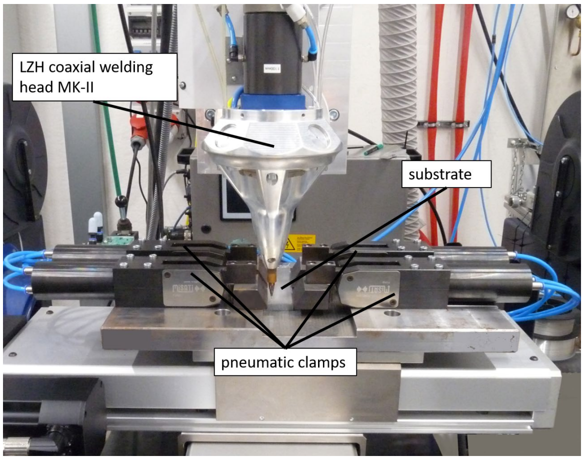

Fig. 1. Experimental setup for coaxial laser metal deposition welding with hot-wire

2.3. Experimental Methods

For the experiments, claddings are manufactured consisting of 8 overlapping welds with a length of 60 mm. The welding is unidirectional. The process parameters wire feed rate, welding speed, current, laser power and overlap ratio of the welds are varied as part of a Response Surface Method (RSM) experimental design for cladding analysis. All parameters are varied in three stages. Shield gas flow rate, wire stickout and focal position are kept constant during the experiments. An overview of the welding parameters is given in Table 2.

Table 2. Process parameters for laser hot-wire cladding of AISI52100

Process parameter	Unit	Values
Wire feed rate	m/min	1/1.5/2
Welding speed	mm/min	400/800/1200
Laser power	kW	1.8/1.95/2.1
Current	A	45/60/75
Overlap ratio	%	20/35/50
Shield gas flow (Argon)	l/min	8
Wire stickout	mm	7
Focal position	mm	-2.5

26 different parameter sets were used for the investigation. Three samples are produced per parameter set. The samples are produced in a randomized order.

2.4. Cladding analysis

The target parameters for parameter optimization are process stability, degree of dilution, pore occurrence and waviness. The process stability is determined by the recorded signals of wire feed rate and current. A drop in the wire feed signal indicates that there is not enough energy available to melt the wire or that the wire feed rate has been selected too high. A drop in the current signal is an indication that the wire is burning back. This happens when the wire is melted too early and thus the connection to the substrate breaks off.

After welding the surface waviness of all samples was measured using a laser scanning microscope VK-X1000 by Keyence. The analysis software MultiFileAnalyzer is used to measure the waviness. The primary profile P of the cross-sectional area is determined from the data points. The cut-off wavelength λ_c is used to extract the roughness profile and waviness profile. The cladding waviness is determined at three different positions for each sample.

In order to determine the dilution one sample per parameter set is cut perpendicular to the welding direction at three positions. The specimens are embedded, polished and etched with Adler etchant. The height, width and degree of dilution of the cladding are determined at four positions. A low degree of dilution is targeted in order to achieve a high purity of the applied layer and, consequently, high hardness values in the cladding.

Ultrasonic measurements are performed on one sample per parameter set to determine pore size and distribution. Ultrasonic testing is performed with the modified PVA TePla SAM 301 system. An ultrasonic pulse is sent into the specimen via distilled water as a coupling medium. In addition, creeping oil is used to protect the specimen from corrosion. The method uses the effect that sound waves propagate at different speeds in different media. At interfaces where, for example, there is a so-called wave impedance at the air-metal transition, some of the sound waves are reflected. Pores or cracks represent such a transition and can therefore be investigated. The reflected radiation is picked up by an ultrasonic probe, the so-called transducer. The probe is mounted on an XY scanner and passed over the sample in a line. By analyzing the transit time signal, the exact location of the material defect can be determined. Thus, an acoustic horizontal section image is calculated.

3. Results and Discussion

With 24 parameter combinations, an analyzable cladding could be produced. Only in two cases, the wire burned up immediately, so that an evaluation of the cladding properties is not possible. In both cases, low wire feed rate and high wire preheating were used. Figure 2 shows an example of a pore-free cladding and a cladding with strong pore occurrence with AISI52100.

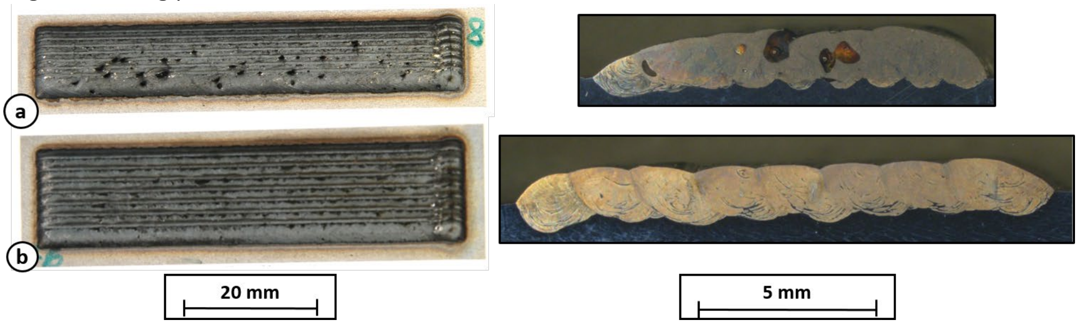

Fig. 2. Top view and cross-section of two claddings made of AISI52100 a) Welding Parameters: laser power 2.1 kW, wire feed rate 2 m/min, welding speed 1200 mm/min, current 45 A, weld seam overlap 50% b) Welding Parameters: laser power 1.95 kW, wire feed rate 1.5 m/min, welding speed 800 mm/min, current 75 A, weld seam overlap 35%

During welding of some parameter sets, a strong sparking occurs. An example of the sparking is shown in Figure 3. The effect occurs especially at a high wire feed rate of 2 m/min while at a wire feed rate of 1 m/min the effect cannot be observed.

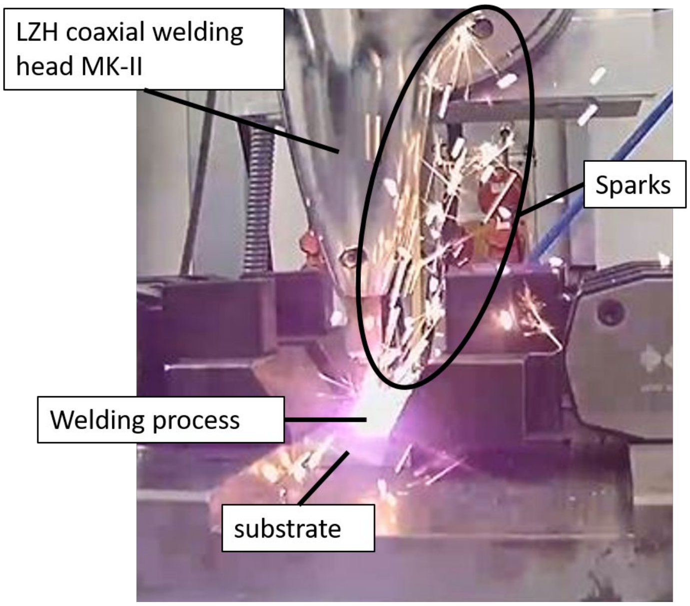

Fig. 3. Strong sparking during the welding process with a wire feed rate of 2 m/min

The statistical software JMP (SAS Institute GmbH, Böblingen, Germany) is used for the evaluation of the RSM experimental design. The factors influencing the target parameters process stability, pore occurrence, dilution and waviness are determined. A significance level of 0.05 is chosen for the statistical analysis. A statistical model is used to describe the correlation between the target parameters and the process parameters. Non-significant factors and interactions are removed from the model. The model is used to determine an optimal set of parameters using the Response Surface Method in JMP. For this purpose, the target parameters are weighted with respect to their importance for the optimization of the welding process. Each target variable is assigned a desirability function that describes which value represents the optimum for that variable and how different values of the variable should be evaluated during optimization. For example, the aim is to achieve as little dilution as possible in order to obtain as pure a cladding as possible. A linear function is used to describe the desirability in this case, which leads to greater desirability for small dilutions and lower desirability for large dilutions.

First, the main process parameters influencing the various target variables are described. The process stability depends on the wire feed rate. At a higher wire feed rate the current signal tends to be stable while at lower wire feed rates a stable wire feed rate signal is observed.

The waviness of the cladding is dependent on the wire feed rate and the welding speed. Increasing the wire feed rate (v_W) and decreasing the welding speed (v) will result in greater waviness and therefore potentially more machining rework for the cladding. The combination of the two influencing factors results in a significant influence of the parameter A_c, which depends on wire feed rate and welding speed and describes the cross-sectional area of the cladding located above the substrate, on the waviness.

The ultrasonic images are evaluated to assess the occurrence of pores in the weld. Depending on the number of pores, points between 0 (no pores) and 3 (more than 10 pores) are assigned. The analysis shows that the wire feed rate and A_c has a statistically significant influence on the pore occurrence. With increasing wire feed rate and A_c number of pores increases. The influence of the wire feed rate is higher at higher overlap ratios.

The RSM analysis shows that laser power, wire feed rate, welding speed and degree of overlap have a significant effect on the degree of dilution. The degree of dilution increases with increasing laser power and welding speed and decreases with increasing wire feed rate and degree of overlap. A higher A_c and thus a higher weld seam leads to a reduction in the degree of dilution.

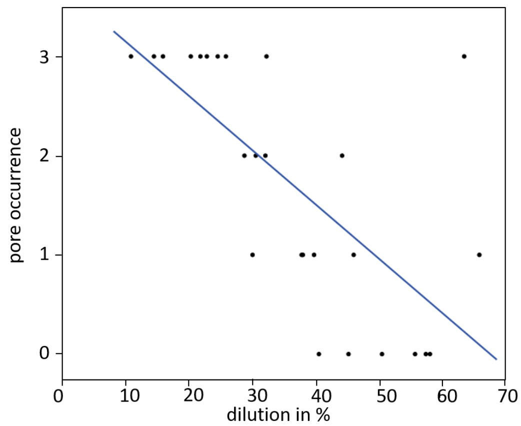

Fig. 4. Dependence of pore occurrence on the degree of dilution of the cladding

Figure 4 shows the relationship between pore occurrence and degree of dilution. Each point represents a dilution and pore occurrence of one cladding sample. Pore-free claddings or claddings with low pore occurrence are achieved at high degrees of dilution, while low degrees of dilution are associated with a high occurrence of pores. This makes simultaneous optimization of these variables difficult.

For the determination of the optimized parameter set, each target variable is assigned a desirability function. For waviness, pore occurrence and degree of dilution a minimization is aimed. A linear function is used to describe the desirability in all three cases. For process stability, a stable process is assigned the desirability 1. Processes with irregularities of wire feed speed signals or current signals are assigned a desirability of 0. Based on this, optimized parameter sets are determined using the statistical software.

Two different weightings of the target variables are used to determine the optimized parameter sets. The first parameter set is determined by equal weighting of all four target variables. A laser power of 1.95 kW, a wire feed rate of 1.5 m/min, welding speed of 1200 mm/min, current of 75 A and weld seam overlap of 35% is determined using the statistical software. According to the prediction of the statistical model, a stable process with a small number of pores, a dilution of 34% and a waviness of 33 µm is expected. The second parameter set focuses on pore occurrence. With a factor of 0.9, this is weighted much more heavily than process stability and dilution, each with 0.05. Waviness is not taken into account for this parameter set. A laser power of 2.1 kW, a wire feed rate of 1 m/min, a welding speed of 400 mm/min, a current of 45 A and a weld seam overlap of 38% is used. According to the model, a pore-free cladding with a high degree of dilution of 57 % is expected.

Claddings were produced with both parameters sets. The results are shown in Figure 5.

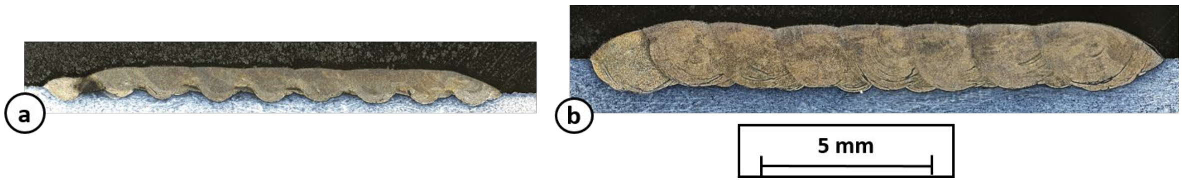

Fig. 5. Cross-section of claddings with optimized parameter set 1 (a) and 2 (b)

Since the first set of parameters does result in a porous cladding, it is unsuitable for manufacturing of protective claddings. The second parameter set leads to a pore-free cladding with very high dilution, so that the desired high hardness values in the single-layer cladding are not achieved. Therefore, multilayer claddings must be used. An example of a three-layer cladding is shown in Figure 6. As the first applied layer leads to a change in substrate properties (e.g. temperature, waviness and roughness), the parameters for the subsequent layers are adjusted. A laser power of 1.2 kW, a current of 30 A and a wire feed rate of 0.8 m/min are selected for the subsequent layers.

Fig. 6. Cross-section of a cladding consisting of three layers

Figure 7 shows the mean hardness profile of a single-layer and a three-layer cladding. Hardness measurements are performed in steps of 0.1 mm from the cladding surface towards the base material at six different positions along the cladding. While the hardness in the first layer is still comparatively low at 270 - 290 HV0.1, the hardness increases with increasing number of layers up to 700-850 HV0.1.

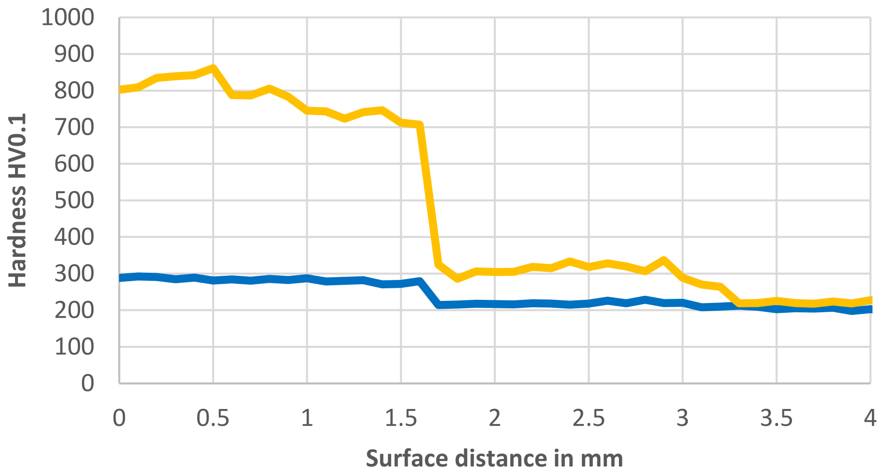

Fig. 7. Cross-section and hardness profile of a cladding consisting of three layers (yellow line) and one layer (blue line)

4. Conclusion

In this work, a laser hot-wire deposition welding process for high carbon steel AISI52100 on AISI316L was developed. The effect of the process variables laser power, wire feed rate, welding speed, current and degree of overlap of the weld seam on the target variables process stability, pore occurrence, dilution and waviness was analyzed and a RSM was used to determine optimal process parameters. It was shown that a simultaneous optimization of pore occurrence and degree of dilution is difficult, since a reduction of pore occurrence is associated with a high degree of dilution. A parameter set for the production of pore-free claddings could be determined. Due to the high degree of dilution, a single-layer cladding does not have the hardness values expected in a AISI52100 cladding. By manufacturing a multilayer cladding, it was possible to achieve a pore-free cladding layer with a high purity and a high hardness of 700- 850 HV0.1.

Parameter sets with a high wire feed rate resulted in strong sparking during welding. The cause of this effect should be investigated in more detail in further experiments.

The investigations were limited to the substrate AISI316L. Transferability to other materials should be examined in further investigations. An applicability of the process to AISI52100 substrates should be investigated in order to determine the possibility of repair welding of such components. The high degree of dilution would not have a negative effect on the welding result in that case. Furthermore, it should be investigated whether preheating of the substrate can be used to reduce pore formation.

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