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Optimizing Process Parameters during the Creation of Powder Laser Weld Cladding Coatings from a Nickel Alloy

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Nowadays, increasing emphasis is placed on the production of parts using additive technologies, particularly for alloys that are difficult to process. In addition to standard additive technologies, such as Selective Laser Melting (SLM), other additive technologies are increasingly being used, including Directed Energy Deposition (DED). DED offers several advantages and is utilized both for producing entire components and for repairing damaged parts through weld cladding. In this study, the possibility of weld cladding of nickel-based hard alloys using DED was tested using a laser as the energy source to melt the additive material. The tests performed showed that selected nickel alloys, suitable for mould repair, are difficult to weld. Therefore, the experiments sought optimal process parameters and defined the accompanying technological operations in order to produce a crack-free weld cladding.

Keywords: Directed Energy Deposition (DED), Laser welding, Nickel-based alloys

1 Introduction

One of the basic requirements of modern industrial production is high quality and precision of products, as well as production efficiency. Various types of additive technologies are increasingly being applied, the biggest advantages of which are almost waste-free production and the ability to process alloys with poor castability, machinability or formability into final parts without the need for further technological operations. One of the methods that ranks among industrially used additive technologies is Directed Energy Deposition (DED).

Especially in the energy industry, it is necessary to use alloys with high temperature resistance. One of the materials that withstands the demanding operating conditions that prevail, e.g., in power plant turbines, are nickel alloys. In addition to heat resistance, they are characterized by a number of other specific properties, e.g., high corrosion resistance or cryogenic resistance [1-3]. However, their disadvantage lies in their high susceptibility to cracking when hot. Therefore, during their welding or surfacing (including the DED method), it is necessary to set the technological parameters and other conditions correctly in order to reduce the risk of cracks [4-6].

In the DED process, the additive material is supplied either as a powder or as a metal wire. The energy source for melting the additive material is a laser (marked as DED-L) or an electron beam (DED-EB). With DED, the part is created in such a way that the powder (or metal wire) is fed to the melting point and directly melted by the concentrated energy source (see Fig. 1B). A related technology is the Powder Bed Fusion (PBF) technology, where the powder is poured into a mold and a laser beam melts the places where the solid material is to be formed (see Fig. 1A). The advantages of DED compared to PBF are a high application speed (up to 2.5 kg/h), the possibility of printing large parts or the possibility of applying different materials from several application heads. On the other hand, the disadvantage is lower printing accuracy [7-9].

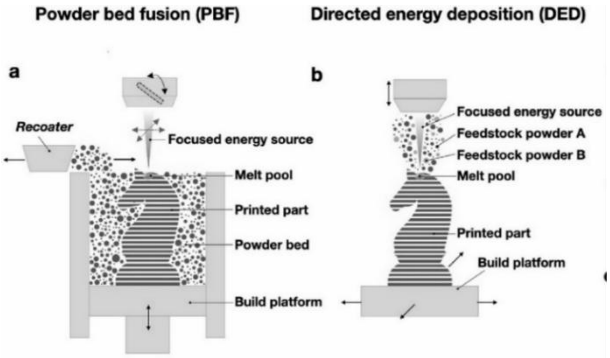

Fig. 1 *Scheme of the PBF method (a) and the DED method (b) [7]*

Nowadays, the DED technology is widely used, from coating to repairing damaged parts up to the production of final parts from difficult-to-process alloys, while it is preferably used for the production of larger components, which do not have such strict requirements for their accuracy [10].

In the case of using the DED technology, we can often encounter defects. Among the most frequently occurring defects are the formation of internal stresses, or deformations in the material, formation of porosity and high surface roughness. The high cooling rate and thermal gradients in the material are responsible for the formation of residual stresses. This defect can be partially eliminated by preheating the substrate, optimizing welding parameters or surface heat treatment. In the case of the formation of porosity, the cause is usually a high energy density in the impact area, the porosity of the substrate, or the entrapment of the gas of the protective atmosphere in the layer. Checking the composition and quality of the powder, as well as optimizing laser settings, can help mitigate this defect. The last frequently occurring defect is high surface roughness, which is usually caused by insufficient laser power, too coarse powder used or high laser scanning speed. Increasing the laser power, using a finer powder, or inclusion of another finishing operation after welding (e.g., grinding) help to reduce the roughness of the surface [9, 11-13].

Within the framework of this article, the problem of optimization of process parameters during the formation of powder laser weld cladding coatings from a nickel alloy was solved. Initial tests of welding nickel powder showed that for specific alloys it is not possible to achieve the formation of a compact weld just by simply adjusting the process parameters [14]. The aim of the experiments was therefore to establish appropriate measures and treatment of welds to prevent the formation of defects.

2 Materials and methods used

The LaserLine LDF 10000 laser source was used for the production of test samples. It is a diode-excited fiber laser operating in the wavelength range of 1030 – 1060 nm. Its maximum output is 10 kW. The laser was guided by a 6-axis KUKA KR60HA robot. Two types of welding heads were used for welding – BLC CNS 37 and Fraunhofer IWS COAX 8. The powder feed was ensured by the GTV PF2/1 feeder. Fig. 2 shows the different strategies for forming the weld cladding coating (A, B, C) that were implemented during the weld deposit tests. In Fig. 2, the "laser step" parameter is also marked. Specific process parameters are given for each type of experiment, with constant parameters including smoothing radius (0.5 mm), carrier gas flow rate (20 l/min) and laser spot diameter (3 mm).

Imaging of the sample surfaces was performed using an Olympus DSX500 optical microscope. The study of the microstructure and sections of the weld cladding coatings was carried out using a scanning electron microscope (SEM) Tescan Mira 3, equipped with an Oxford UltimMax65 detector for determining the local chemical composition (EDX).

Different types of nickel alloys in powder form were used as welding materials – alloy 10.16.6 (high hardness), 10.12.6 (medium hardness), 31.10.10 (low hardness) and Inconel 625 (for filler material tests). The chemical composition of the powders used is indicated in Table 1. The matrix on which the welding was performed was steel ČSN 19 552 = DIN 1.2343 = X38CrMoV51.

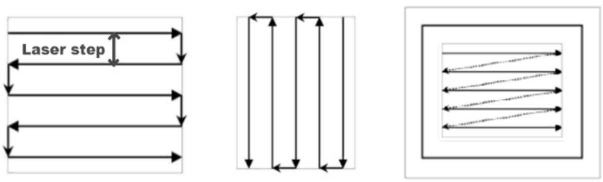

Fig. 2 *Used variants of the weld cladding coating creation strategy*

Tab. 1 *Chemical composition of the powders used to create weld cladding coatings*

Powder	Chemical composition (wt. %)														
	Ni	**Cr**	**Fe**	**Mn**	**Si**	**Cu**	**C**	**S**	**Mo**	**Nb**	**Co**	**Al**	**Ti**	**P**	**B**
10.16.6	66	16	3.5	-	4.5	3.0	0.5	-	3.0	-	-	-	-	-	3.5
10.12.6	85	7.5	2.5	-	3.5	-	0.25	-	-	-	-	-	-	-	1.7
31.10.10	95	-	1.0	-	2.3	-	-	-	-	-	-	-	-	-	1.3
Inconel 625	58	20-23	5.0	0.5	0.5	-	0.1	0.015	8-10	3.15-4.15	1.0	0.4	0.4	0.015	-

3 Experiment results

3.1 Initial tests

The aim of the initial tests was to design a wide range of process parameters (a total of 78 different variants were tested) and then focus on the parameters that can be used to achieve welds without defects. Six of the designed and tested parameters were selected for the article, which show the evolution of weld quality. Coatings made from the powder marked 10.16.6, which were the hardest and therefore most resistant to abrasion, were preferred. With the use of process parameters (see Tab. 2), which are used in VÚTS for the creation of weld coatings from most materials, all test samples were cracked (see Fig. 3).

When studying the microstructure, it turned out that cracks are formed either at the interface between the matrix and weld (see Fig. 4), or on precipitating hard secondary phases based on carbides and borides (see Fig. 4 and EDX in Fig. 5).

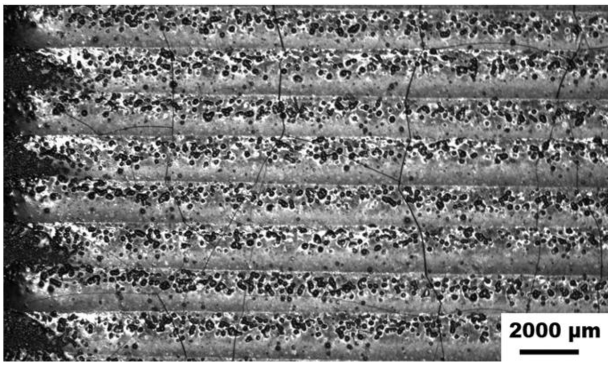

Fig. 3 *Cracks on the surface of the weld cladding coating made using standard VÚTS's process parameters*

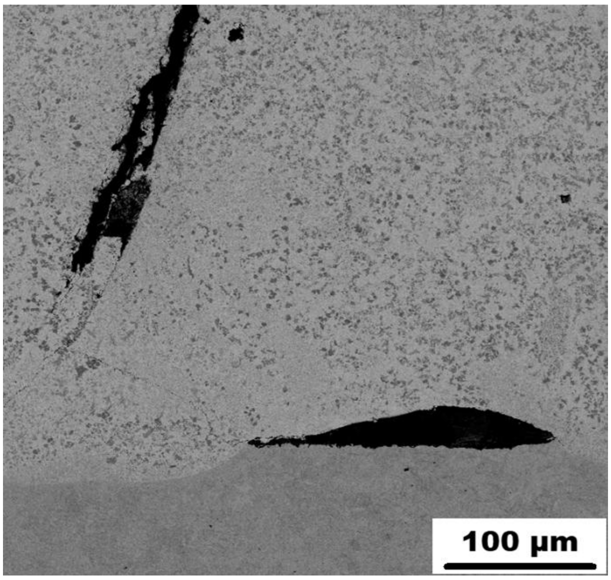

Fig. 4 *Microstructure of the weld cladding coating with visible cracks at the transition between the matrix and the weld cladding coating and along the hard secondary particles (SEM, 10kV, BSE)*

Tab. 2 *Standard process parameters used for creating laser weld cladding coatings*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
2000	1000	1.4	25	YES	A

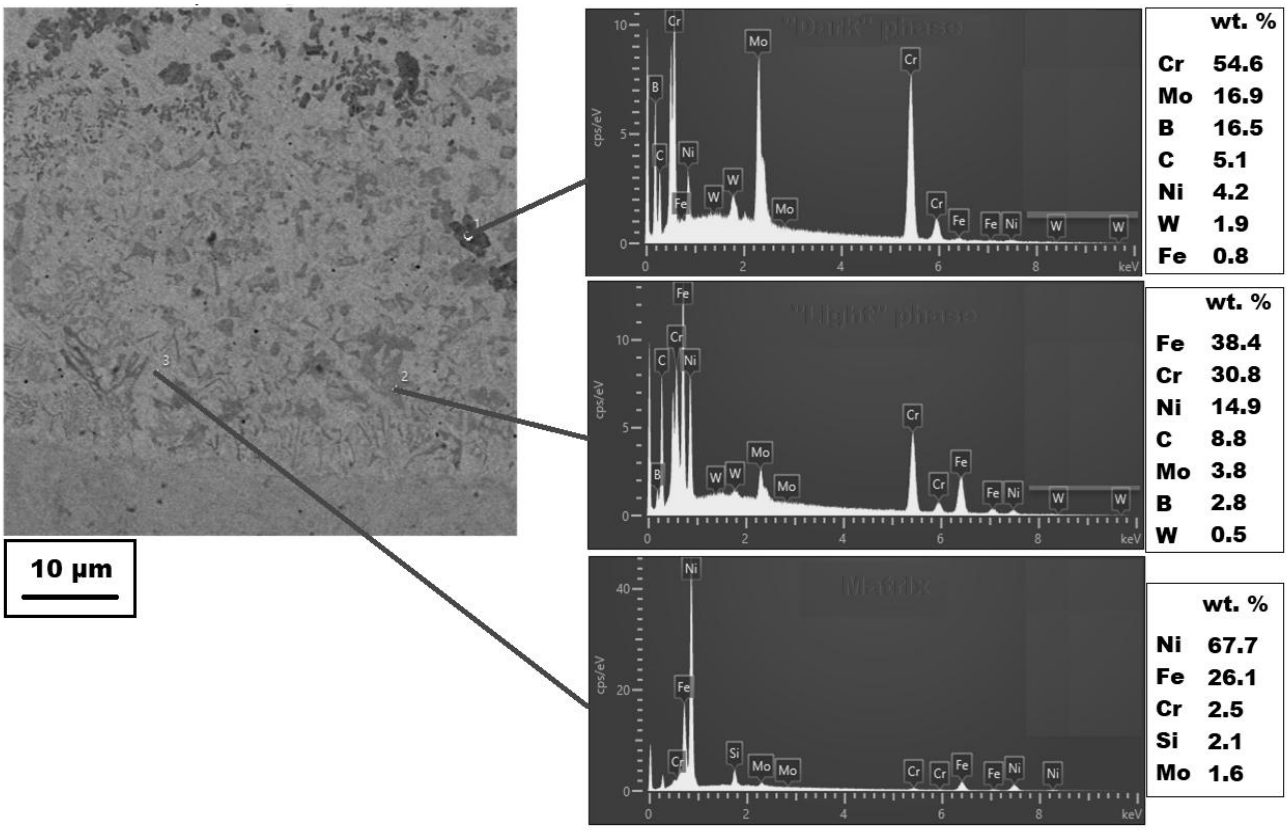

Fig. 5 *EDX point analysis of the phases formed in the weld cladding coating*

3.2 Reduction of heat input

Nickel alloys are generally susceptible to heat cracking. For this reason, the first measure to prevent cracks was proposed to reduce the amount of heat input. This was achieved by reducing the laser power (see the used parameters summarized in Tab. 3). The results of the experiment showed that this measure has only a limited effect. Cracks continued to occur in some areas of the weld cladding coating. The only positive finding was that the cracks showed a smaller width.

Tab. 3 *Process parameters used for the creation of laser weld cladding coatings with a reduced amount of heat input*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
800	1000	1	8	YES	A

3.3 Reducing the heat input and increasing the cooling rate by cooling into the water

The second measure, in addition to reducing the heat input, was also to increase the cooling rate by cooling into the water. This treatment was aimed at limiting the formation of low-melting eutectics, which are responsible for hot crack initiation. To create experimental weld cladding coatings, even lower laser power values were used compared to the previous case (see Tab. 4). When this combined measure was used, intact weld cladding coatings without cracks were created (see Fig. 6 and 7). On the other hand, the weld cladding coatings formed showed significant surface topological error and minimal height. The possibility to eliminate this negative was the creation of a multilayer weld cladding coating. Samples of a four-layer weld cladding coating were tested, however, the study of their surface showed that there was a further increase in the topological error and very fine cracks appeared on the surface of the weld cladding coating. For that reason, even this measure was not evaluated as suitable for use in industrial practice.

Tab. 4 *Process parameters used for the creation of laser weld cladding coatings with a reduced amount of heat input and subsequent cooling in water*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
670	1350	1.5	2	YES	A

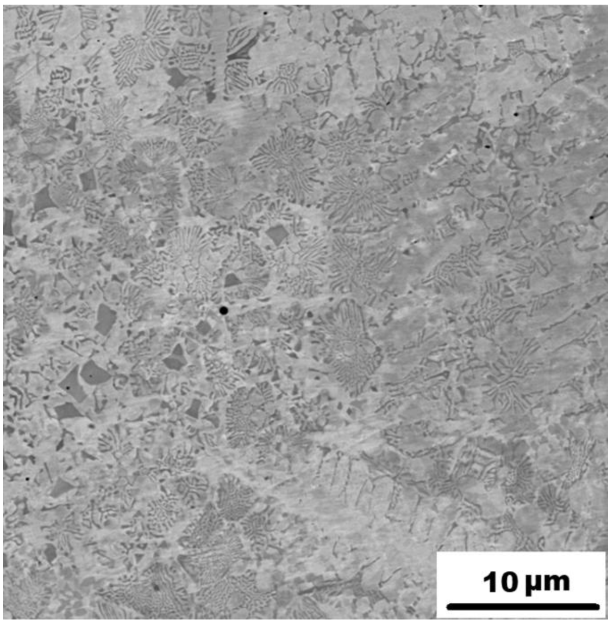

Fig. 6 *Microstructure of the weld cladding coating produced with parameters respecting the low value of heat input and high cooling rate by cooling in water - the center of the weld cladding coating without visible cracks (SEM, 10kV, BSE)*

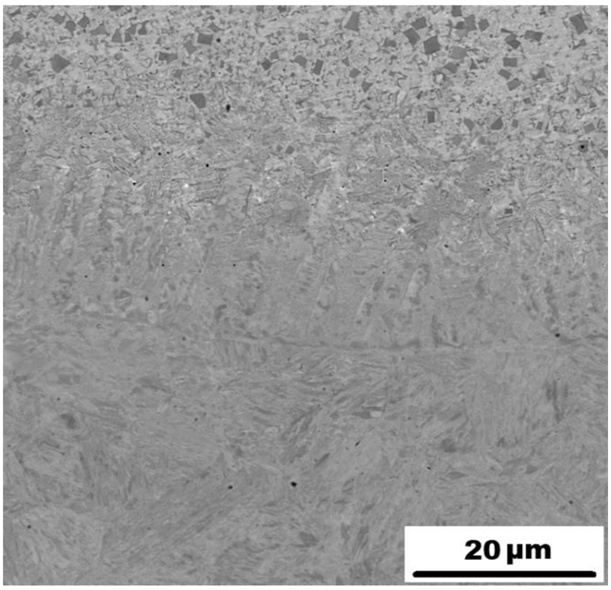

Fig. 7 *Microstructure of the weld cladding coating produced with parameters respecting the low value of heat input and high cooling rate by cooling in water - the transition area between the matrix and the weld cladding coating without visible cracks (SEM, 10kV, BSE)*

3.4 Increasing the cooling rate by cooling in water and subsequent cleaning of oxide layers

During the analysis of weld cladding coatings using an electron microscope, it was observed that an oxide layer of Al_2O_3 is formed on the surface of weld cladding coatings (see EDX analysis Fig. 8). Aluminum comes probably from contamination - technological process contamination or contamination of input powder. For that reason, the process of cleaning the surfaces of the weld cladding coatings from oxide layers was included as the next step. Rapid cooling in water and subsequent removal of oxides together with the use of the process parameters given in Tab. 5 led to the formation of the first weld cladding coatings without cracks and topological errors (see Fig. 9 of the surface of the weld cladding coating and Fig. 10 from the metallographic section).

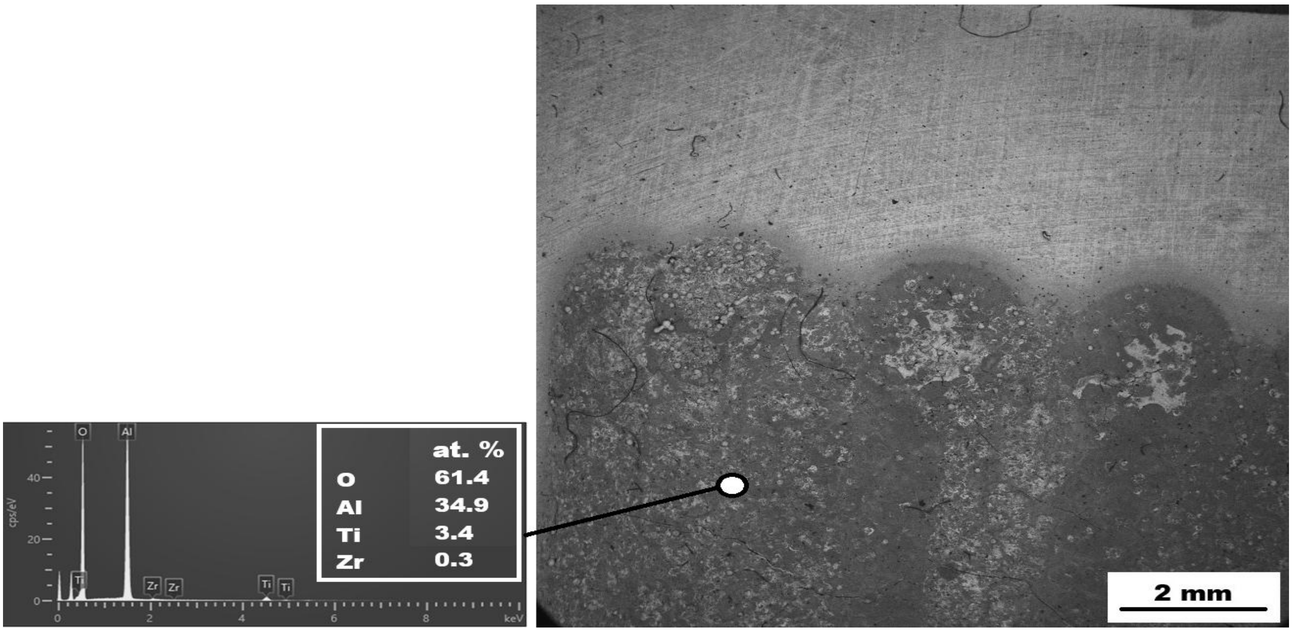

***Fig. 8** Contamination of the surface of the weld cladding coating by Al_2O_3 (SEM, 10kV, BSE)*

***Tab. 5** Process parameters used for the creation of water-cooled laser weld cladding coatings and subsequently cleaned of oxide layers*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
1800	900	1.5	12	YES	A

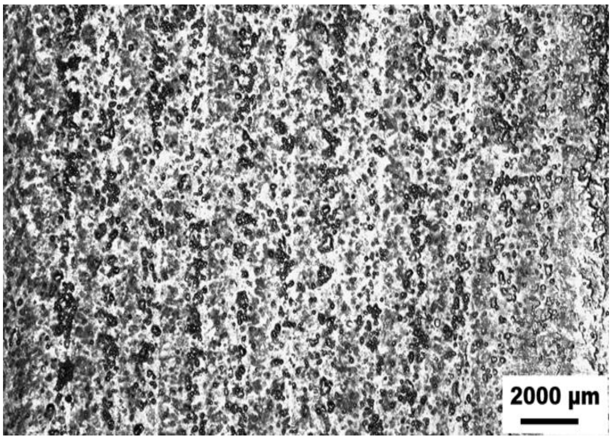

***Fig. 9** The surface of the weld cladding coating cooled in water and subsequently freed of oxide layers; The Figure demonstrates that the weld cladding coating was free of cracks*

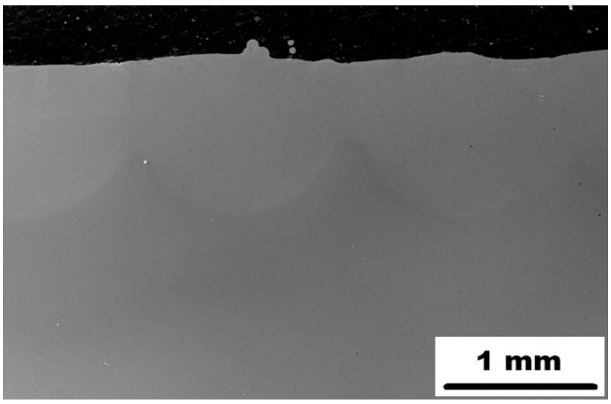

***Fig. 10** Cross section of the weld cladding coating after cooling in water and cleaning of oxide layers; The Figure demonstrates that the weld cladding coating was free of cracks and without topological error (SEM, 10kV, SE)*

3.5 Effect of protective atmosphere

The effect of the protective atmosphere on the surface integrity of the weld cladding coatings was tested in a special closed chamber filled with argon. The big disadvantage of this solution was poor heat dissipation, as a result of which, the samples were being overheated considerably. Opening the chamber required considerable time, so even the samples subsequently cooled in water remained at a high temperature for a long time. The same process parameters as in the previous case were chosen for the production of weld cladding coatings – see Tab. 5.

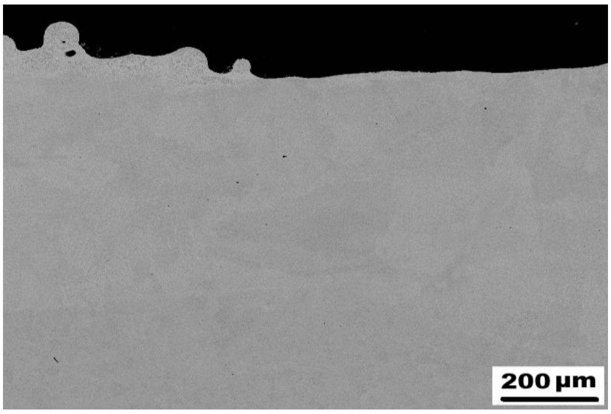

Fig. 11 *Microstructure of a weld cladding coating produced in a protective argon atmosphere and cooled in a chamber with an argon stream - without cracks (SEM, 10kV, BSE)*

The samples were cooled in two ways. Either the weld cladding coating was cooled directly in the chamber with a stream of argon, or the chamber was opened and the weld cladding coating was cooled in water. In the case of cooling the samples with an argon stream, the formed weld cladding coating was intact without cracks (see Fig. 11). When cooling in water, the weld cladding coating cracked in one place. However, the subsequent metallographic analysis showed that the crack originated in the place of the inclusion, which probably got into the weld cladding coating from the abrasive used to clean the base material.

3.6 Welding of powders of lower hardness

Experiments were also carried out with powders of lower hardness 10.12.6 and 31.10.10. The assumption when using the mentioned powders was that cracks would not occur due to the lower hardness of the weld cladding coating. For the welding of powders 10.12.6 and 31.10.10, the variant of welding in a protective chamber was chosen. Process parameters were selected according to Tab. 6, while two variants of the laser step size – 0.7 mm and 1.5 mm – were tested. The results of the experiments showed that at a lower step size (0.7 mm) all weld cladding coatings cracked. On the contrary, with a step size of 1.5 mm, all weld cladding coatings were produced without cracks (see Fig. 12 and 13).

Tab. 6 *Process parameters used for the creation of laser weld cladding coatings from powders of lower hardness 10.12.6 and 31.10.10*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
1200	900	0.7 / 1.5	12	YES	A

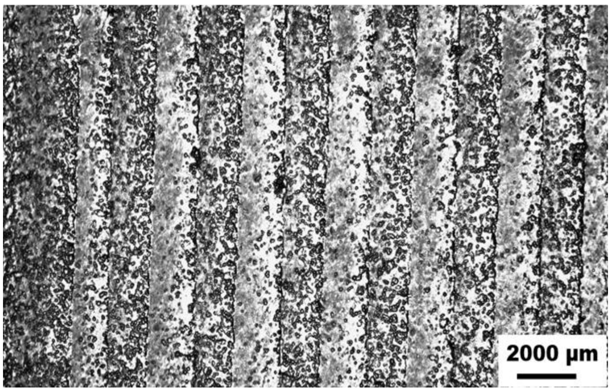

Fig. 12 *The surface of the weld cladding coating made from powder of medium hardness 10.12.6 with a laser step size of 1.5 mm used – no cracks*

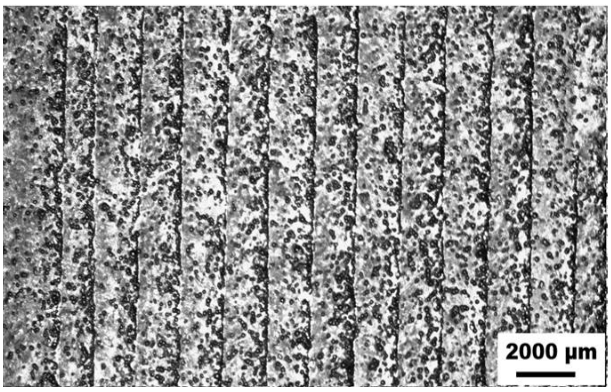

Fig. 13 *The surface of the weld cladding coating made from low hardness powder 31.10.10 with a laser step size of 1.5 mm used – no cracks*

3.7 Welding of powders onto an Inconel 625 interlayer

The last variant tested was the production of a multi-material weld cladding coating. The goal was to create a filling of a deep defect from Inconel 625, which is generally very weldable, and to weld a covering layer of one of the harder powders – 10.12.6 (medium hardness) or 10.16.6 (high hardness) onto this filling. The welding parameters of the covering layer are summarized in Tab. 7.

The results of the experiment showed that when welding hard powder 10.16.6 on Inconel 625, the cover layer cracked in all cases (see Fig. 14). In contrast, when using medium hardness powder 10.12.6, the cover layer was intact without cracks in all samples (see Fig. 15), but pores appeared in the layer (see Fig. 16). A typical "wrinkled" pore morphology, as the gas was trapped inside, is clearly visible from detail in Fig. 16 right. These pores could be caused by a number of factors. To eliminate them, it could help to dry the input welded powder just before use, or according to some authors [15], the formation of pores can be influenced by increasing the laser power. In such a case, however, the limitation of the heat introduced into the weld cladding coating must also be taken into account. Another option to eliminate pores could be the additional use of HIP (Hot Isostatic Pressing) technology [16].

Tab. 7 *Process parameters used for welding cover layers to Inconel 625 filler layer*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
1800	900	1.5	12	YES	A

Fig. 14 *The surface of a weld cladding coating made from high hardness powder 10.16.6 on a layer of Inconel 625 – cracks appeared in the weld cladding coating*

Fig. 15 *The surface of a weld cladding coating made from medium hardness powder 10.12.6 on a layer of Inconel 625 - the weld cladding coating was free of cracks*

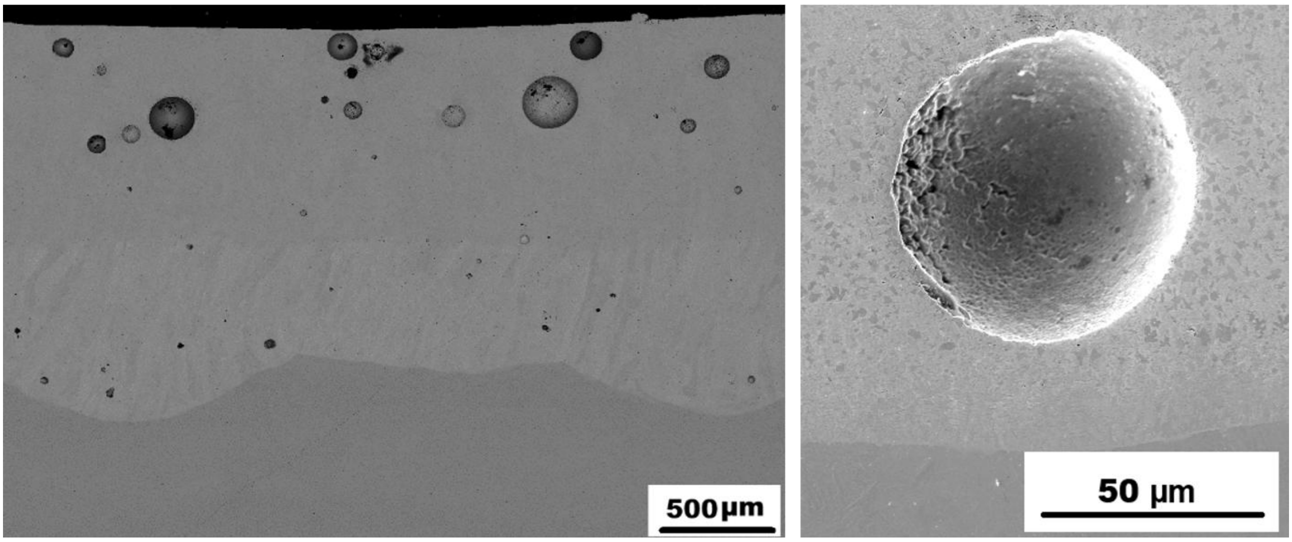

Fig. 16 *Microstructure of a weld cladding coating made from medium hardness powder 10.12.6 on a layer of Inconel 625 – without cracks, but with a large amount of pores (left), and detail of one of the pores (right) (SEM, 10kV, BSE)*

4 Conclusions

On the basis of the conducted experiments, it was evaluated that it was not possible to create an intact weld cladding coating without cracks from the hard material 10.16.6 simply by adjusting the process parameters. Water cooling had a positive but only limited effect on surface integrity. If the cleaning of the surfaces of the weld cladding coatings from oxide layers was added to the water cooling of the weld cladding coatings, this measure had a very positive effect under the given process parameters. The use of a protective atmosphere was also beneficial and led to the formation of weld cladding coatings without defects. However, in the case of the introduction of this variant into industrial practice, it is necessary to expect higher financial demands for the production of the weld cladding coating. During testing of multi-layer weld cladding coatings, cracks usually appeared in the surface layer. It was therefore possible to create weld cladding coatings of only a limited height from the hard powder 10.16.6. The technology mentioned would therefore be suitable, e.g., for the renovation of heavily stressed machine parts with small defects (e.g., rollers of printing machines). In the case of the need to repair deeper defects, it would be necessary to use powders of medium hardness (10.12.6) or to weld the hole with a soft powder (Inconel 625 or 31.10.10) and then create a covering layer of powder 10.12.6. In such a case, however, the risk of pores forming in the welded layer must be taken into account.

The most suitable process parameters for welding hard nickel alloy 10.16.6 are given in Tab. 8. When using these parameters, it is also recommended to cool the samples in water and clean their surface from oxide layers.

Tab. 8 *Recommended process parameters for welding hard powder 10.16.6*

Laser power [W]	Laser feed [mm/min]	Laser step [mm]	Powder sprinkle [g/min]	Interrupting the laser on step transition	Application strategy
1800	900	1.5	12	YES	A

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