PRZEGLĄD SPAWALNICTWA
Welding
TECHNOLOGY REVIEW

DOI: https://doi.org/10.26628/simp.wtr.v95.1160.67-77

Original Article

Coaxial Laser Wire Deposition of AISI 316L steel - research on influence of processing parameters

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Received: 17.07.2022; Accepted: 12.07.2023; Published: 13.07.2023

Abstract: Laser cladding technology is a well-established process, commonly used for deposition of improved-property coatings, repair of machine parts and additive manufacturing. Currently, in terms of application of laser cladding, the method based on powder deposition is much more common, as the use of an adapted nozzle allows the coaxial and direction-independent feeding of additional material into the weld pool. However, laser cladding with powder also has some significant drawbacks, e.g., limited powder feeding and melting efficiency, lower productivity and the resulting dust that poses a health risk to operators. The solution to these limitations is the use of additional material in the form of wire. To maintain the ability to coaxially feed the wire to the laser beam interaction point, a specialized cladding head is necessary. In mentioned system the laser beam, while being passed through the optical system, is divided into three separate beams that are focused on the substrate on the working point of the head. In this study, the COAXwire cladding head was integrated into the robot station and laser cladding process was carried out to determine the influence of the processing parameters on the deposition results. The parameters of the cladding system were identified, including the measurement of laser beam caustic. The experimental trials were carried out using AISI 316L wire deposited on S420MC substrate. The effect of the processing parameters on the geometry of the clad was determined with particular emphasis on the wire feeding.

Keywords: laser cladding with wire; austenitic stainless steel; processing parameters; COAXwire; surface modification

Introduction

Laser cladding (LC) technology, also known as DMD (Direct Metal Deposition), LENS (Laser Engineered Net Shaping) or LMD (Laser Metal Deposition), is based on deposition of additional material on the surface using laser power. The weld pool is being created by the impact of the laser beam. Then process follows by the introduction of a supplementary material in form of powder or wire into the weld pool. Melting of added material continues principally by absorbing energy from the liquid metal and directly from the laser. When continuing the addition of material, volume of the fluid starts to increase and with the surface tension forces a convex shape is formed. While the process continues with the movement of the laser head, regions without further delivery of heat start to solidify and preserve obtained shape – which result in formation of cladding track - clad.

Laser cladding technology can sometimes be associated with welding technologies because similar process of deposition can be performed using standard arc welding techniques, e.g., MIG, TIG. But in contrast to them, in LC technology the energy source (laser beam) provides much higher power density, which results in high heating and cooling rates and relatively small heat-affected zones (HAZ) [1,2]. A much lower overall amount of energy is delivered to the material which can lead to higher accuracy in clad geometry. Due to that, this technology finds application in the field of additive manufacturing [3]. Compared to other AM technologies connected to processing metals, LC has some specific capabilities. Among them, worth mentioning is ability of manufacturing large-sized objects, larger than size of workspaces of most "conventional" machines (kinematics based on two-direction moved head and vertically moving table). Laser cladding head is often mounted od robotic arm, sometimes cooperating with moving table which gives ability of manipulating building object and ensure access from different angles, thus it allows to carry out laser cladding process in non-vertical position. It’s also quite effective – objects can be built with feed rate up to 8 kg/h [4]. This technology allows to use multiple materials, e.g.: steel, nickel, aluminum, copper and their alloys and gives ability to mix used materials forming composite clad structure [5–8].

Supplementary material in the laser cladding technology can be delivered in the form of powder or wire [9]. The use of material in powder form offers the possibility of flexible modification of the composition of the added material due to the possibility of mixing two or more types of metallic powders or metallic powders with ceramics. However, this process presents several disadvantages, the most important of which are the hazard of working with powders due to their effects on human health and the relatively low productivity of powder deposition process. Typically, only a part of the delivered powder is melted and used to form a clad, which accounts for the low efficiency of this method [10]. There is also a lack of dynamic control of the amount of fed material. The solution to the problems mentioned above is the use of additional material in the form of wire. In this case, both the level of work safety is increased due to the elimination of respirable powder particles, as well as improved process efficiency - up to 100% of the material is used. The simplest way to implement the process with wire is lateral feeding using a standard laser head - however, this solution requires a strictly defined orientation of the wire feeder-head system with respect to the process direction. Independence of the depositing direction from the orientation of the cladding head is possible for the process with coaxial wire feeding called Coaxial Laser Wire Deposition/Melting (CLWD/CLWM). Such solutions require modification of the optical system to focus the laser beam at the point of material feeding, while avoiding the obscuring of the beam by the wire. A ring beam or several separate, evenly spaced beams are usually used [11,12].

There is ongoing research on the applications of laser cladding technology with wire feed. A comparison of cladding with powder and with wire for the IN718 alloy showed greater efficiency of the LWD process and provided slightly higher strength and elongation of the fabricated samples [13]. A similar study for the In 625 alloy highlights significant differences in the clad geometries depending on the material feeding method due to different beam energy distribution ratios between the supplementary material and the substrate [5]. Work has also been carried out on comparing laser, arc and electron wire surfacing technologies for austenitic stainless steels [2,14] and the possibility of using an aluminum alloy [7]. It was shown that by using additional energy sources in the process in the form of arc or induction heating, the efficiency of the process can be increased [15].

The subject of this work is the study of the effect of process parameters (simple and complex) on the geometric properties of single 316L steel clads on S420MC steel substrate with the aim of determining the qualitative relationship between process parameters and the applicability of the CLWD process for selected materials. The study is a representative example of the application of the technology as a modification of the properties of a component by applying a material with better anticorrosion properties to a substrate that is relatively inexpensive and accessible. Additional elements of the work include the estimation of the causes of process errors such as non-melting of the wire and substrate or uneven deposition of the surfacing (globular cladding). In addition, relationships between the properties of the clad and the process parameters were proposed, which can be used in the development of the CLWD process.

Materials and Methods

Experimental setup

This study was carried out using 4 kW HPDL unit Laserline 4000–30 as the laser beam source and a Coaxworks wire M (COAXwire) cladding to conduct laser cladding experiments. The head was mounted on a 6-axis Reis RV60–40 robot. The wire feeding system from DINSE GmbH consisted of DIX FDE-PN 100L main unit and DIX FD 101 LS end wire drive unit. Proper shielding gas (argon) flow rate was provided by flow controller Vögtlin GSC-C9SA. Process setup is presented in **Fig. 1**. Process details in the beam interaction point is shown in **Fig. 2.**

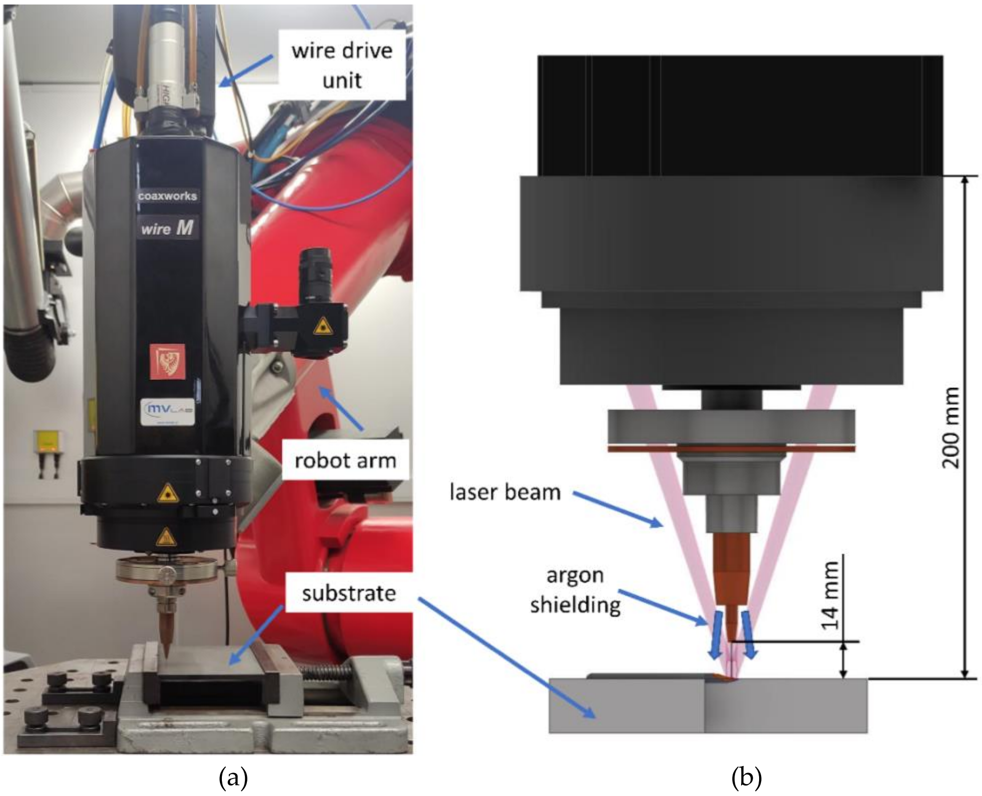


Fig. 1. Process setup: (a) laser cladding head mounted on the robot arm, (b) scheme of the head positioning

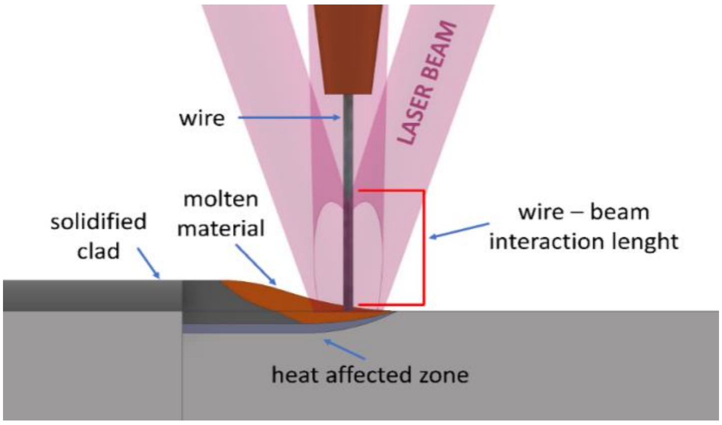


Fig. 2. Laser cladding process with coaxial wire feeding scheme

Cladding head was being held at 200 mm above the sample surface to provide beam crossing and focal point at the substrate surface. This resulted in 14 mm free wire end. Substrate was S420MC steel plate with dimensions of 100 mm x 200 mm with 4 mm thickness. Filler wire was AISI 316L steel with 0.6 mm diameter. Chemical composition of the materials is shown in **Table I**. In order to find the chemical composition of both substrate and wire material the energy-dispersive spectroscopy (EDS) was used during the analysis on the scanning electron microscope (SEM).

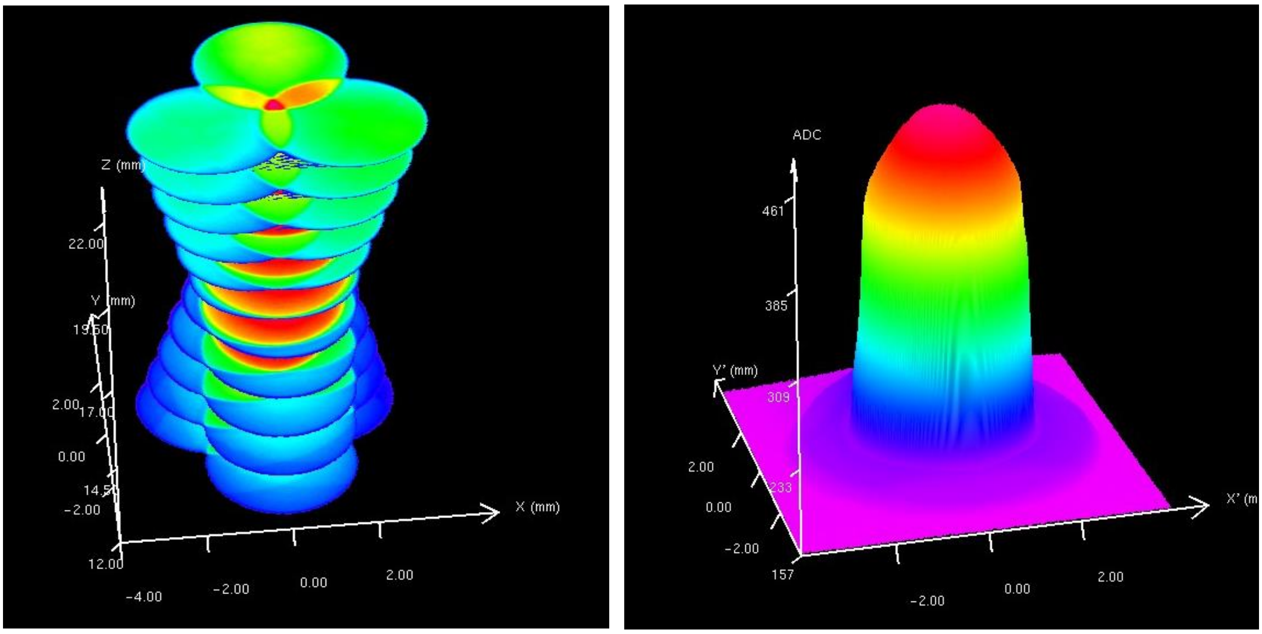
Table I Chemical composition of the materials used in the study measured with EDS method

Material	Chemical Composition (wt. %)							
	Fe	C	Mn	Cr	Ni	Mo	Cu	Si
S420MC	bal.	0.12*	1.84	-	-	-	-	0.31
AISI 316L	bal.	0.03*	1.99	17.51	10.68	1.67	0.27	0.54

*The value stated in the material certificate

Working beam characteristic

The laser beam was delivered to the processing head with the 600 μm diameter fiber. Within the COAXwire head the main beam is being divided into three separate beams and directed to the surface of the object equally from three different sides with the incidence angle of 20°, allowing coaxial introduction of the filler wire (see **Fig. 1b**). Final processing beams were focused with the 300 mm focal length lens. This allows the optical system to obtain a spot diameter of 4.55 mm. The beam power intensity distributions at several planes near the focal point were measured using a PRIMES FocusMonitor instrument. Results of the measurements are presented in **Fig. 3.**



(a) (b)

Fig. 3. Presentation of the laser beam used in the Laser Wire Deposition process: (a) the superposition of three individual laser beams in the focal point of the COAXwire optical system, (b) the laser beam intensity in the focal point

Methodology

The purpose of the work was to study the effects of the basic parameters of the laser deposition process with coaxial wire feeding on the geometric and quality parameters of the clad. Experiments were carried out for three variable parameters: laser beam power, feed rate and wire feed rate. Constant parameters were the type and amount of shielding gas fed and the length of the free wire length. The ranges and values of the parameters used during the process are shown in Table II. Chart in **Fig. 4** shows the parameter sets to be tested according to the proposed plan. It also marks the densification points proposed based on the results of the basic tests to provide a more detailed examination of the relationship at the transition points.

Table II List of process parameters used during experimental trials of CLWD process

Parameter	Abbreviation	Value
Laser power	P_{las}	1000 - 3000 [W]
Feed rate	f_{clad}	5 – 15 [mm/s]
Wire feed rate	f_{wire}	2 – 6 [m/min]
Inert gas	-	Argon, 20 [l/min]
Free wire length	-	14 [mm]

Before the process, the substrate was sandblasted and cleaned with isopropanol. Each clad was 40 mm long. A minimum gap of 10 mm was maintained between successive depositions and each process was carried out on the cooled surface.

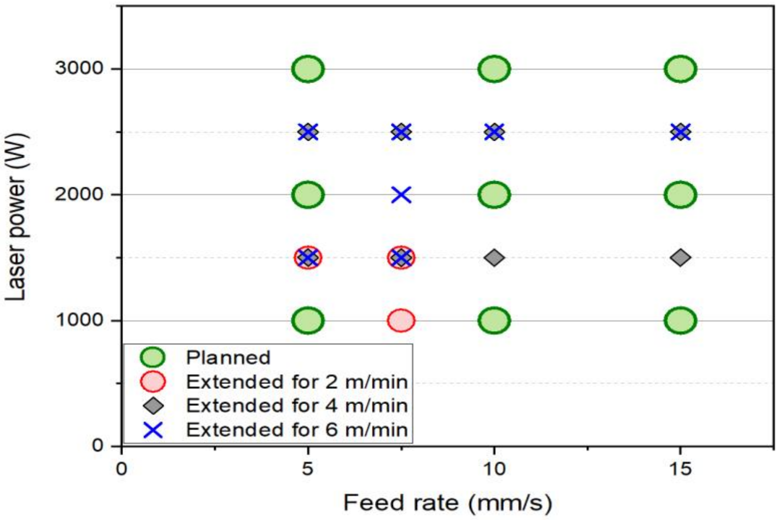


Fig. 4. The schematic representation of the planned experimental research of the LMD process

Results and discussion

Qualitative analysis

The first issue described in this paragraph concerns the determination of process applicability maps. This will permit to define preliminary process parameters set called "process window" which ensures that the process is carried out properly without any bold errors. In this matter 4 different descriptions of CLWD process results were defined:

- Lack of deposition – the wire feed rate is to high compared to the possibility of the wire melting in the weld pool induced by laser radiation. This causes the wire tip to bounce off the substrate and the CLWD process is not carried out.
- Intermittent clad – this is a situation that occurs when the process is on the brink of stability in terms of feeding wire into the weld pool. Therefore, the resultative clad appears to be irregularly deposited and intermittent (**Fig. 5a**).
- Globular cladding – when the laser power parameter is high enough to cause the melting of the wire before it reaches the melt pool, the deposition of the wire material has a globular character. The outcome of such a process is a clad composed of big discrete droplets (**Fig. 5b**).
- Correct clad – a subjective visual assessment allows to state that the clad was correctly deposited without bold flaws and errors (**Fig. 5c**). It is worth emphasizing that only the clads from this group were analysed in terms of quantitative properties.

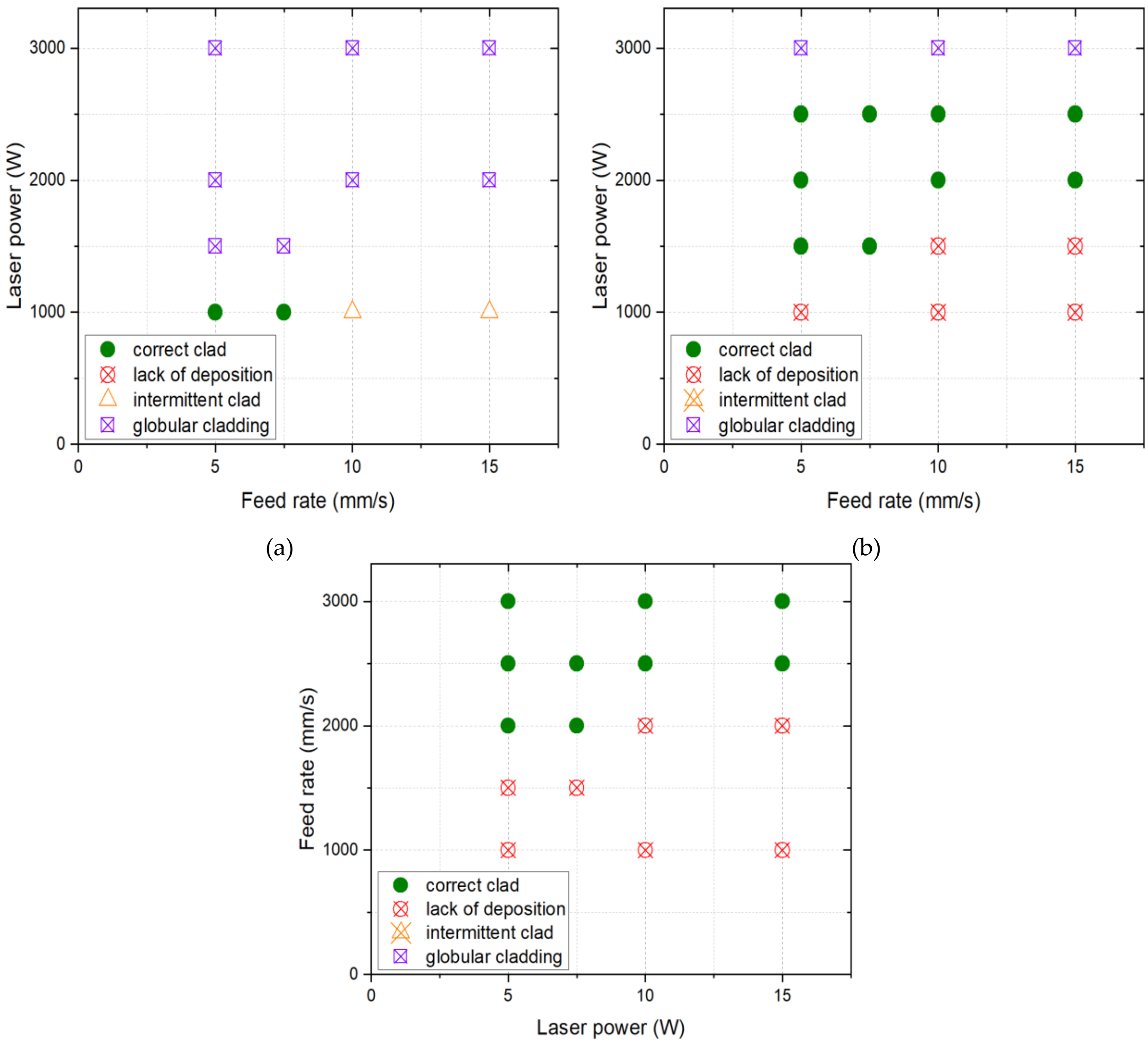
(a) (b)

(c)

Fig. 5. Sample photos of the faces of the clads showing

The CLWD process applicability maps were shown in **Fig. 6** for each wire feed rate (f_{wire}) separately. The coordinates in these maps are other two variable process parameters – laser power (W) and feed rate (mm/s). Generally, it can be said that for analysis of the single wire feed rate the increase of laser power leads to globular cladding, whereas its decrease may result in lack of deposition process. The range of process parameters, where the result of the process can be called a correct clad lay between those two mentioned anomalous zones. the qualitative types of LMD process results. However, the occurrence of the zone with globular cladding relates to complex parameter wire heat input, that is the quotient of laser power and wire feed rate. The emergence of globular cladding phenomena is present when its value exceeds 45 J/mm. This explains why no globular cladding was observed with wire feed rate of 6 m/min, since the laser power should then be 4500 W, what exceeds the laser unit capabilities.

Moreover, the process window is moving towards the higher powers of the laser beam with the increase of wire feed rate. In case of the highest value of wire feed rate (6 m/min) no globular cladding was observed. The intermittent clads were noticed only during CLWD process with the f_{wire} of 2 m/s, yet lack of deposition was not observed with this wire feed rate. In addition, the increase of feed rate (f_{clad}) in the CLWD process has an impact on the "correct clad zone" in the form of its narrowing as these parameters increases and reduces laser beam interaction time with substrate that is responsible for the formation of the weld pool.



(a)

(b)

(c)

Fig. 6. Coaxial Laser Wire Deposition applicability maps for various wire feeding parameters: (a) 2 m/min, (b) 4 m/min, (c) 6 m/min

Quantitative analysis

The more complex analysis was conducted on deposited clads remarked as correct. This gives 20 parameters set that were investigated in terms of geometrical properties of the deposited clads. The values of process parameters as well as resultative properties of the clad were assembled in **Table III**
In addition, the complex process parameters were also determining such as heat input (Eq. 1) or newly defined wire heat input (Eq. 2) and wire feed rate coefficient (Eq. 3).

$$Heat\ input = \frac{P_{las}}{f_{clad}} \tag{1}$$

$$\text{Wire } Heat\ input = \frac{P_{las}}{f_{wire}} \tag{2}$$

$$Wire\ feeding\ coefficient = \frac{f_{wire}}{f_{clad}} \tag{3}$$

Table III contains also the values of clad geometrical properties measured with digital microscope (Keyence VHX-6000) e.g. clad height or penetration and HAZ depth. Furthermore, a width of the clads was also measured to calculate aspect ratio (AR, Eq. 4) and dilution (Eq. 5) of the clads. All the measurements were carried out on transverse metallographic cross-sections of the specimens (**Fig. 7**.).

Table III List of process parameters and clad properties for group of correct clad

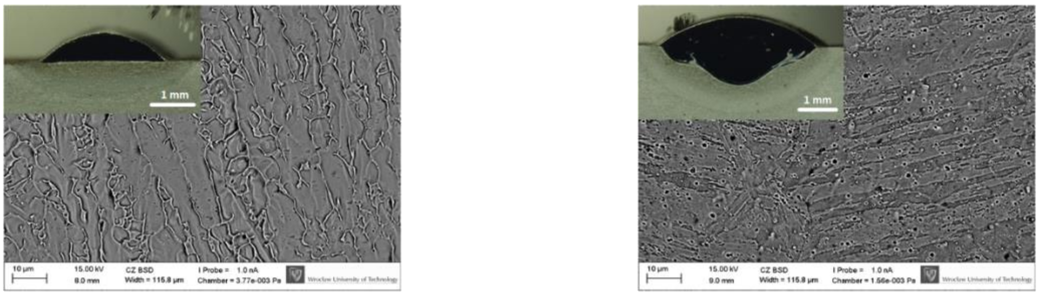
Wire feed rate	Laser power	Feed rate	Heat input	Wire heat input	Wire feed coefficient	Clad height	Penetration depth	HAZ depth	AR	Dilution
(m/min)	(W)	(mm/s)	(J/mm)		(1)		(µm)		(1)	(%)
2	1000	5	200	30	6.67	801	38	1162	4	5
		7.5	133.(3)	30	4.44	670	33	877	4.3	5*
4	1500	5	300	23	13.33	1328	402	1210	2.8	23
		7.5	200	23	8.89	989	288	1081	3.5	23
	2000	5	400	30	13.33	1406	1137	2135	2.8	45
		10	200	30	6.67	786	774	1471	4.4	50
		15	133.(3)	30	4.44	596	511	1215	5.6	46
	2500	5	500	38	13.33	1228	1401	2396	3.6	53
		7.5	333.(3)	38	8.89	871	1139	1908	5	57*
		10	250	38	6.67	724	886	1643	5.9	55
		15	166.(6)	38	4.44	562	648	1314	6.3	54
6	2000	5	400	20	20	1755	654	1596	2.6	27
		7.5	266.(6)	20	13.33	1427	611	1336	2.5	30
	2500	5	500	25	20	1717	934	1969	2.5	35
		7.5	333.(3)	25	13.33	1308	670	1816	3.2	34
		10	250	25	10	1102	606	1426	3.5	35
		15	166.(6)	25	6.67	780	493	1386	4.6	39
	3000	5	600	30	20	1690	1404	2442	2.8	45
		10	300	30	10	910	626	1466	4.2	41
		15	200	30	6.67	750	720	1378	5.3	49

*Samples selected for extended microstructure and chemical composition analysis

$$AR = \frac{clad\ width}{clad\ height} \tag{4}$$

$$\text{Dilution} = \frac{penetration\ depth}{penetration\ depth + clad\ height} \tag{5}$$

In the **Fig. 7** two representative cross-sections of the clads were shown since the clads are characterized by extreme dilution values of 5 (**Fig. 7a**) and 57% (**Fig. 7b**) respectively. In the latter case an extensive penetration in the centre zone of the clad can be observed what is the result of high value of laser power compared to wire and cladding feed rates (**Table III**).



(a) (b)

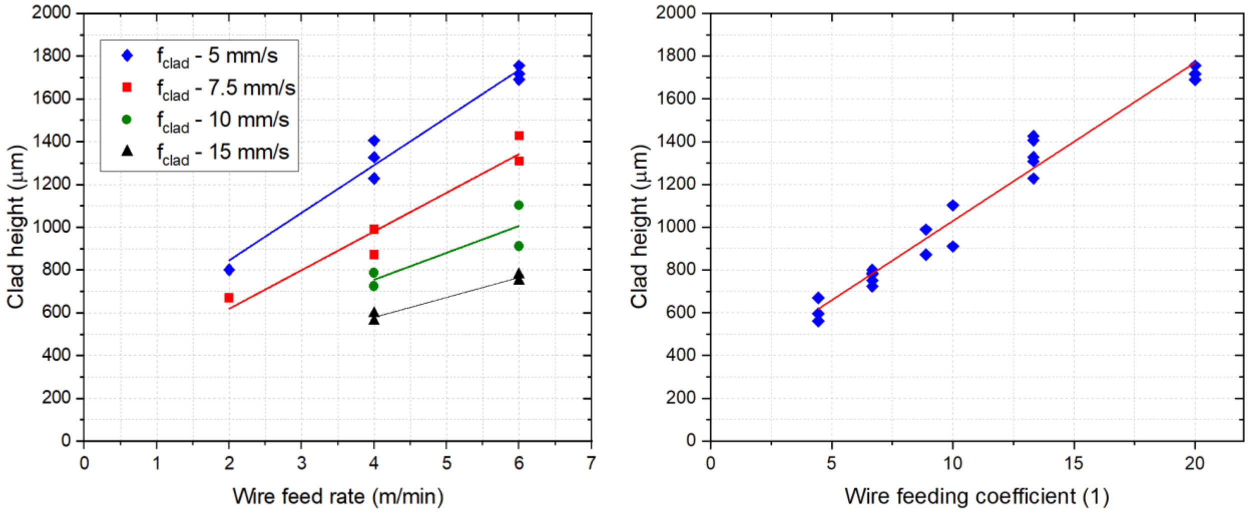
Fig. 7. Cross-sections of clads with extreme values of dilution parameter: (a) minimal value of dilution – 5%, (b) maximal value of dilution – 57%

Moreover, the clads differ in case of content of alloying elements such as Cr, Ni and Mo. With higher dilution value the composition of the clad significantly deviates from the chemical composition of the wire material. The decrease of alloying elements that stabilize austenitic structure in the resulted information of lath martensite in the clad (**Fig. 7b**).

Table IV Chemical composition of clads with minimal and maximal value of dilution parameter

Dilution (%)	**Chemical Composition (%)**						
	Fe	**Cr**	**Ni**	**Mn**	**Mo**	**Cu**	**Si**
5	bal.	17.36	10.55	2.04	1.65	0.17	0.47
57	bal.	7.96	4.67	1.91	0.62	0.13	0.23

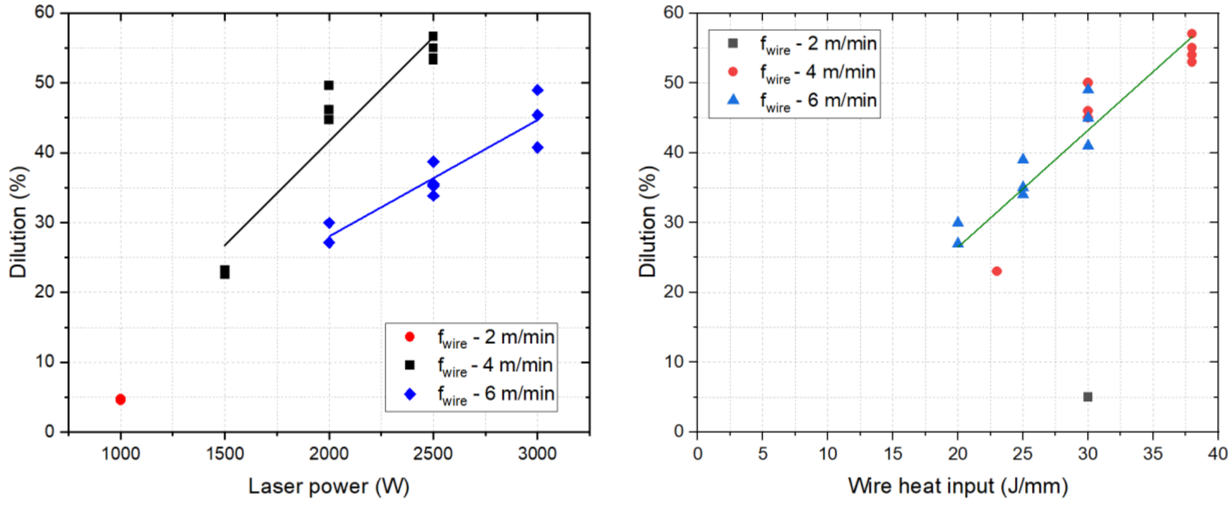
The influence of process parameters on geometrical clad properties is shown in the **Fig. 8÷Fig. 10.** The vital property of the clad in CLWD process is its height. In the **Fig. 8a** the dependence on wire feed rate for each feed rate of the cladding process is illustrated. With the increase of the cladding feed rate the slope factor of the linear fit is decreasing. The differences between clad heights for constant wire feed rate and variable cladding feed rate seem to be proportionate. This leads to conclusion that the wire feeding coefficient can be used as an independent variable resulting in receiving. the linear dependence with R^2 equal 0,97 (**Fig. 8b**).



(a) (b)

Fig. 8. The dependence of the clad height on the parameters of the CLWD process: (a) wire feed rate, (b) wire feeding coefficient

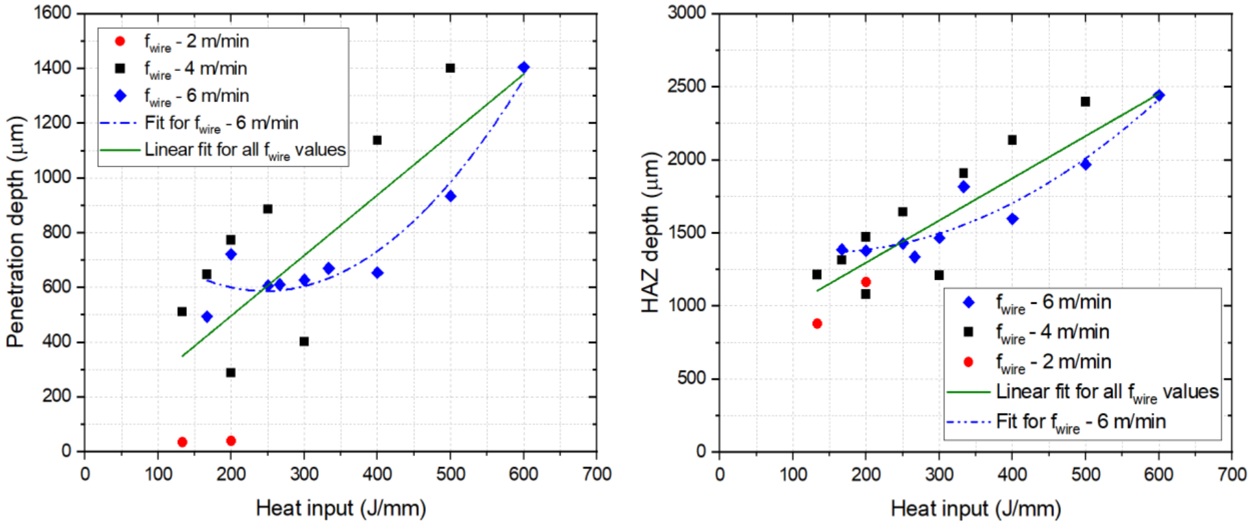
In case of clad dilution, the separation of results according to the wire feed rate is needed. Then one can obtain the linear dependency of the dilution on the laser power for each f_{wire} (**Fig. 9a**). The use of complex parameter like wire heat input is also useful to introduce single linear dependence for data characterized by f_{wire} equals to 4 or 6 m/min (R^2 – 0,86). Considering the 2 m/min f_{wire} such simplification is not valid, as the dilution is relatively small in case of trials carried out with this wire feed rate compared to other.



(a) (b)

Fig. 9. The dependence of the dilution on the parameters of the CLWD process: (a) laser power, (b) wire heat input

The geometrical properties of the clad, which are related with the properties of the substrate material are penetration depth and HAZ depth. In the **Fig 10** the measured values of these parameters were plotted against the heat input calculated for every experimental trial. The penetration depth shows weak linear dependence (R^2 – 0.59) on this complex parameter (**Fig. 10a**), whereas the HAZ depth can be determined using a linear relationship with the heat input without committing a significant error (**Fig. 10b**), since R^2 is equal to 0.78. On the other hand, one can analyze the results for each fwire separately. In case of 6 m/min wire feed rate it turns out that both the penetration and HAZ depth are characterized by a square dependence on the heat input to the substrate.



(a) (b)

Fig. 10. The properties of the clad related to substrate properties versus heat input parameter with dataset categorized by wire feed rate value: (a) penetration depth, (b) HAZ depth

Conclusions

The aim of this study consisting of determination of qualitative and quantitative influence of basic and complex CLWD process parameters on geometrical properties of the clad was achieved. The “process window" for deposition of 316L wire material on S420MC substrate was described for variable wire feed rate. Moreover, the basic causes of CLWD process failure such as lack of deposition or globular cladding were discussed and connected with the values of process parameters in qualitative analysis. The occurrence of globular cladding was successfully connected with the value of complex parameter – wire heat input.

In quantitative analysis of CLWD process results the linear dependencies between geometrical clad properties and process parameters were found;

- The clad height can be described by the linear dependence on wire feeding coefficient or wire feed rate when a single cladding feed rate is considered.
- The dilution of the clad shows linear dependence on wire heat input for higher wire feed rates, but it can be also determined from linear dependence on laser power, when single wire feed rate is considered.
- The penetration depth shows weak linear dependence on heat input, whereas the penetration depth for clads deposited with 6 m/min wire feed rate is clearly showing square dependence on the heat input.
- The HAZ depth is linearly dependent on heat input to the substrate material. However, one can find the square relationship between these two quantities when 6 m/min f_{wire} is analyzed.

Moreover, the analysis of chemical composition of clads with minimal dilution (5%) showed high similarity with the wire material, whereas the composition of the clad with much higher dilution (57%) differs in case of content of Cr, Ni and Mo as well as the resultative phase composition.

Author Contributions: conceptualization, P.K., P.R. and J.K.; methodology, P.K. and P.R.; software, P.K..; validation, P.K. and P.R.; formal analysis, P. K. and P.R.; investigation, P.K.; resources, P.K., P.R. and R.D.; data curation, P.S. and R.D.; writing—original draft preparation, P.K. and P. R.; writing—review and editing, P.K.; visualization, P.K. and P.R.; supervision, J.R.

Funding: This research received no external funding

Conflicts of Interest: The authors declare no conflict of interest.

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